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REVIEW

Exploring the Major Watershed Basins All Around the World: A Meta-Analysis for Basins Characteristics

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ABSTRACT

Analysis of major watershed basins in a global vision provides a crucial information on sustainable management of water resource throughout the Earth. In this review, a globally significant watersheds were reviewed including the Murray-Darling Basin (Australia), Yangtze River basin (Asia), Volga River Basin (Europe), Nile River Basin (Africa), Hudson Bay Watershed & Mississippi Basin (Canada/North America), and the Amazon Basin (South America). A detailed overview was performed on emphasizing climate, agriculture, hydrology, groundwater, and ecological aspects of the watershed basins, providing holistic knowledge in terms of their environmental and socio-economic impacts. This review explores the challenges which are encountered by these watershed basins, involving over-allocation of water, loss of biodiversity because of water deficiency, deforestation, and advancement of hydroelectric power. Also, it examines the fundamental strategies for sustainable management of water, including climate adaptation, improvement of water quality control, and incorporation of ecosystem health principles. The result of review suggests that future research should emphasize advancing basin management, with specific attention to the Mississippi and Nile basins, to balance human demands with sustainability of ecology. Further, the review presents critical insights and guidelines for protecting these essential watersheds basins, supporting additional effective decision-making and sustainable management practices that can certify their long-term sustainability in the face of growing environmental impacts.

Keywords: Major watershed basins, Climate and environmental sustainability, Hydrological characteristics, Biodiversity and ecological systems

1. Introduction

1.1. Research background

Water is crucial for all living organisms, including humans life supporting, economic growth, ecological stability, and human civilization [1]. However, global water crises are intensifying due to factors such as rapid population growth, urbanization, economic development, changes in land cover, and climate change challenges [2, 3]. These mentioned pressures exacerbate the uneven distribution of freshwater, with almost 4 billion people experiencing intense water shortages annually for at least one month [4, 5]. In addition, modern social pattern driven by industrialization, agricultural irrigation, increased energy demands, and global worming to further contributes to water scarcity and declining water quality as around the world [6–8]. A deeper understanding of how these factors effects water supply, demand, and quality is crucial, requiring the need to enhanced capabilities for analyzing the underlying processes and their influence on water availability and usage. This calls for a thorough approach for integrating hydrological operations at the watershed level to determine the holistic

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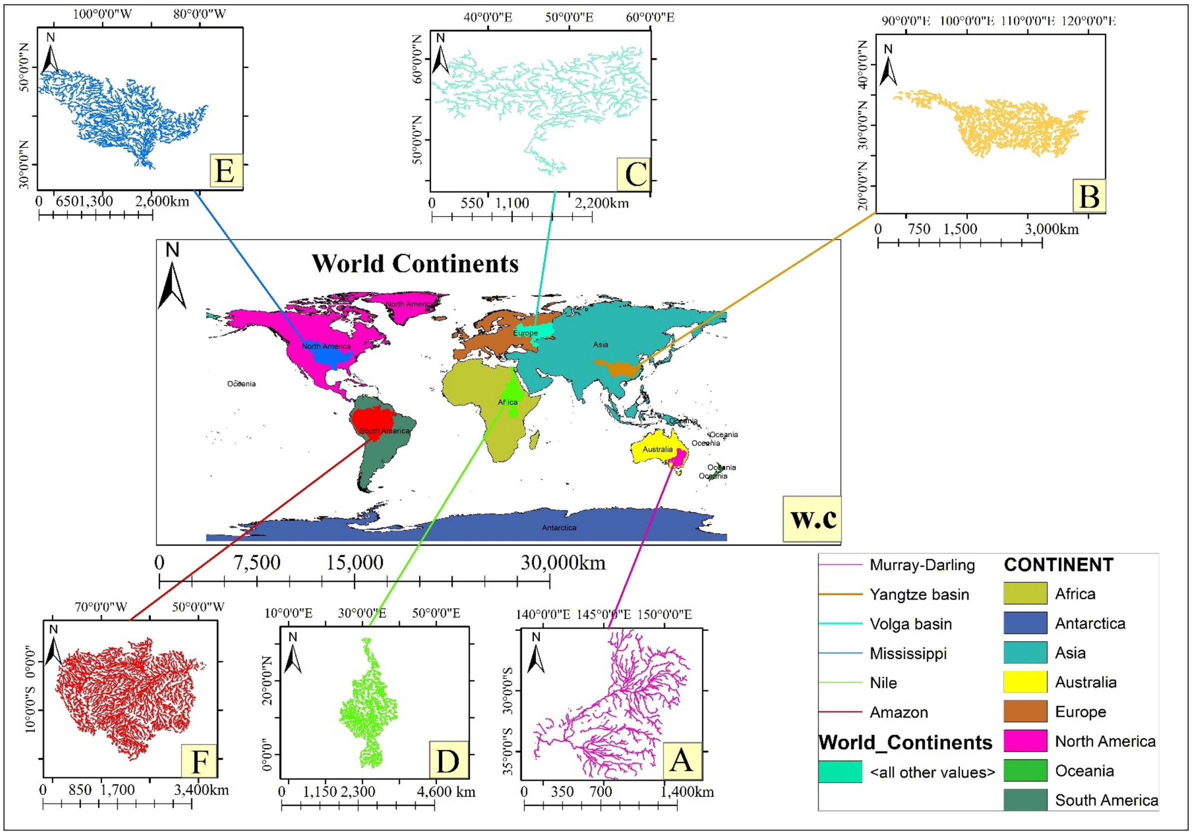

Fig. 1. The distribution of major watershed basins worldwide, with every watershed basin labeled according to the legend. The central map (w.c) shows the world planet, while specific watersheds are highlighted in inset maps with their respective scales: (A) Murray-Darling (Australia), (B) Yangtze (Asia), (C). Volga (Europe), (D). Nile (Africa), (E)- Mississippi (North America). And (F). Amazon (South America), and This layout presents a particular perspective on the location and scale of these essential watersheds across continents.

watershed response to alignment with user demands and climate change [6]. The main watershed basins focused on this review were displayed in Fig. 1.

