

On hydrosphere: Its definition, concerns, and challenges [version of record]

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ABSTRACT

The hydrosphere, a concept stemming from geology and geography, is conventionally recognized as a layer of water on the Earth. Despite its frequent mention in literature, systematic studies on this subject are rare yet. Presented in this paper is our recent perspective on the hydrosphere, providing a comprehensive overview of the research focused on the functions of water in global cycling. We defined the hydrosphere as a dynamical system comprising water materials in solid, liquid, or vapor states, which cyclically interact on a global scale, forming a complex network in alignment with the inherent nature of water and its cycling process. The challenges associated with studying the hydrosphere are discussed, emphasizing the significance of understanding its dynamics, topology, and infordynamics. Furthermore, potential approaches to achieve a thorough comprehension of the hydrosphere are discussed.

KEYWORDS

Hydrosphere, water cycle, dynamics, topology, infordynamics.

1 What is the hydrosphere?

1.1 From water to hydrosphere

Water, one of the most abundant and fundamental compounds on the Earth, exists in a variety of forms, including water vapor drifting in the atmosphere, liquid flowing in rivers, lakes, and oceans, and solid piling as snow, ice, and glaciers upon the Earth surface, even as important part of crystals deeply buried beneath the Earth surface. It plays a key role in the existence, development, and stability of the ecological and social systems of the Earth. Therefore, the study of water encompasses numerous disciplines, including major ones such as hydraulics, geophysics, geochemistry, ecology, hydrology, meteorology, coast, ocean and many others within the realm of hydro-science. Each discipline focuses on a specific aspect of water materials. For instance, hydrology investigates terrestrial water movement and storage, meteorology examines atmospheric moisture transport and precipitation processes, oceanography studies marine water circulation, and ecology focuses on water-vegetation interactions and evapotranspiration. This intricate cycle involves evapotranspiration from land soils and plant leaves, the transport of water vapor through atmospheric circulation, precipitation resulting from thermal and dynamic forcing caused by various meteorological phenomena, and eventually culminating in surface runoff flowing into the oceans.

Although there are considerable differences between those disciplines with close or loose relation to hydro-science, they share a common concept, i.e., the hydrosphere. Figure 1 shows the results of searching for the keyword “hydrosphere” in the SCI-E citation index of the Web of Science Core Collection Database from 1900 to 2023. There are 1,953 in total relevant publications. The main disciplines involved are Environmental Sciences (430 articles, 22% of the total), Geosciences (394, 20%), Geochemistry Geophysics (321, 16%), Water Resources (158, 8%), Multidisciplinary (117, 6%), Meteorology Atmospheric (109, 6%), Oceanography (94, 5%), Engineering Environmental (78, 4%), Astronomy (71, 4%), and Chemistry (69, 4%).

The concept of hydrosphere was first introduced in 1875 by the Austrian geologist Eduard Suess (Suess, 1875). Currently, the hydrosphere is commonly defined as the total amount of water present on Earth, including water on the surface, underground, and in the atmosphere. It encompasses all forms of water including liquid, solid, and vapor. While specific definitions may vary slightly across sources, the essential concept remains consistent: the hydrosphere represents the entirety of Earth’s water in all its physical states and locations.

It is no doubt that the hydrosphere plays a vital role in the existence, evolution, and sustainability of both natural systems and human societies because of its indispensable support to livings on the planet to be possible. However, it is intriguing to observe that while numerous studies, both loosely and closely related to the concept of the hydrosphere, have been reported, a comprehensive understanding of the hydrosphere as a unified entity remains far from satisfactory. For example, how the earlier hydrosphere originated is still under debate due to lack of sufficient evidence (Henderson-Sellers et al., 1982; Bindeman et al., 2022); how it evolves in time is not fully understood because the whole picture of the hydrosphere has not been established; how it interacts with other spheres is a cutting-edge topic in the sense of reaction, adaption, and feedback of the hydrosphere to climate change. This interesting situation can be largely attributed to the inherent complexity of the hydrosphere, the mysteries of which cannot be unraveled through a single thread of investigation. Nevertheless, our understanding of the hydrosphere has undergone significant evolution since the concept was initially

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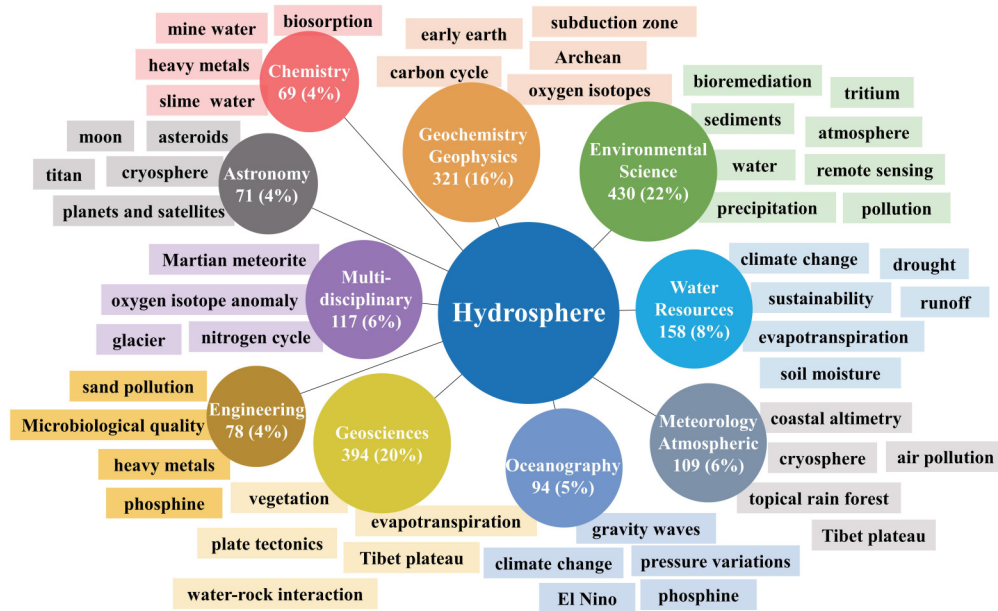


Fig. 1 Disciplines related to the hydrosphere and their keywords. The top ten disciplines that publish articles on the hydrosphere are represented by circles radiating from the central circle. The number of articles is displayed beneath each discipline's name, and their percentages of the total articles are shown in parentheses. The circles with similar colors are enclosed in boxes, indicating the high-frequency keywords associated with the hydrosphere within each discipline.

introduced centuries ago. Through sustained interdisciplinary research endeavors, scientists have achieved substantial advancements, yielding confirmed results and conclusions that establish a strong foundation for deepening our comprehension of the hydrosphere.

1.2 Definition of hydrosphere and its characteristics

A precise definition is of utmost importance when developing theories concerning the hydrosphere. Historically, the understanding of the hydrosphere has evolved through stages: from the classical conception of the hydrosphere as the totality of water on Earth since Suess (1875), to the functional classification of water materials into blue water, green water (Falkenmark and Rockström, 2004), and white water (Li et al., 2018) based on their distinct roles in the global water cycle. While the widely adopted definition suffices in conveying its general meaning as a sphere or layer of water materials, we aim to delve deeper into this topic based on the most up-to-date knowledge available about the hydrosphere.