Fig. 1 illustrates a visual overview of the major watershed basins universally, showing their geographical distribution throughout the whole planet. This figure highlights the presence global key watershed basins, involving Murray-Darling, Yangtze, Volga, Nile, Mississippi, and Amazon watershed basins in the world, which play critical roles for regulation of water resource, providing support for both ecological balance and human civilization. The specific depiction of these basins emphasizes the unequal distribution of freshwater resources around the whole world, underscoring the necessity of integrative, transboundary approaches to mitigate water scarcity, quality, and management of water resources. The varying scales involving every watershed basin's inset map further emphasizes the variability in watershed sizes and conditions, as well as the divers' challenges faced in each region.

Fig. 2 shows the quantitative perspective on the water discharge pattern of these major watershed basins. This visualization highlights the significant variation in discharge rates among Murray-Darling, Yangtze, Volga, Nile, Mississippi, and Amazon watershed basins in the world, underscoring the Amazon Basin's dominant contribution to global freshwater flow. The disparities in discharge reflect not only the size and climatic conditions of each basin as well as the challenges associated with water resource management to meet ecological and human demands throughout these different regions.

Watershed basins play an important role in regulating water resources worldwide, influencing both water accessibility and quality [9, 10]. As global land use changes, driven by urbanization, agriculture, and deforestation, natural land cover within watersheds is undergoing degradation, leading to pollution growth and modified hydrological processes [11, 12]. This degradation leading significant implications for water supply systems all around the world, as the loss of ecosystem services like stabilization of soil and nutrient filtration can lead to higher sediment concentrations and pollutant levels in water bodies [13, 14]. Understanding the global impact degradation of

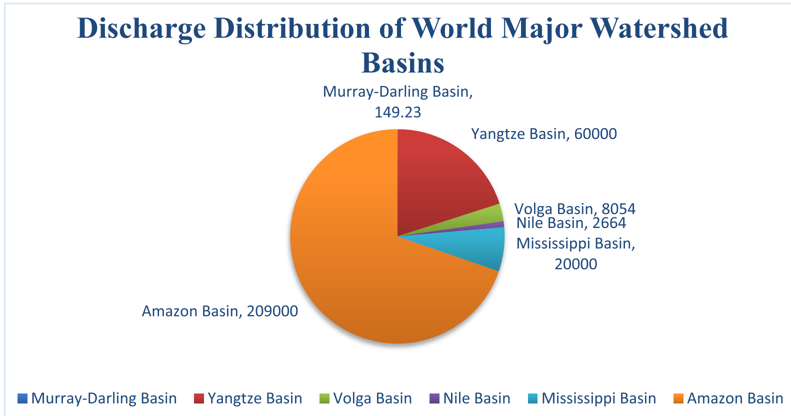

Fig. 2. Discharge distribution in major global watershed basins.

watershed is necessary for protecting water quality and managing effectively water resources [9].

Over the past hundred years, the global focus on major basins and watersheds has enhanced. Deficiency in clean water availability and sanitation in many developing regions, along with growing competition for water, depletion of groundwater, and the degradation of water resources worldwide, has resulted in a higher level of international contribution in the management and analysis of these critical water systems, specifically regarding global transboundary watersheds [15–17]. Particular significance are share boundary basins, distributed among two or more nations, which cover more than 45% of the Earth's land surface and are home to 40% of the global population [18]. The sustainable management of these transboundary, water resources is crucial for ensuring water access for future generations, making the research of major watershed basins a critical priority in the world.

Quantifying water scarcity degree variation across different regions, the Clarity Index (CI) is a vital indicator to assess the balance between water availability and demand under different climatic and socio-economic conditions. CI is classified into four levels: CI = 1 showing water surplus, CI = 2 represents marginal vulnerability, CI = 3 reflects water stress, and CI = 4 denotes water scarcity. for assessing regional water vulnerabilities, such a kind of classifications are critical, particularly during dry years when precipitation is below the 10th percentile [19]. The current situation of water shortage shows that, based on calculations across all watershed basins, 30% of the global population (5.6 billion) live in areas with a water surplus (criticality index CI = 1) [19]. At the same time, 20% reside in slightly vulnerable watersheds (CI = 2), 6% in regions experiencing water stress (CI = 3), and 44% in watersheds facing water deficiency (CI = 4). In years with average precipitation, the proportion of human living in water-scarce regions decreases to 29%, this demonstration shows significance impact of climate variability on water resource availability [19]. While such evaluations provide significant insights into regional vulnerabilities, they also point to the broader need for a global understanding of watershed dynamics to clearly highlight the water shortage and hydrological systems challenges. Existing research has improved our knowledge of watershed basins at local and regional levels, involving transboundary management [20]. However, a universal, integrative review is needed to address how these systems collectively affect global water resources [21]. The seven river basins such as Murry-Darling, Yangtze, Volga, Nile, Mississippi, Hudson Bay and Amazon were selected for their global significance and their different climatic representations, socio economic, and ecological conditions. These watershed basins highlight key universal challenges, like Water quality monitoring, water governance and climate change impact (Nile, Mississippi) [22–30], biodiversity loss (Amazon, Yangtze), and degradation of ecosystems, and hydrological behavior of (Murray- Darling) [31], make them ideal for a comprehensive analysis of global river basin dynamics. This study aims to fill that gap, providing a complete analysis of major watershed basins worldwide. To better understand the characteristics, contributions, and challenges of major watershed basins globally. Table 1 presents a detailed overview of key basins across different continents. It highlights essential data such as basin area, discharge, population, main contributions, and the major challenges faced by these regions. Further, Table 1 identifies critical future research needs for sustainable management and the protection of ecosystems within these significant water systems. In

Table 1. Global major watershed basin's characteristics.