The hydrosphere can be described as a system characterized by intricate structures, comprising water entities at various scales in the forms of liquid, solid, or vapor, which is dynamically interconnected through global and local water cycles. It also participates in material transport, energy transfer, and carbon cycle to interact with the biosphere, lithosphere, atmosphere, and cryosphere in the earth systems (Himiyama et al., 2020). The upper boundary of the hydrosphere is primarily affected by radiation from solar radiation, while its lower boundary is determined by the cessation of water movement. The hydrosphere exhibits the following general characteristics:

- (1) It is complex, sharing the periodical, chaotic, self-organizable features of general nonlinear systems.
- (2) It is topological, owing to global and local structures developed due to both external and internal organized driving forces.
- (3) It is stochastic, making long-term behaviors of the hydrosphere blurred by drift and diffusion due to randomness.

We acknowledge that the definition we have presented is not the definitive and final version, despite our sincere efforts to provide a specific, clear, and comprehensive understanding based on current knowledge. It is crucial to recognize that as our future studies progress, our understanding of the hydrosphere will inevitably evolve. Consequently, the definition itself may undergo further depth, modification, or even significant revisions. Science is an ongoing and iterative process, where new insights and discoveries continuously shape and refine our comprehension of complex phenomena, including the hydrosphere. Therefore, we maintain an open mindset, eagerly anticipating future research and scientific progress that may lead to additional revisions and advancements in our understanding of this intricate realm.

2 Why should the hydrosphere be studied?

First and foremost, it is important to recognize that the hydrosphere is not merely a superficial layer of water materials on our planet. Currently, the hydrosphere is known by nature that it serves as a container, a propeller, or a linker which provides space, forces, and connections that hold water of different states in the planet to exist, cycle, and interact with other sphere systems including the carbon-sphere, biosphere, lithosphere, atmosphere, and cryosphere (Himiyama et al., 2020). This realization highlights that the hydrosphere exhibits specific structures, both in terms of its geometry and dynamics. The geometric part, or the static part, depending on the geographical characteristics of different regions, accounts for the global distributions of water bodies; while its dynamical part, typically represented by the water cycle, facilitates the interconnections among subsystems such as catchments of rivers, oceans, atmospheric circulations within the hydrosphere. The water cycle, as the most significant component of the hydrosphere representing the dynamic properties of the complicated system, provides us with a direct lens through which we can examine how the structures within the

hydrosphere link to each other. Figure 2 presents a conceptual schematic of the hydrosphere structure, illustrating its three functional roles (container, propeller, and linker), its geometric and dynamic components, and its interactions with other Earth system spheres.

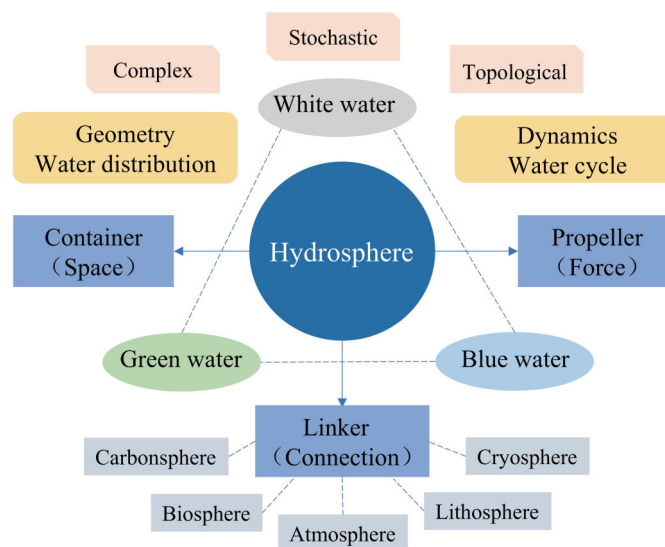


Fig. 2 Conceptual schematic of the hydrosphere structure.

Second, the water materials within the hydrosphere have been examined and approached from various perspectives, leading to a significant expansion in the understanding of its composition. In light of their diverse functions, the water materials on our planet can be categorized into three distinct parts. They are green water (Falkenmark et al., 2004), blue water (Falkenmark et al., 2004), and white water (Li et al., 2019). The green water is those water flows participating in evapotranspiration which is crucial in ecosystems (Falkenmark et al., 2004; Wang-Erlandsson et al., 2022; Mastrotheodoros et al., 2020); the blue water is those flows as surface runoffs that provides fresh water resources (Hoekstra et al., 2012; Rodell et al., 2018; Scanlon et al., 2023); while the last one was firstly given by Wang et al. (2020), which refers to the atmospheric water having the potential to precipitate. Delicate differences between cloud water and white water can be found in Wang et al. (2020) and the significance of the concept lies in the fact that the white water makes the flows of water in the hydrosphere a complete cycle.

Third, applications of novel technologies have revolutionized our traditional perspectives on the hydrosphere. Booming advances in remote sensing technologies, coupled with the rapid increase in the numbers of either ground-based or space-based observatories worldwide since the previous century, have facilitated the accumulation of an extensive volume of data related to hydrosphere-related topics. In recent decades, the rate of data generation has soared, resulting in the emergence of Big Data on a scale never before witnessed in centuries past. Concurrently, accompanied by the accretion in Big Data, AI (artificial intelligence)-based methods have opened up new avenues for uncovering the essential mechanisms underlying the hydrosphere, which conceal deeply beneath the vast realm of Big Data. For instance, by virtue of methods developed in the studies of flow-based communities, the authors of this paper found the linkage of surface/ground water to atmospheric vapor water by evapotranspiration/precipitation processes as local procedures that leads to globally existing catchment-like structures in the atmosphere (Zhang et al., 2020). Without the invention of sophisticated big-data methodologies, the global property of the water cycle, as revealed in this study, would have remained undiscovered. Looking ahead, it is anticipated that AI-based methods plus Big Data with information theories will help us to form a global view of the hydrosphere, which is necessary to make long-term prediction behaviors of the hydrosphere possible.

In summary, it is high time to study the hydrosphere as an inseparable integrity. The purpose of this paper is to provide a conceptual framework for our ongoing and future research on the hydrosphere. To clarify the scope of this framework, it is important to distinguish it from existing Earth system modeling approaches. Although modern Earth system models (e.g., CMIP models) simulate interactions among atmosphere, land, and ocean components, they primarily provide numerical representations of coupled processes based on predefined model structures. In contrast, the hydrosphere framework proposed here emphasizes conceptual and diagnostic integration of water cycling processes across disciplines and scales, aiming to provide a unified perspective on system organization rather than a specific numerical modeling architecture. Our approach involves treating the hydrosphere by regarding it as a dynamic system, where the topology of internal structures, response to external forcing, and interaction with other systems are key issues. We must admit it might be incomplete, more like a research proposal rather than a matured paper; however, thanks to the new journal *Hydrosphere* permitting us to revise this paper when it is necessary. We would like to present it to readers of this journal in its current state and make an on-time-revision as long as our research progresses and this journal continues to thrive.

3 What have we known about the hydrosphere?

The hydrosphere can be understood from various perspectives, such as geophysical, geochemical, hydrological, or ecological viewpoints. In this study, we adopt a functional perspective that emphasizes the role of water as a natural resource within the Earth system. Under this framework, the hydrosphere is divided into three categories: blue water, green water, and white water, each representing a distinct

component in the land-atmosphere water cycle. It is important to note that although seawater comprises the majority of Earth's water and is a key part of the hydrosphere, it is not included in this classification. The blue-green-white water framework primarily focuses on terrestrial water processes and their links to ecological functions, freshwater availability, and atmospheric interactions.

3.1 Blue water

Bluewater is the fresh water in reservoirs, lakes, rivers, and aquifers, i.e. fresh surface and groundwater. It plays a fundamental role in sustaining life on Earth and serves as a direct water resource for human societies. To gain insights into the current state of blue water resources, Figure 3 illustrates the global distribution of blue water availability at the country level (Food and Agriculture Organization of the United Nations, 2022). The estimation of global renewable water resources (TRWR) stands at approximately 50,000 km³/a. However, the availability of blue water exhibits significant spatial heterogeneity, both in terms of per capita and total quantity.

In addition to examining the total quantity and spatial distribution of blue water, it is essential to investigate the long-term changes in blue water storage, often referred to as terrestrial water storage (TWS). This topic has gained significant progress due to the advancements in satellite remote sensing, which enable the monitoring and analysis of TWS dynamics over multiple decades. Scanlon et al. (2023) estimated the global TWS changes over 2002–2022 based on the Gravity Recovery and Climate Experiment (GRACE) satellite data, and Table 1 shows the TWS trends of the major basins and aquifers where the coefficient of determination (R^2) of the trends exceed 0.6. Trends in terrestrial water storage (TWS) with relatively high confidence are predominantly characterized by negative values, primarily

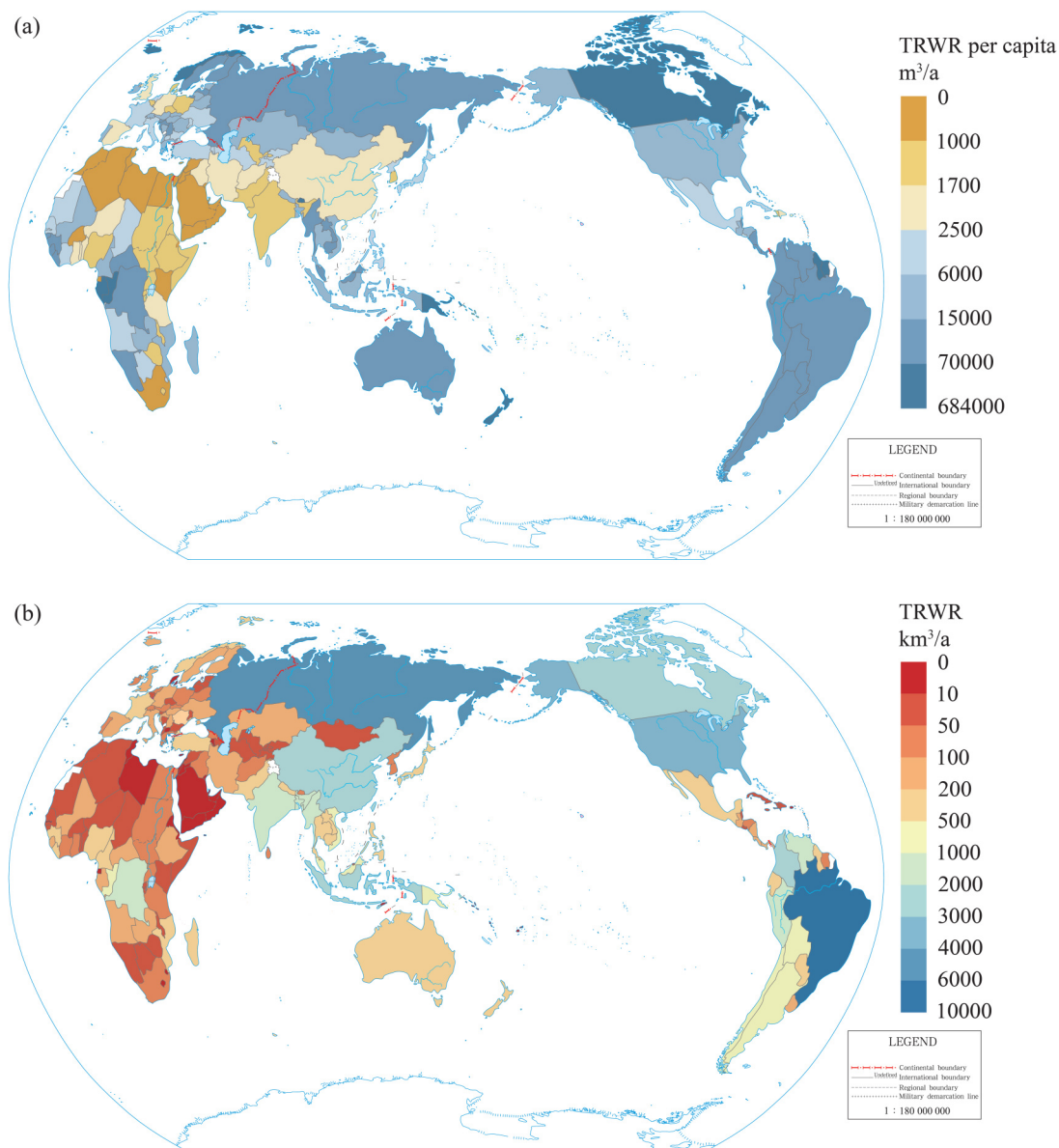


Fig. 3 The global distribution of blue water availability (total renewable water resources (TRWR) per year), supported by Food and Agriculture Organization of the United Nations (2022). (a) Global distribution of TRWR per capita (m³/a); (b) Global distribution of TRWR (km³/a). Map Content Approval Number: GS 京 (2024) 0140 号.

Table 1 TWS trends for major basins and aquifers ($R^2 \geq 0.6$) adapted from Scanlon et al. (2023).

Basin or aquifer name	Area (km ²)	TWS trend (mm-year ⁻¹)	TWS trend (km ³ in 19 years)
Hai	163,076	−19.3	−60.9
Ganges-Brahmaputra	634,565	−18.9	−231.5
São Francisco	613,748	−18.7	−221.9
North China Plain	437,748	−11.5	−97.1
North Caucasus	295,468	−10.6	−60.4
Iran	1,648,268	−9.9	−309.9
Dnieper	513,997	−9.6	−95
Don	424,826	−9.2	−75.6
Arizona Alluvial	225,404	−7.9	−34.5
Arabian	1,771,399	−5.8	−199.7
Tarim	468,333	−2.6	−28.8
Nubian	2,203,920	1.4	59.9
Yangtze	1,831,074	3.0	104.7
Iullemeden	594,821	5.1	58.8
Niger	2,123,649	6.3	260.1

concentrated across broad Eurasia. A similar investigation was carried out in a previous study conducted by Rodell et al. (2018) wherein they provided a concise explanation for the underlying causes of TWS trends observed in global hotspot regions. Their findings revealed that human interventions, including activities such as reservoir filling, groundwater overexploitation, and irrigation, exert a substantial influence on regional TWS trends. And the Inter-governmental Panel on Climate Change (IPCC) Working Group II (WGII) further confirmed with high confidence the disturbance of the hydrological cycle by human factors. Under the combined effects of climate variability and anthropogenic pressures, the decline in global TWS has continued to intensify: satellite observations show that global TWS declined abruptly after 2014 and had not recovered by 2023, with ENSO-driven oscillations superimposed on this long-term drying trend causing dry extremes to become increasingly dominant since 2012 (Rodell et al., 2024; Rateb et al., 2025).