Watershed Basin	Continent	Main River(s)	Basin Area (km^2)	Discharge (m^3/s)	Population in Basin (millions)	Main contributions	Major Challenges	Future Research Needs	References
Murray-Darling Basin	Australia	Murray River, Darling River	~1,000,000	149.23	2.0 (plus 1.3 million depen-dent)	Agricultural Production, Economic Value, Biodiversity, Cultural Significance.	Ecosystem degradation; over-allocation of water; climate impact on runoff.	Clarify flow impacts on fish. Align research with management. Identify knowledge gaps. Conduct longitudinal studies. Integrate ecology and socioeconomics. Study fish life stage needs. Evaluate management effectiveness.	[33–35]
Yangtze Basin	Asia	Yangtze River	1,800,000	3–9 × 10^4	459	Agriculture Hydropower- Flood Control Water Storage Hydrological Data Climate Change Insights	Decline in biodiversity due to fishing activities. Managing fishermen and boats. Pollutant accumulation in sediments. Impact of hydropower projects on ecosystems.	Biodiversity surveys in tributaries. Understanding aquatic biodiversity background. Evaluating protection measures. Habitat restoration management.	[36, 37]
Volga Basin	Europe	Volga River	1,380,000	254 km^3 annual flows		Water supply, Hydro power, Transporta-tion.	Pollution, Contamination of Reservoirs, Environmental Management.	Integrated sustainable water management Climate change adaptation strategies Enhanced stakeholder collaboration Innovative technologies for drinking water quality Comprehensive water-related risk assessments Integration of ecosystem services and biodiversity	[38–40]
Nile basin	Africa	Nile river	3 400 000	2,664	400 (2012), projected 700 by 2030.	Agriculture and hydropower.	Deep-Seated Mistrust Colonial-Era Water Use Arrangements Significant External-Actor Influence	Studying land use impacts on hydrology. Improve soil data for modeling. Identify effective conservation measures. Integrate hydrology with ecology and socioeconomics. Enhance field data collection. Develop water management strategies. Assess climate change impacts. Improve monitoring efforts.	[22–25]

(continued on next page)

Table 1. Continued.

Watershed Basin	Continent	Main River(s)	Basin Area (km^2)	Discharge (m^3/s)	Population in Basin (millions)	Main contributions	Major Challenges	Future Research Needs	References
Mississippi Basin	North America	Mississippi River	3 208 700	>20,000	70	biodiversity, water purification. irrigation, -drinking water, Flood control and prediction agriculture, transportation Cultural and historical importance	Hydraulic alterations. Ecosystem vs. socioeconomic balance, Adaptive management gaps. Need for innovation. -Ecohydrology integration.	Climate change assessment Water quality monitoring Ecosystem health protection Flood control Integrated water management.	[26–30]
Amazon basin	South America.	Amazon River	6,100,000	(209,000)		Biodiversity hotspot, carbon storage, Key source of recycled precipitation.	Environmental degradation, Socio-economic improvement, Environmental and social insecurity.	Assess hydropower impacts. Evaluate ecosystem variations. Analyze costs/benefits. Investigate geopolitical issues. Enhance strategic planning.	[41–44]

watershed research, the key gap lies in integrating multiscale strategies that address both global and regional contexts, as well as the lack of interdisciplinary collaboration among natural and social sciences, limiting the thorough analysis of watershed systems on a global scale [32].

1.2. Related literature

The literature highlights the importance of global watershed basins for biodiversity, agriculture, and hydropower. Major basins, including the Murray-Darling, Yangtze, Mississippi, Amazon, and face challenges such as over-allocation of water, biodiversity decline due to hydropower, deforestation, and water scarcity [33, 36, 41]. Effective management strategies like climate adaptation, enhanced water quality control, and ecosystem health integration are identified as essential for sustainability. Future research should focus on sustainable water use and improved management, particularly in the Mississippi and Nile Basins, to support ecological and human needs [22, 26]. Watershed basins across Australia, Asia, Europe, Africa, and the Americas are crucial for regional ecological and economic stability, however these region faces substantial environmental challenges due to population growth, climate change, and water scarcity [45–50]. Sustainable water management policies, such as the European Union's (EU) Water Framework Directive and India's National Mission for Clean Ganga, emphasize the importance of international cooperation and participatory approaches to address these issues [51–53].

1.3. Current review motivation

The increasing global demand for water, coupled with climate change, urbanization, and population growth, has intensified the need for sustainable management of watershed basins [54]. These basins are essential for supporting biodiversity, agriculture, and economic development; however, many watershed basins face significant challenges, including water scarcity, pollution, and resource overallocation. While research on individual basins exists, there is a lack of comprehensive, global analysis that addresses the shared challenges and management strategies across major watersheds.

This review aims to fill this gap by providing a holistic examination of key global basins, including the Murray-Darling, Yangtze, Volga, Nile, Mississippi, and Amazon focusing on their environmental, hydrological, and socio-economic roles. The review identifies the critical need for integrated management approaches and highlights future research directions, particularly in the Mississippi and Nile Basins. By offering a comprehensive analysis, this study contributes to the development of sustainable water management practices that balance ecological health with human needs, ensuring the long-term viability of these vital systems.

1.4. Research objectives

In view of the explained facts on the existence of major watershed basins all around the world, the main research objectives of the current review were designed as follows: (i) To review the mega basins all around the continents and give a reliable brief of their essential contributions to the society, (ii) To study the climate, environment, hydrology, and ecological aspects of those basins, (iii) To determine the main challenges and the future research avenue of those basins Ultimately, the final aim of this review is to draw the road map for better mega watersheds sustainability, assessment and evaluation.

To achieve these objectives, the seven watershed basins selected from all continents of the world in this study such as Murray-Darling, Yangtze, Volga, Nile, Mississippi, Hudson Bay, and Amazon River basin were chosen for their global significance, diversity across the continents, and the variety of challenges, that they highlighted. These watershed basins were selected for representation of different climatic regions, ecological systems, and socio-economic conditions, making them ideal for studying the contribution of society, hydrological and environmental aspects, and the challenges they face. For instance, the Amazon and Yangtze River basins provide insights into the impact of climate change and deforestation, decline of biodiversity, and hydropower impacts [36, 37, 41–44]. while the Nile and Mississippi river basins highlight challenges associated with transboundary water governance and management, land use impact on hydrology [22–30]. Regarding this selection, the study aims to prepare a comprehensive analysis of major global river basins and their role for water resource management strategies, ultimately supporting the development of the more effective road map for handling these critical water systems.