Looking towards the future, IPCC WGII has provided a synthetical projection of runoff changes of major river basins at different global warming levels (Caretta et al., 2022). There is a high level of confidence that substantial alterations in streamflow will transpire across ice-free land areas. It is anticipated that the magnitude of these changes will escalate as global warming intensifies. However, it is crucial to acknowledge the uncertainties surrounding the direction of these changes, whether they will be positive or negative. This highlights the immense challenge in comprehensively characterizing the intricate interplay between climate change, human activities, and the hydrological cycle.

Moreover, it should be aware that an estimated 50% of the world's population encounters severe water scarcity during certain periods of the year due to a combination of both climatic and non-climatic factors (Caretta et al., 2022). In light of this situation, the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs) adopted by all United Nations Member States in 2015, have identified SDG 6 as the “water goal”, i.e., ensuring availability and sustainable management of water and sanitation for all (United Nations Development Programme, 2022), which also indicates that blue water scarcity, availability, and sustainability still remains a big challenge for human society in the near future.

3.2 Green water

The green water (flux) refers to the water temporarily stored in the soil–vegetation system, particularly as soil moisture in the unsaturated zone and water retained on vegetation surfaces, which finally returns to the atmosphere as evapotranspiration (ET), which mainly includes soil evaporation, plant transpiration (T) and evaporation of intercepted water (Falkenmark et al., 2006; Hoekstra et al., 2011; Schyns et al., 2015). Precipitation (P) undergoes partitioning into green water and blue water once it reaches the land surface. Green water primarily involves the movement of water through evapotranspiration (ET) from the land into the atmosphere, while blue water refers to water that moves through channels on the land surface or through aquifer pore spaces. Globally, the flow of green water constitutes approximately two-thirds of the total global water flow (Li et al., 2007), making it the dominant component of the hydrosphere. The distribution and volume of green water align with ET patterns, which can be assessed through a combination of ground-based observations, satellite data, and modeling techniques.

From a global perspective, Table 2 provides the average monthly and yearly ET from synthesized analysis of various global ET datasets (Elnashar et al., 2021). The results show that the average global annual ET from 1982 to 2019 is 567 mm. Seasonally, the average ET is 137 mm in spring, 169 mm in summer, 132 mm in autumn, and 129 mm in winter. Among all the months, July exhibits the highest synthesized ET value, reaching 59.17 mm.

Furthermore, Table 3 shows the continental-average yearly ET (Elnashar et al., 2021). The average annual evapotranspiration (ET) values from 1982 to 2019 are as follows: 389 mm for Asia, 983 mm for South America, 548 mm for Africa, 377 mm for North America, 402 mm for Europe, 426 mm for Australia, and 843 mm for Oceania. These continents contribute to 29.1%, 21.7%, 19.9%, 16.7%, 7.9%, 4.2%, and 0.5% of the total global ET, respectively. In terms of countries, Malaysia, Singapore, and Indonesia, as well as the northern part

Table 2 The average decadal synthesized monthly ET (mm-month⁻¹) and yearly ET (mm-year⁻¹) adapted from Elnashar et al. (2021).

	1982–1989	1990–1999	2000–2009	2010–2019	1982–2019
January	43.22	44.10	44.94	45.99	44.56
February	39.73	41.14	42.83	42.09	41.45
March	44.83	45.09	43.73	42.93	44.15
April	45.84	46.04	39.32	38.57	42.44
May	52.86	53.36	47.13	46.61	49.99
June	56.15	57.31	53.98	54.00	55.36
July	60.83	61.80	57.06	56.99	59.17
August	58.02	58.77	51.25	50.25	54.57
September	49.99	50.15	44.10	42.79	46.76
October	46.76	46.91	38.53	38.77	42.74
November	42.55	42.45	41.52	42.29	42.20
December	42.66	43.58	42.92	44.43	43.40
Annual	583	591	547	546	567

Table 3 Spatial distribution of the average decadal synthesized yearly ET (mm-year⁻¹) adapted from Elnashar et al. (2021).

	1982–1989	1990–1999	2000–2009	2010–2019	1982–2019
Africa	541	555	538	556	548
Asia	377	387	393	398	389
Australia	445	438	397	425	426
Europe	403	424	399	384	402
North America	413	423	333	338	377
Oceania	903	892	811	766	843
South America	1002	1015	960	953	983
Global	583	591	547	546	567

of South America, exhibit higher ET values. Among different land cover types, croplands show higher ET compared to forests, followed by grasslands, with average annual ET values of 597 mm, 548 mm, and 542 mm, respectively. Based on the aridity index classification by the United Nations Environment Program, the average annual synthesized ET values are 392 mm for arid areas, 532 mm for semiarid areas, 497 mm for dry sub-humid areas, and 583 mm for humid areas. (Elnashar et al., 2021)

Another captivating research direction for studying green water is its partitioning. The integration of Earth system models with field measurements reveals that the global estimate of the T-to-ET ratio is 0.62 ± 0.06 , and the leaf area index is identified as the main factor influencing spatial variations in T/ET (Lian et al., 2018). In addition, Global Land-surface Evaporation: the amsterdam Methodology (GLEAM) combines a wide range of remotely-sensed observations to derive that annual land evaporation is estimated as $67.9 \times 10^3 \text{ km}^3$, 80% corresponding to plant transpiration, 11% to evaporation of intercepted water, 7% to soil evaporation and 2% snow sublimation (Miralles et al., 2011). Consequently, the quantity of green water is primarily determined by the water consumed by vegetation and is strongly linked to biomass production in terrestrial ecosystems.

Last but not least, climate change is expected to enhance the terrestrial hydrological cycle by increasing the water exchange between the land surface and the atmosphere. Growing evidence suggests that future changes in ET are driven by alterations in temperature and relative humidity (Douville et al., 2021). In addition, regional evolution in evapotranspiration (ET) can also occur due to changes in soil moisture and vegetation, influencing the moisture flow from the land to the atmosphere. Furthermore, studies have indicated that transpiration (T) increases as a result of climate change impacting the length of the growing season, leaf area, and evaporative demand. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), Working Group I (WGI), assessed that it is highly likely that human-induced forcing will generally lead to an increase in ET over most land areas, with regional exceptions in drying areas where soil moisture limitations exist (Douville et al., 2021). Moreover, the Coupled Model Intercomparison Project (CMIP6) multi-model ensemble projection shows a broad spatial range of the ET anticipation, with an increase of about 25% in mid/high latitudes but a decrease by up to 10% in most of tropical South America, southern Africa, and Australia at 4 °C global warming (Caretta et al., 2022). However, the high uncertainty of regional ET projection should be acknowledged, particularly at seasonal scales, due to the insufficient parametrizations of the complex physiological processes in global climate models. Recent evidence further highlights the intensification of the global water cycle. Swain et al. (2025) synthesized observations showing that hydroclimate volatility is increasing on a warming Earth, with both wet and dry extremes becoming more frequent and intense. This growing volatility directly affects green water dynamics, as shifts in precipitation intensity, timing, and distribution alter soil moisture availability and evapotranspiration patterns across diverse climatic regions.