1.5. Overview of the research structure on global watershed basins

Fig. 3 displays the organizational structure of this review paper, systematically leading the reader through the study's main aspects and objectives. The framework starts with the Introduction, which involves four key elements: Research background,

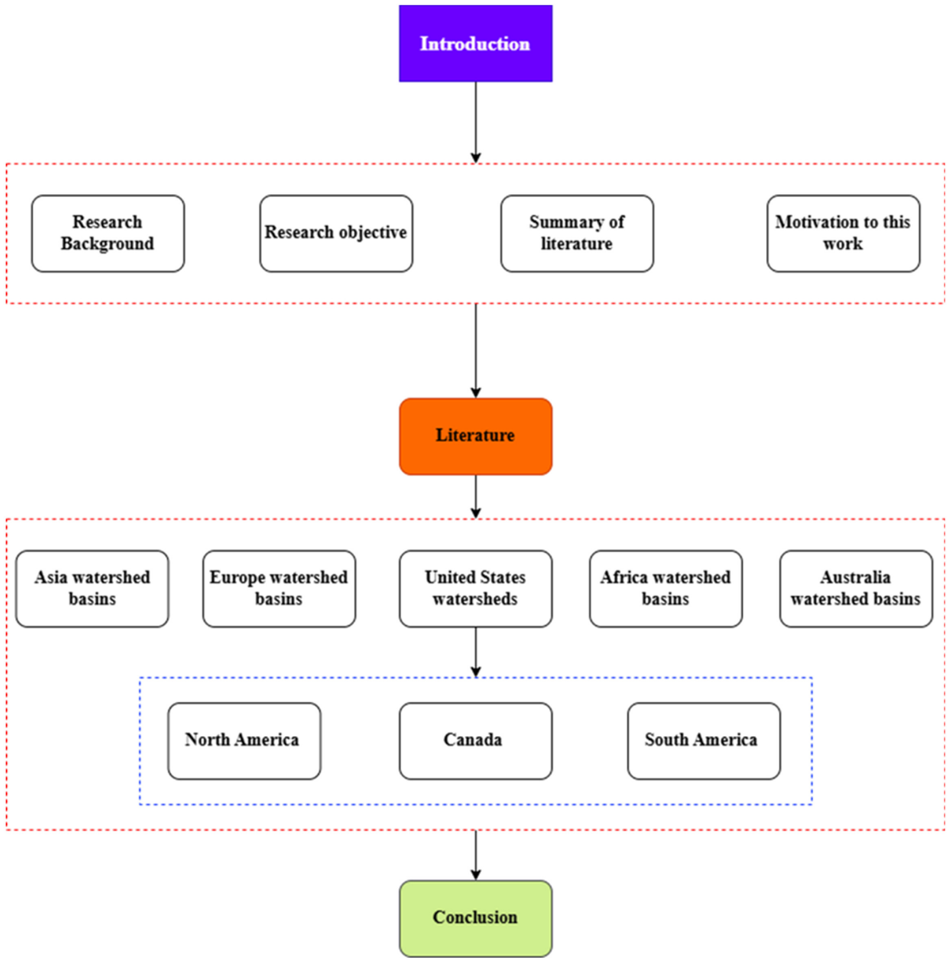

Fig. 3. The process of the adopted review for the mega watersheds all around the world.

research objective, related literature, and motivation for this work. These fundamental elements set the context, summarizing the research aims, reviewing relevant current literature, and highlighting the significance of review paper. Following the introduction, review of literature is organized geographically, analyzing watershed basins thorough Asia, Europe, United States, Africa, and Australia. To increase regional focus within the United States category, the framework subdivides this section into North America, Canada, and South America, facilitating a more emphasizing examination of watershed management in these regions. The structure is intended to provide a comprehensive and systematic analysis of watershed basins across global regions, contributing to a cohesive understanding of world watershed dynamics. The article wraps up with the Conclusion part, analyzing main outcomes and discussing the broader implications of this study. This well-organized approach adheres to research articles principles, promoting clarity, coherence, and academic overview throughout the paper.

2. Literature review

2.1. Australia region related watershed basins

Australia's unique landscape is characterized by several watershed basins that play a critical role in its hydrological system. The country's long-term water resource development, driven by the demands of agriculture, industry, and urban expansion, has led to integral degradation of its freshwater ecosystems [55]. As the driest inhabited continent, with an average annual rainfall of only 450 mm [56]. Australia confronts considerable challenges in managing its water resources, especially in the context of its highly variable climate, which is influenced by large-scale atmospheric patterns such as the El Niño Southern Oscillation and the Indian Ocean Dipole [45].

This review highlights the major watershed basins of Australia, investigating their geographical characteristics, hydrological behavior, and environmental challenges that they face. Among these, the Murray-Darling Basin stands as the largest watershed basins, covering over 1 million square kilometers, or one-seventh of the country. This basin, home to Australia's three largest rivers—the Murray, Darling, and Murrumbidgee—supports 70% of the country's irrigated crops and pastures and a population of over 2 million [31]. The Murray Darling Basin accounts for more than 40% of agricultural production in Australia. However, the basin is dominated by extensive dryland agriculture, confronting critical hydrological challenges, especially during the periods of drought. The Millennium Drought (1997–2009) intensively effected water availability, with reservoir levels dropping by 73% between 2000 and 2003 and reaching historic lows in 2007 [57]. This prolonged drought reduced surface water resources, degradation of ecosystems, rising temperatures, increasing evaporation rates and intensifying water scarcity [57]. and irrigated agriculture account for almost 70 percent of all utilization of water in Australia [58].

Another critical system is the Great Artesian Basin (GAB), which extends 1.7 million square kilometers beneath semi-arid and arid regions, covering about one-fifth of the country. The GAB's groundwater resources, discovered in the 1880s, have been crucial in enabling pastoral activities, establishing homesteads and towns, and assisting petroleum and mining ventures [51]. The Lake Eyre Basin, a remote river system in Central Australia, covers nearly one-sixth of the continent (1.14 million square kilometers) and stretches over four state and territory boundaries. This basin supports a rural population of approximately 60,000 people, scattered across Queensland, South Australia, the Northern Territory, and New South Wales [59].