3.3 White water

White water (flux) refers to atmospheric water vapor that has the potential to be transformed into precipitation, while the remaining portion is referred to as Background water. It represents the active precipitating component of atmospheric moisture, functioning as a state-dependent variable rather than a fixed physical attribute. Driven by the inherent variability of precipitation across different scales and regimes, the magnitude of white water fluctuates over time and space. Consequently, it serves as an indicator of the dynamic conversion intensity of atmospheric water, moving beyond a simple fixed partition of moisture. Recent studies have developed quantitative methods to identify and assess white water using threshold-based approaches. Li et al. (2018) proposed a method based on a dynamic precipitation threshold to determine whether a grid cell is precipitation-active. The identification procedure involves three key steps: (1) establishing the historical baseline of daily precipitation for each grid cell; (2) computing the 90th-percentile threshold from this baseline to define precipitation-active conditions; and (3) cross-referencing with concurrent atmospheric moisture indicators, including column-integrated water vapor, relative humidity exceeding 70%, and moisture flux convergence. When both the precipitation threshold and the favorable moisture conditions are met, the atmospheric water vapor within that grid cell is classified as white water; otherwise, it is regarded as background water (Li et al., 2018; Li et al., 2019). The connection between blue, green, and white water is described in Figure 4. Generally, precipitation comes from the condensed white water, which then adds either green water (around 64% on a global scale) or blue water (around 36% on a global scale) (Falkenmark, 1995; Li et al., 2007). Besides, according to Cheng et al. (2006), the blue water in the upstream basins can be further converted to green water in the downstream basins.

Figure 4 presents the interactions among different components of the hydrosphere, highlighting the crucial role of white water. To better understand the characteristics of white water, four indices have been introduced, and their spatial variations are depicted in Table 4 (Li et al., 2019). (1) The White Water Ratio (WWR, unit: %) refers to the ratio of white water to the total amount of atmospheric water vapor, which indicates the availability of white water in a region. (2) White Water Saturation (WWS, unit: %) is further defined as the saturated white water, which is used to fairly reflect the local abundance of white water considering the large difference in the magnitude of atmospheric water vapor in different regions. (3) The Total Water Precipitation Efficiency (TPE, unit: m^{-1}) refers to the ratio between precipitation flux (unit: m/s) and total atmospheric water vapor flux (unit: m^2/s), which represents the regional utilization of atmospheric water vapor flux. (4) The White Water Precipitation Efficiency (WPE, unit: m^{-1}) refers to the ratio between precipitation flux (unit: m/s) and white water flux (unit: m^2), which represents the regional utilization of white water.

Generally, the WWR is lower near the equator and higher towards the poles, exhibiting a similar pattern to precipitation distribution. Moreover, the WWR tends to be relatively higher in China compared to the global average. The spatial characteristics of the WWR are significantly influenced by land, sea, and topography. On the other hand, the WWS is less affected by topography and more influenced by water vapor saturation and cloud cover. In the middle and low latitudes, the southeast coastal region of China exhibits a relatively high WWS.

Regarding TPE, regions with high altitudes such as the northern mountains of South America and the eastern Tibetan Plateau exhibit high values, while the northern part of Africa experiences lower values. China, on average, has a moderate TPE compared to global levels, and the Sanjiangyuan Basin stands out as one of the regions with the highest TPE worldwide. On the other hand, WPE generally shows higher values than TPE and has a larger spatial range. The average WPE in China is also at a moderate level globally, although it is lower in most major basins compared to the Amazon Basin and Congo Basin.

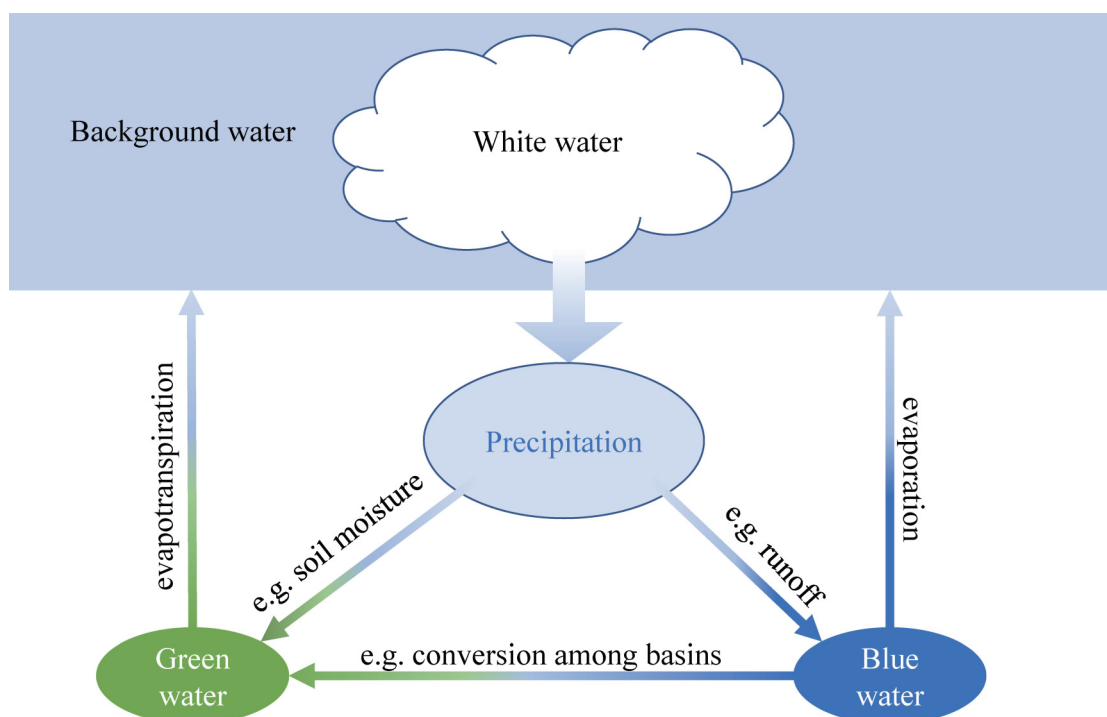


Fig. 4 The connection and mutual transformation between blue, green, and white water.

Table 4 The global range and regional value of four indices related to white water adapted from Li et al. (2019).

		WWR (%)	WWS (%)	TPE (10^{-6} m^{-1})	WPE (10^{-6} m^{-1})
Global high value		≥ 48	≥ 90	≥ 0.4	≥ 1.6
Global low value		≤ 8	≤ 15	≤ 0.02	≤ 0.1
China mean		≈ 30	≈ 60	≈ 0.2	≈ 0.6
Factors impacting spatiotemporal variations		Land-sea cover topography	Latitude, cloud cover	Large-scale circulation, aridity, season	Large-scale circulation, aridity, season
Major basins in China	Yangtze River Basin	28.4	51.9	0.3	0.8
	Yellow River Basin	26.3	22.3	0.2	0.7
	Pearl River Basin	26.8	43.3	0.2	0.7
	Sanjiangyuan Basin	44.5	28.5	0.4	1.0
Major basins worldwide	Amazon Basin	12.3	25.9	0.3	2.1
	Mississippi Basin	31.2	41.9	0.2	0.5
	Congo Basin	8.0	13.1	0.3	1.8

In a word, the variations in these four indices are closely connected to the local environment and meteorological conditions. Accurate evaluation and detailed studies of these indices are of great significance for the exploration and utilization of atmospheric water resources.

4 What will be found in the future?

4.1 Dynamics of hydrosphere

As a dynamic system, the hydrosphere is expected to be firstly examined by means of theories developed in the field of system dynamics. Three subjects require investigation:

1. System configurations. The initial stage of investigating the hydrosphere as a complex system involves identifying the subjects of study, establishing their interrelations, and designing their configurations within the system. For instance, when examining the effects of water materials on ecology, water resources, and the carbon cycle, the primary objects of interest are white water, green water, and blue water. These configurations are developed by integrating geophysical, ecological, and hydrological processes.

2. System dynamics. System dynamics examines the behaviors and responses of the hydrosphere, which are driven by diverse external factors. Previously, the dynamics of the hydrosphere were extensively studied within different individual disciplines. Hydraulics focused on the study of water flows in rivers, atmospheric dynamics explored the transport of vapor in the air, and ocean dynamics investigated marine currents. However, as a system that encompasses all water materials cycling in a coupled manner, with significant differences among them, combining various dynamic models, such as general circulation models, river models, and marine models, presents considerable challenges in portraying a comprehensive picture of the hydrosphere.

3. System stabilities. One of the key issues in the study of the hydrosphere is to assess its stability as a representative complex system. The hydrosphere has the ability to transmit, transport, dissipate, or amplify disturbances originating from various sources. Consequently, the stability of the hydrosphere system not only impacts the availability of water resources but also serves as a crucial parameter in understanding climate change, ecosystem evolution, and other phenomena closely linked to the hydrosphere.

4.2 Topology of hydrosphere

Topology is originally a phrase from mathematics; especially, topology theories. Among the various features of topology, topological invariants hold particular significance as they indicate the unchanging properties of a topological space. Loosely speaking, topology investigates the invariants of topological sets through continuous transformations, also known as homeomorphisms. When we refer to the topology of the hydrosphere, we mean that there exists a collection of states of the hydrosphere forming a topological space that satisfies the axioms of topology. There are three specific aspects that require our attention:

1. Topological invariants of hydrosphere. Regarded as a topological space consisting of its states, the hydrosphere evolves in time. However, there are some variables or relations that remain unchanged, which can be used to identify different objects in the hydrosphere. Such variables or relations are referred to as topological invariants of the hydrosphere. In our previous studies (Zhang et al., 2020), for example, the source and sink relations for the transport of water vapor in the atmosphere are found to be topological invariants, which can be used to study the global and regional relations for water vapor transfer along with evapotranspiration and precipitation.

2. Topological structures of hydrosphere. As we know, the existence of structures of a system means there are some mechanisms leading to achieving certain functions of the system. The hydrosphere, being a typical system, is topologically structured. For instance, what is presented in Figure 5 is a globally existing topological structure found in paths of evapotranspiration and precipitation (Zhang et al., 2020). It shows that there exist statistically stable local regions, where the internal water cycles are dominant. The topological structures shown in Figure 5 are the result of invariance in the source and sink relations for the transport of water vapor in the atmosphere. Although Figure 5 presents a typical example of topological structures found in the hydrosphere, it is expected other similar structures will be found in the future study.

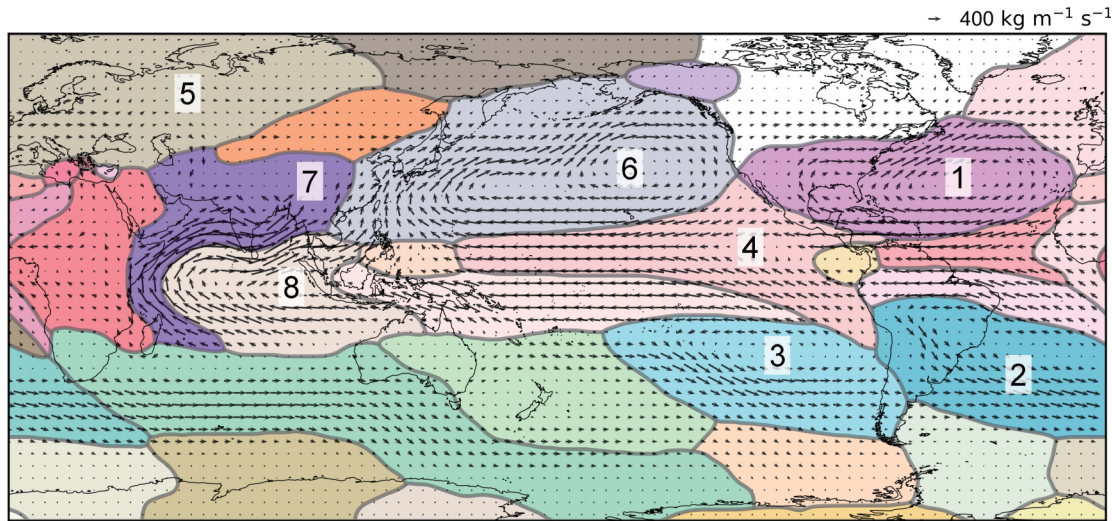


Fig.5 Global topological structures found in evapotranspiration-precipitation. Regions marked with different colors are local areas with internal evapotranspiration-precipitation being dominant, with numbers indicating the eight most stable regions. It shows that inter-region transfers of water vapour, represented in the figure by arrows, are weak, leading to these regions being quasi-independent.

3. Measures of hydrosphere. Determining the measurement of topological structures in the hydrosphere is yet another crucial issue. There are three difficulties to be resolved.

(1) They are stochastic. Whatever we believe in nature is uncertain, in the other word, our knowledge is uncertain. The hydrosphere exhibits pronounced characteristics of randomness, necessitating the use of probability measures to comprehend its structures. Moreover, the stochastic processes found in the hydrosphere are often non-Markov processes, further adding to the complexity of the problem.

(2) They are multi-scales. Due to the complex nature of processes occurring within the hydrosphere, which span both local and global phenomena and encompass vast temporal and spatial scales, the topology of the hydrosphere exhibits a multi-scale structure. Therefore, it is essential to employ high-resolution methods that can effectively capture a wide range of scales in order to study the hydrosphere.

(3) They are “big data”. It is no doubt that the hydrosphere itself is represented by a collection of really big data sets of various types. Finding the underlying principles of complicated systems is more than theoretical actions in the digital or AI eras; big data methods and AI-based methods are becoming predominant in a variety of disciplines. However, studies on the hydrosphere possess unique characteristics in which both correlations and cause-and-effect relationships play crucial roles. This necessitates the utilization of physics-informed big data or AI methods to effectively analyze and understand the complex dynamics of the hydrosphere.