These three major watershed basins—Murray-Darling, Great Artesian, and Lake Eyre—are essential to Australia's water supply, agriculture, and ecological health, underscoring the importance of sustainable management and effective policy frameworks to address the challenges proposed by environmental stressors [60]. Building on this introduction, it is essential to analyze the existing body of research that delves into the management, challenges, and hydrological dynamics of Australia's watershed basins, highlighting the environmental significance of their sustainable management and ecological perspective.

2.2. Asia watershed basins

Asia is involving some of the world's most significant and vital watershed basins, such as Yangtze, Yellow, Ganges, Indus, and Mekong Rivers, which play an important role in maintaining ecological stability and supporting the livelihoods of billions throughout the continent. Although, these basins confront a multitude of challenges, specifically in the Hindu-Kush-Himalaya region, where declining productivity of agriculture and intense soil erosion significantly reduce the efficiency of arable land [46, 61].

More specifically, the Ganges Basin, which encompasses parts of Nepal, India, and Bangladesh, assists over 500 million people and is important for agriculture, water supply, and waste drainage [62]. Despite its resources, the basin is plagued by poverty, infrastructure development, and pressing environmental issues like flooding and pollution. Initiatives such as National Mission for Clean Ganga emphasize the urgent demand for sustainable water management and share boundary cooperation to enhance resilience and livelihoods in the region [62].

In the Central part of Asia, agricultural practices, specially the cultivation of water-intensive crops such as cotton and rice, dominate the water utilization landscape, placing additional stresses on already scarce resources of water [47]. This region is characterized as arid and has been confronted recurrent droughts that exacerbate water scarcity ecological degradation [52]. Furthermore, the trans-boundary river basins in Central Asia frequently experience mismatches among available water resources and socio-economic requirements, causing to political tensions and cooperative conflict water-related events [63].

In addition, major watershed basins in Asia, for instance Yellow, Yangtze, Pearl, Red, and Mekong rivers, have historically carried considerable sediment to the western Pacific Ocean. However, sediment delivery has significantly decreased as a result of dam construction and human-induced soil erosion, impacting coastal environments by resulting delta sinking and wetland loss [64, 65]. Climate change is anticipated to intensify water shortage in Central part of Asia, further complicating the region's water management challenges [66].

The Yangtze River Basin, stretching 6,300 km, is particularly significant, supporting over 400 million people and featuring vital lakes and reservoirs, including Taihu, Poyang, and Danjiangkou [67]. This basin is one of the most global regions for biodiverse, playing a critical role for sustaining freshwater habitats and supporting several species. as presented in Fig. 4.

The basin's biodiversity presents its ecological richness, it hosts around 10% of all known species and a third of vertebrate species. The Yangtze River Basin is one of the largest rivers in China with a watershed area of approximately 1.8 million km^2, plays a critical role in supporting human populations, biodiversity, and economic development and irrigation

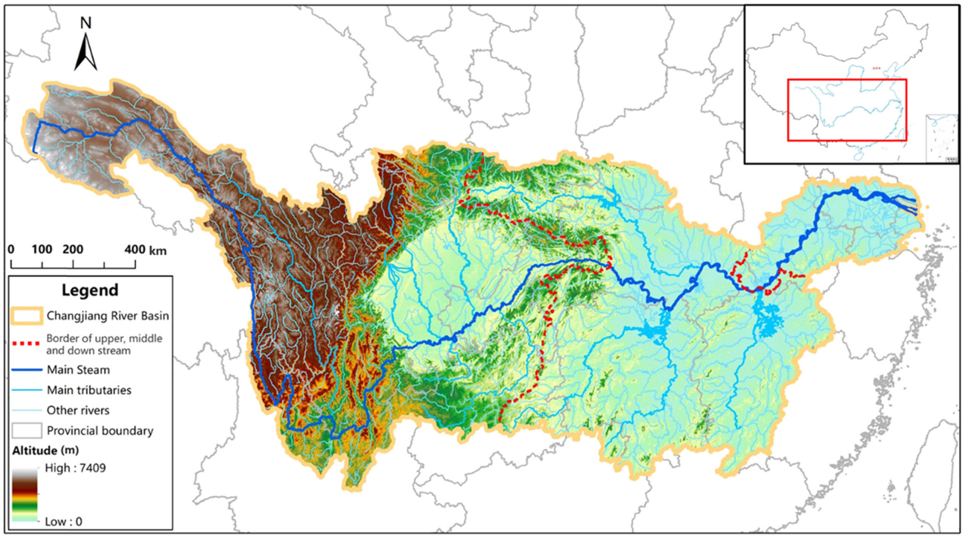

Fig. 4. Illustration of Yangtze River basin biodiversity rich ecological habitats and different species [68].

requirements and has a developed water system, addition the development of the urbanization river is shifted to a sustainable approach. The basin involving over 7,000 tributaries, with 437 having watershed areas exceeding 1,000 km^2, supporting to developed and extensive water resource system which is crucial from the point of economic and human likelihood [68]. The Yangtze River Basin supports a population of approximately 459 million, accounting for 33% of China's population, and generated a GDP of 29.3 trillion yuan in 2017, as economic perspective it is representing 35.4% of the national total. It is also a hub for hydropower generation, with theoretical water energy reserves of 268 million kW, of which 197 million kW are technically exploitable. Further, the Yangtze River Basin stands out globally for its rich biodiversity, hosting some of the global most diverse ecosystems as it is crucial for protecting the divers species life [68, 69]. The accompanying Fig. 4. highlights the basin's ecological significance and altitudinal variations, which influence biodiversity distribution, Environmental conservation goals. Although microbial communities in rivers and lakes have been studied, comprehensive watershed comparisons remain limited, hindering our understanding of microbial patterns and assembly mechanisms [70]. Anthropogenic activities and land use significantly affect microbial diversity and stability, necessitating effective management strategies to preserve the ecological integrity of these essential freshwater systems.

In Southern and Southeast Asia, the rapid growth of developing countries is driving substantial investments in water infrastructure, highlighting the need for a comprehensive understanding of future water availability and its spatial and temporal distribution [71]. Effective river basin management plans and disaster risk reduction strategies are essential for assessing associated risks in this dynamic context. In addition, the challenges facing watershed management in Asia include the lack of availability of reliable data for the Soil and Water Assessment Tools (SWAT) modeling, which is often restricted or not freely accessible, as well as insufficient reporting of parameterization, calibration, and validation procedures in existing studies [72].

To address these challenges, watershed management has shifted towards participatory approaches; however, persistent issues related to inadequate policy frameworks, poor coordination among agencies, and limited stakeholder involvement remain [73]. Future research must focus on integrating social dimensions, improving monitoring systems, and fostering collaboration among all watershed users to enhance management effectiveness across Asia's diverse watershed basins.

2.3. European watershed basins

Watershed basins play a critical role in Europe's hydrological systems, influencing water distribution and supporting biodiversity. However, structural connectivity across European river networks is intensely impacted, particularly in southern Europe, where challenges corresponding to future hydropower development and climate change could further exacerbate these issues [48]. European watershed basins are central to shaping the continent's geography, ecology, and socio-economic activities. These basins host some of the world's most significant river systems, including the Danube, Rhine, Volga, and Po rivers, which

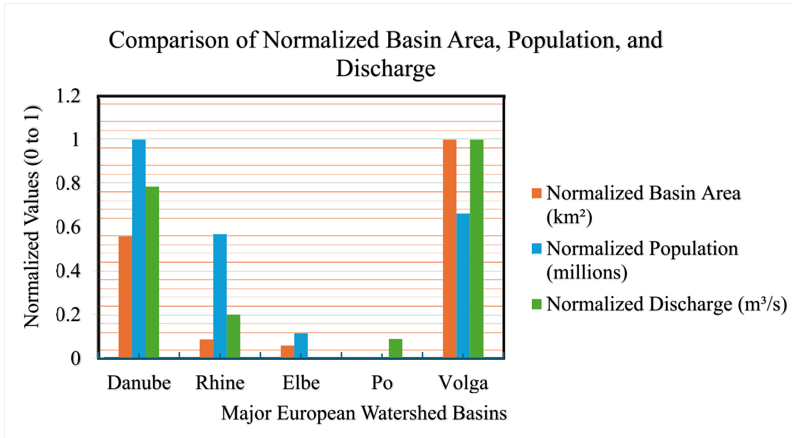

Fig. 5. Illustrates normalized values for Basin Area, Population, and Discharge across various River basins, scaled from 0 to 1. This normalization facilitates direct comparison by presenting the relative size of each parameter in the dataset, emphasizing variations among the river basins.

support various sectors—household use, energy production, industrial processes, and agriculture [74]. Fig. 5. illustrates normalized values for Basin Area, Population, and Discharge across major European river basins, including the Danube, Rhine, Volga, and Po. By scaling each parameter from 0 to 1, the figure provides a clear comparison of the relative sizes and water resource capacities of these basins, highlighting differences that reflect the unique hydrological and socio-economic roles each basin plays within Europe.

Among the major river basins in Europe the most significant river basins are Volga as it stands a key river basin due to it's ecological, economical, and hydrological importance, particularly within Russia, and highlights a clear example of how climate change is expected to have significant effects on water resources management and environment impact in the region.

Volga river is the longest river in Europe, and it is the 16th longest river globally. This basin has complex ecological system, and significance for agriculture, social, and industrial production, particularly for Russia. The total river length is 3531 km, has a basin area of 1431296 km^2, and further the basin has 42 people per km^2 population density. The mean annual discharge is 8364 m^3/s with peak monthly discharge of 25805 m^3/s in May. And the lowest mean monthly discharge 3085 m^3/s in January [75]. The Volga basin is significant economic region for Europe particularly for Russia. The Volga system is important for waterborne transport, navigation, shipping, and agricultural development. Russia's produces 25% hydroelectricity from the hydropower plant which eight of the plant is run by Volga River water [75]. The climate change projections for the Volga River basin show a potential increase in the annual mean air temperature, with a rise of 2.5 °C under global warming by 1.5 °C. Global warming by 2 °C and 3.4°C under 2°C warming leads to significant impact in ecosystem of the basin [76]. This warming occurs most in spring and least in autumn summer it shows seasonal variation of the basin. Precipitation in the basin is expected to increase by 8% under 1.5°C causing by global warming and 11% under 2°C, with a significant increase in winter precipitation [76, 77]. Although, the annual runoff is projected to decrease by 10–11%, with a potential decrease in the Oka and Upper Volga rivers in different regions [76]. This highlights a shift in the seasonal distribution of runoff, with winter runoff increasing and spring and summer-autumn runoff decreasing which is most caused by global warming. Further, the result shows that the runoff coefficient will decrease, highlighting a greater effect of evaporation in the water resource sustainable management and balance. Given the Volga River significant role in Europe's hydrological, economic, agriculture and ecological systems, it's challenging due to climate change in the region presents the broader issues facing many European watershed basins, particularly in terms of water quality, ecosystems health and water resources sustainable management strategies.

In addition, besides providing water resources, these basins also serve as key transportation routes, crucial to historical and modern trade. The transboundary nature of rivers such as the Danube presents challenges for coordinated water management, needing international cooperation for water quality, flood control, and ecological sustainability under frameworks like the EU's Water Framework Directive [53]. Europe's aquatic ecosystems face pressures that

Table 2. European Major Watershed Basins Characteristics.