4.3 Infordynamics of hydrosphere

The ultimate goal of research on the hydrosphere is to predict its evolution, at least a general description of how it evolves. In the past decades, observations by means of both cutting-edge techniques and advanced Earth models (Canepa et al., 2017) were developed to achieve this goal. However, due to its multi-physics and multi-scale nature, the hydrosphere exhibits complexity surpassing that of other systems encountered in hydraulics or hydrology. It comprises diverse subsystems, necessitating the introduction of a complex network with dedicated functions to connect relevant physics. Within this network, actions and interactions occur, manifesting as information signals propagating throughout. Information theory applied to the hydrosphere plays a crucial role in understanding its intricacies and developing reliable models for predicting its behaviors.

1. Entropy of hydrosphere. For the hydrosphere, signals retrieved from observing and modeling natures possess strong uncertainty; screening of these signals with appropriate theories should lay a solid foundation for studies on the hydrosphere. The modern information theory is established based on Shannon’s entropy (Shannon, 1948), which measures the amount of information by means of

$$H = - \int dy P(y) \ln P(y) \quad (1)$$

where $P(y)$ is the probability of signal y . On the one hand, the information of the hydrosphere belongs to the category of general information, which obeys the laws of information theories. On the other hand, the information of the hydrosphere is employed to obtain what is beneath the signals. Therefore, properly defining the entropy of the hydrosphere is the first step towards establishing a theory for information derived from the big data of the hydrosphere.

2. Transmission of information in hydrosphere. The word “transmission” means actions and interactions in the network composed of subsystems in the hydrosphere, which are observed as signals transmitting among them. Studies on signal transmission in the hydrosphere provide us with a new angle to view the hydrosphere as a complex system. Cause and effects, as well as correlations, are identified; dynamics of the hydrosphere are examined; and finally, the information network of the hydrosphere is established and its behaviors are investigated.

3. HydroGPT. An AI-based generative model for the hydrosphere is anticipated to emerge. The field of AI for scientific research has recently emerged as a new paradigm, with large-scale models designed for images and natural language driving transformative

advancements in various disciplines, including hydrosphere science. The transformer-based generative pre-trained language model has demonstrated remarkable performance in traditional scenarios, suggesting that scaling up model parameters may pave the way for “intelligent” capabilities. Therefore, there is a possibility of developing a specialized model called HydroGPT, tailored specifically for hydraulics, hydrology, and hydrosphere science. HydroGPT will not only learn, comprehend, and apply the specialized knowledge of hydro-science but also have the potential to independently discover scientific theorems. Undoubtedly, HydroGPT will bring new momentum and revolutionize hydrosphere research.

5 How hydrosphere is studied?

5.1 Correlations or conservation equations?

Models based on conservation equations of mass, momentum, and energy for fluids, water vapor, and solids such as ice and glacier are dominant in the studies of water cycles. Successful applications have been reported both in engineering and sciences. Nevertheless, challenges are encountered when large-scale and long-term evolution of complex systems are concerned: constitutional relations usually suffer from empirical treatments; calculation capacities and resources are still limited and expensive; most importantly, in many circumstances, conservation equations do not exist, and we have to rely on correlations.

For example, let $X \in M$ and $Y \in N$, a map $F: M \rightarrow N$ relates M and N by

$$Y = F(X) \quad (2)$$

If F is assumed to be smooth, linearization of Eq. (2) could be

$$\dot{Y} = A\dot{X} \quad (3)$$

and

$$\ddot{Y}(t) = -a(t)\dot{Y}(t) + \xi(t) \quad (4)$$

where $A = \partial F / \partial x$, $a(t) = -\dot{A}(t)A^{-1}(t)$, and $\xi(t) = A(t)\ddot{X}(t)$.

Conventionally, one of the direct ways of determining A is to adopt linear regression (LR) (James et al., 2013) or non-linear regression. LR is a classic and efficient statistical learning approach that not only reveals the strength of the linear relationship between X and Y , but also tells us the relative importance of each dimension of X , which has been widely used to quantify relationships among different components of the hydrosphere (Milly et al., 2005; Zhang et al., 2018). LR is simple in form and easy to implement and many powerful non-linear models can be obtained by introducing hierarchical structures or high-dimensional mappings on top of it.

To determine the matrix A , we rewrite Eq. (3) as

$$\dot{Y} = A\dot{X} + \varepsilon \quad (5)$$

where A quantifies the association (the average effect on $\dot{Y}$ of a one unit increase in $\dot{X}$) between the variable and the response. ε is the error between true values and the estimated values. Here A is estimated using the least squares approach which aims to minimize the sum of squared residuals S :

$$S = \varepsilon \varepsilon^T \quad (6)$$

It is a simple convex optimization problem and can easily find the global optimal solution theoretically, or technically by gradient descent method. Regardless of the method used, we ultimately obtain an estimate of A as

$$A = \dot{Y}\dot{X}^T(\dot{X}\dot{X}^T)^{-1} \quad (7)$$

then, a local linear approximation is achieved through differentiation and LR. Finally, we can revert the “entire picture” (namely F) with these “fragments”, which in essence is a matter of differential manifolds and is our key problem to be solved in the future.

As for non-linear cases, most of the time we do is transforming them into a linear form that can be modeled with the LR approach. But unfortunately, not all non-linear relations can be treated in this way. For those that cannot be linearized, we just apply numerical optimization methods to solve them. The equation is powerful, but we cannot always find the one that correctly describes the system. Or we have got one, but it is hard and expensive to solve it. As the complexity of the system grows, the limitation of such approaches gradually emerges. This is exactly when the map-based approaches start to draw attention.

One of the typical representatives of map-based approaches is deep learning (LeCun et al., 2015) which has strong fitting and prediction capabilities (technically implemented through neural networks). The structure of the neural network is inspired by the human brain. Figure 6 shows a fully connected neural network with two hidden layers. The basic component of the neural network is called a neuron, which sequentially combines simple linear calculation and non-linear activation. Through the stacking of neurons along width and depth, we can implicitly obtain the map F :

$$Y = F(X; \Theta) \quad (7)$$

where Y is the output of the network, Θ are the learnable parameters optimized by back-propagating prediction errors of the network. It needs to be pointed out that adding non-linear activation functions is the key to obtaining strong fitting ability of the network but the form of activation function cannot be learned automatically.

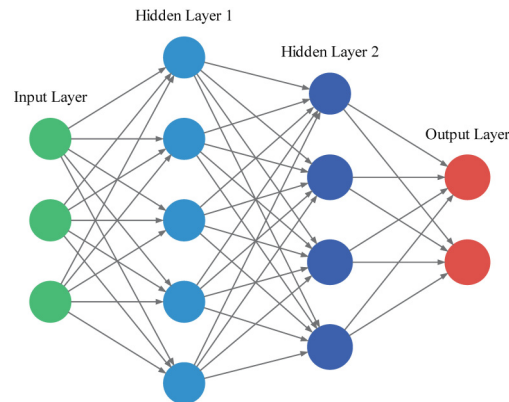


Fig. 6 A simple fully connected neural network with two hidden layers. Each of these layers has some learnable parameters that are initialized as white noise. We can implement a simple classification or regression task based on this network.

Such a method performs very well in handling complex problems, spontaneously learning features, rules, and patterns from massive data, and can effectively model non-linear dynamic systems. DL has been increasingly applied in hydrosphere science to extract hydrologic information from remote sensing imagery, dynamically model hydrologic variables collected from sensor networks, and learn as well as generate complex data distributions (Shen et al., 2018). As the acquisition of data becomes more convenient and the problems become more sophisticated and difficult, map-based methods show great potential.