River basin	Basin area (km^2)	Population in basin (millions)	Average annual discharge (m^3/s)	Water use for agriculture (%)	Water use for industry (%)	Water use for household (%)	References
Danube	801,463	90	6,500		32	20	[80–82]
Rhine	185,260	58	2,300				[83, 84]
Elbe	148,268	24.5	861				[84]
Po	71,000	16	1,500	45	37		[85]
Volga	1,380,000	65	8,049				[86]

impact water availability, ecological conditions, and ecosystem functions. These stresses vary regionally but generally involve pollution, over-extraction, and extreme weather conditions like droughts and floods [78]. In addition, human-induced alterations, such as drainage, soil erosion, and barriers construction, significantly impact water quality and ecosystem health [78]. To address these issues, the European Union has implemented policies since 2000, notably the Water Framework Directive, aimed at improving water ecosystem health and ensuring sustainability [79].To better know the complexities and challenges faced by European watershed basins, it is essential to explore existing literature on regional basins. Table 2 provides general information about Europe's watershed systems.

2.4. African watershed basins

Africa possesses approximately 9% of the world's freshwater resources, despite accounting for 15% of the global population. It is the second driest continent after Australia, with an annual per capita water availability of 4,008 m^3 in 2009, significantly lower than in most other regions, except Asia, the world's most populous continent [87]. The limited access to water for both domestic and agricultural purposes remain a substantial constraint on agricultural productivity, perpetuating poverty and hunger in Sub-Saharan Africa (SSA) [88]. Groundwater, often considered a critical buffer during periods of low rainfall or drought, is essential for rural communities across Africa due to its storage capacity, which frequently exceeds the annual recharge rate [89].

Further Africa's drainage systems are relatively young, with many major rivers having undergone significant shifts in their courses since the breakup of Gondwanaland during the Cretaceous period. However, the lack of reliable hydrological data presents a substantial challenge to effective water resource planning and management across the continent. Water scarcity, particularly in Eastern and Western Africa's drylands, exacerbates poverty, affecting an estimated 300 million people. This number is projected to increase by 65–80% by 2030 [49].

Additionally, the availability of water resources in reservoirs, particularly for electricity generation, is intricately tied to climate and weather conditions. Africa, being the world's most capital-deficient inhabited continent, sees much of its rural population relying on ecosystem services for their livelihoods. Over 300 million of the 800 million people on the continent live in areas experiencing water scarcity, with 11 out of the 16 countries facing "absolute water scarcity," defined as having less than 1,000 m^3 per person per year of water. This situation poses a continuous threat of food shortages and worsens water scarcity [90].

Freshwater availability in sub-Saharan Africa is fundamental to economic growth and social development. More than 70% of the population resides in rural areas, largely depending on agriculture, where water availability is one of the most critical limiting factors [91]. Timely rainfall is essential for the economy, yet rainfall across Africa varies significantly on annual, decadal, and longer time scales [92]. While average annual temperatures across the continent are generally high, exceptions occur at the northern and southern extremes and at higher elevations. Nevertheless, seasonal and daily temperature variations are evident throughout Africa. Given its tropical location, precipitation remains the key climatic factor distinguishing one season from another. Africa's major river basins, such as the Nile, Congo, and Niger, provide freshwater, support agriculture, and are essential for hydropower generation. The Nile watershed basin, home to the world's longest basins as it spans 6781 km, hydrologically and geographically complex system which traverses 11 countries and covers one – tenth of the Africa continent [93]. Major tributaries, involving the Blue Nile, Tekes, and Baro- Akobo, sustain the river's flow during different seasons of the year. Despite a significant contribution to agriculture, ecosystems, and hydropower, the Nile river basin has 85 km^3 average discharge per year, measured at Aswan, is relatively low compared to other larger rivers, a result of the arid and hyper-arid hydrological conditions that dominate over 40% of this basin [93]. However, managing these water resources presents a unique challenge due to Africa's highly variable rainfall, widespread water scarcity, and the pressures of a rapidly growing population [93].

To further explore the complexities and significance of Africa's watershed basins, a detailed examination of existing literature is important. Such an analysis will provide valuable insight into the hydrological, socio- economic, and environmental aspects, supporting the effective water resource management strategies for the associated region.

2.5. Canada/north & South America watershed basins

2.5.1. Canada

Canada, the second-largest country in the world by area, features a diverse range of landscapes within its watersheds, including mountains, forests, agricultural regions, and water bodies, which are integral to regulating its vast freshwater resources [50]. These watershed basins support a variety of ecosystems and are crucial for sustaining economic activities such as agriculture, hydropower generation, and fisheries. Covering an area of 9.1 million km^2, with nearly 0.9 million km^2 consisting of inland water bodies, Canada stretches from 42°N to 83°N latitude and is bordered by three major oceans. Of the total area, 75% of the land drains northward into Hudson Bay and the Arctic Ocean, 15% flows into the Atlantic Ocean, and the remainder drains elsewhere [94].

The hydrology of the Canadian Prairies is defined by its semi-arid, cold-region conditions, where snowmelt runoff over frozen soils is a key driver of streamflow. Much of this runoff is retained in depressions, reducing the areas contributing to basin flow, while summer rainfall mainly supports evapotranspiration for crops [95]. Canada's continental interior is witnessing an overall increase in moisture, following a west-to-east and south-to-north gradient. Northern areas of the Hudson Bay Basin may experience a significant increase in moisture—up to 35% above historical annual averages from 1981 to 2010—while the Nelson River prairie basins face a potential, though uncertain, decrease of around 5% [96, 97].

Canada's major watershed basins play a significant role in the hydrological system. The Mackenzie River Basin, the largest in northern Canada, spans Alberta, Saskatchewan, British Columbia, the Northwest Territories, and the Yukon, covering around 1.8 million square kilometers, which is approximately one-fifth of Canada's total landmass [98]. Similarly, the Fraser River Basin (FRB), the largest in British Columbia, drains approximately 230,000 square kilometers, with elevations ranging from sea level to around 4,000 meters [99]. In addition to these, the Great Lakes-St. Lawrence Watershed is also projected to face impacts from climate change, with a projected reduction in average annual discharge between 4% and 24% over the next 90 years [100].

Continental-scale hydrologic and land surface models are critical for understanding the available freshwater resources all over Canada, specifically in the context of climate change [96].Between the decades 1976–85 and 1986–95, Canada experienced considerable shifts in hydrological patterns because of varying temperature and precipitation, resulting to changes in streamflow, with earlier spring runoff in warmer regions and delayed runoff in cooler areas [98].These including hydrological conditions underscore the significance of continuous monitoring and assessment to manage and sustain Canada's essential freshwater ecosystems.