It should be noted that both model and map methods are important tools for us to study the hydrosphere. In the future, we believe that hybrid models will play an important role as they effectively combine the advantages as well as avoid the limitations of the two methods: strong fitting ability, good interpretability, revealing stable causal relationships under long-term changes, and a faster and more accurate systematic response.

5.2 Deterministic or stochastic?

Uncertainty makes us feel upset. Whether the macroscopic world is deterministic or stochastic has long been a question under debate in both public and scientific communities. Nevertheless, we had to admit that as an observable fact, processes in the hydrosphere, e.g., global or local hydrological processes, exhibit strong randomness. The randomness of complicated systems can be practically interpreted by the fact that the ensemble of microscopic system states could be different considerably, even if they are from the processes with the same macroscopic boundary and initial conditions. When the ensemble averages (which are in essence a filters with corresponding spatial or temporal scales) are applied to the microscopic system states with the same macroscopic boundary and initial conditions, some kinds of randomness appear, having the spatial or temporal scales smaller than that of the filter. This is a practical treatment of randomness before the theory regarding how the world works has been resolved.

The deterministic treatment is based on the ensemble-averaged system, and its interconnecting states and processes. The reliability of deterministic approaches thus depends on the choices of filters—the ensemble average—which governs to what extent the small-scale processes are taken into account. For example, the Navier-Stokes equations for fluid flow experiences different approximations chronically of the Reynolds Averaged Navier-Stokes (RANS), Large Eddy Simulation (LES), and Direct Numerical Simulation (DNS) (Pope, 2000). The stochastic methods reported in various disciplines rely on the stochastic characteristics of the systems as a priori. For instance, by assuming turbulence as Gaussian white noise, the Navier-Stokes equations can be solved by the Probability Density Function (PDF) approach (Pope, 2000; Zhong et al., 2020).

When we talk about the hydrosphere, things become complicated. It not only involves geophysical flows but also covers a wide range of processes with different spatial and temporal scales. Consequently, we cannot find a single ensemble average to separate deterministic and stochastic parts of the system. This is a big challenge in determining what kinds of routes will be selected to model the hydrosphere.

5.3 AI-based or model-based prediction?

Conventional model-based methods for prediction have achieved abundant accomplishments in hydraulics, hydrology, hydrosphere, and other fields. By using differential equations or partial differential equations (PDEs), we can not only precisely describe the causal relationship among variables and establish their time dependency, but also clearly explain the connotation of each parameter. For example, the Saint-Venant equations, which are PDE derived from conservation of mass and momentum, have been used extensively for flood routing and open-channel flow modeling. Such methods follow inherent physical laws and are suitable for short-, medium-, and long-term forecasting. However, there are still some difficulties: how to find the only optimal equation from a multitude of possibilities, how to determine assumptions when establishing a model, the space and time cost of equation solving, the sensitivity of initial values when numerically solving certain problems, and the need to establish a specific model for a specific problem.

In recent years, AI-based data-driven forecasting methods have shown great application potential, trying to solve a class of problems with a common framework. We have seen their excellent performance in global numerical weather forecasting, solution of complex PDEs in fluid mechanics and other scenarios, etc. Such methods can effectively handle non-linear situations and accelerate calculations on GPUs. End-to-end mapping does not require manual discovery and understanding of physical laws. With the rapid increase in data volume and the development of hardware, the advantages of such methods are gradually expanding. In global weather forecasting, the deep-learning-based FourCastNet and GraphCast models, developed by Nvidia and DeepMind respectively, have demonstrated comparable or superior

accuracy to state-of-the-art numerical weather prediction systems while requiring significantly less computation time. Similarly, Nearing et al. (2024) showed that deep learning models can predict extreme floods in ungauged watersheds at a global scale with accuracy matching traditional hydrological models, while Explainable AI techniques have begun to reveal the physical relationships implicitly captured by these networks (Slater et al., 2025). However, there are still some drawbacks: laws and relationships are hidden among a large number of parameters, making it harder for us to understand and explain; high demand for the quality and quantity of data; the numerical optimization process cannot guarantee convergence to the global optimal solution, etc.

Both AI and model-based have their respective applicabilities, advantages and disadvantages, and the coupled prediction models of the two are now being deeply studied. The hydrosphere is a complex non-linear system with a vast amount of data that need to be collected and utilized. We need to leverage the characteristics of the two methods in order to better solve practical problems in hydro-science.

6 Summaries

Since the concept of the hydrosphere was first put forward by Suess (1875), it has been documented in numerous scientific papers and research reports. However, it has not been studied as integrity due to difficulties such as lack of tools, insufficiency of theories, and most importantly, absence of organized and dedicated research.

In the past decades, our dedicated efforts have been directed toward providing a comprehensive explanation for the significant decline observed in both runoff and sediment load in China and other countries and regions. Additionally, we have strived to develop reliable predictions of runoff and sediment load for future centuries. Throughout this journey, we have come to realize that a thorough understanding of real-world phenomena, ranging from local river morphology to catchment-scale variations, necessitates placing them within the broader context of the hydrosphere. This holistic approach enables us to obtain a multidimensional perspective that incorporates relevant information from every possible angle, resulting in a complete and interconnected picture. The content presented in this paper represents a general overview and a proposed direction for future studies on the hydrosphere.

(1) We discussed the definition of the hydrosphere. We suggest defining the hydrosphere as a network formed by global and local water cycles of water in the states of liquid, solid, or vapor. This definition is much clearer than the “water bodies on the Earth”. Moreover, it contradicts the common knowledge about the hydrosphere: it is not a static layer of water but an active network containing water materials of different states to exist, evolve, and act.

(2) We discussed what we have known about the hydrosphere. We tend to discuss it from the angle of water materials cycling as blue water (surface runoffs), green water (evapotranspiration fluxes), and white water (cloud water). In fact, this is an appropriate way to discuss water cycles as a human-being-affected natural phenomenon.

(3) We discussed the major aspects of the hydrosphere. We propose that prioritizing the establishment of its dynamics, topology, and infordynamics is crucial. By focusing on these aspects, we can effectively investigate the hydrosphere as a complex system, addressing fundamental questions such as its spatial and temporal evolution, the topological interconnections among its individual components, and the potential for prediction in the era of emerging AI technologies.

(4) We discussed the challenges in future studies on the hydrosphere. We are currently confronted with the critical decision between employing correlations or conservation equations, deterministic or stochastic approaches, and model-based or AI-based predictions. While these challenges have long been a subject of consideration, they have gained unprecedented significance in the study of the hydrosphere.

Again, as the title suggests, the present paper provides only a bird’s view of the general definition, concerns, and challenges of studies on the hydrosphere. Following this paper, we will report several studies on the blue water, green water, and white water in the sense of the hydrosphere. We encourage the hydro-science community to provide insightful comments, constructive criticisms, and, most importantly, contribute their research to this journal.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interests

The authors have no competing interests to declare that are relevant to the content of this article. The author Guangqian Wang is the Editor-in-Chief of this journal. The authors Deyu Zhong, Tiejian Li, and Yuefei Huang are the members of Acting Executive Editor of this journal.

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