2.5.2. North America

Watershed basins in North America, particularly in the U.S, are significant to the region's environment, economy, and social systems. These basins mold landscapes and support economies over vast regions by preparing critical water resources for agriculture, industry, and recreation. In addition, they significantly impact on weather patterns, biodiversity, and the accessibility of natural resources. This highlights the importance of watershed systems within the broader ecological and hydrological framework of the planet.

The United States contains numerous significant watershed basins with substantial environmental and economic impact. The Mississippi River Basin, is the third largest basin globally, drains almost half of the nation's land area, playing a critical role in sustaining a variety of ecosystems and human activities [1]. As it is an extended basin, it consists of climate, hydrology, and land cover characteristics variation across the region. Mean annual discharge and precipitation is varied throughout the basin as shown in Fig. 6. The Mississippi river basin has six main subbasins: Ohio, Tennes-see, Upper Mississippi, Lower Mississippi, Missouri, and Arkansas-White-Red Rive [101].

Further, the basin has been affected significantly by climate change, experiencing more variable and extreme weather patterns. Record- breaking floods, such as the May 2011 Vicksburg reached 17.1 meters, 4 meter above flood stage have occurred due to cyclonic activities bringing moisture from the Gulf of Mexico [28]. Conversely, intense droughts for instance those in 2012 resulted historically low river stage, showing 18-meter variation within a year. These fluctuations highlight the potential for more

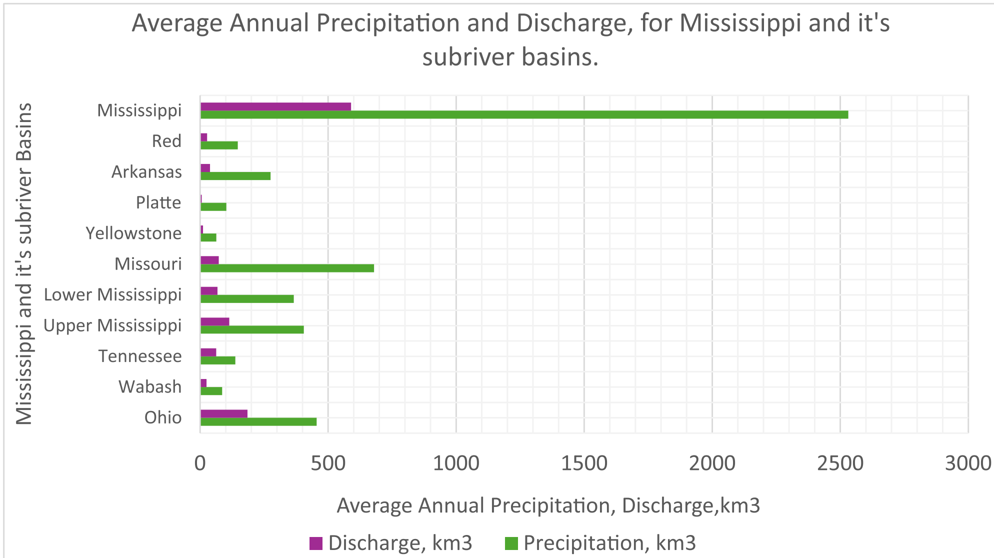

Fig. 6. Mississippi and it's sub-basins mean annual discharge and precipitation [101].

extreme weather events, like sever rainfall and prolonged drought, which causes further impact on the region's hydrology and ecosystems [28].

The Columbia River Basin, the fourth-largest river system in North America, Carries an average of nearly 247 billion cubic meters (200 million acre-feet) of water annually, providing both ecological health and economic activities in the Pacific Northwest [102, 103].The Rio Grande also ranks as the fifth-longest river in North America, further focusing on importance of these watersheds and management of water resources and environmental sustainability [104].

Hudson Bay drainage basin is another key watershed which spans north-central Canada and portion of the northern United States [105]. This watershed encompasses major rivers such as Nelson and Moose, whose flows are heavily regulated for hydropower production. This emphasizes the critical intersection of water resource management and energy requirements within North American watersheds [105].

In the twentieth century, the United States faced significant challenges in water resource management. These included the development of water resources, structural flood control, and the establishment of centralized systems for drinking water and wastewater treatment [106]. As the focus shifted to the twenty-first century, the emphasis transitioned toward managing land uses to reduce polluted runoff, addressing groundwater contamination, restoring the physical integrity of rivers to reverse declines in aquatic ecosystems, and protecting the natural capital of watersheds to enhance ecosystem services [106].

The North American watershed study area includes significant drainage basins such as the Yukon, Mackenzie, Saskatchewan, Missouri, and the upper Mississippi River basins. These watersheds span diverse landscapes, from the Great Plains to the Canadian prairies, and include the boreal and tundra regions of Canada and Alaska. Together, they capture much of the continent's variability in snow cover and seasonal streamflow [107].

2.5.3. South America

South America is among the most diverse continents in water resources, hosting the world's largest river (the Amazon), the longest mountain range (the Andes), and the driest desert (the Atacama) [108, 109]. However, the continent faces a growing environmental issue as pollution of rivers and other surface waters has become increasingly documented in the literature [110]. South America's watershed basins, including major ones like the Amazon, La Plata, and Orinoco, are subject to substantial environmental pressures from rapid urbanization, agricultural expansion, and nutrient loading. These pressures have a significant impact on water quality, ecological balance, and sustainable management practices across the continent's varied landscapes [111].

The Amazon drainage basin, the largest hydrological basin on Earth, spans approximately 6,000,000 km^2, covering nearly 5% of the global land area above sea level [112]. It also boasts the highest average discharge worldwide at 209,000 m^3/s and includes four of the world's ten largest rivers—the Amazon, Negro, Madeira, and Japura—alongside 20 of the 34 largest tropical rivers as tributaries [41]. Amazon basin has five main tributaries such as Negro River, Solimoes River, Madeira River, Tapajos

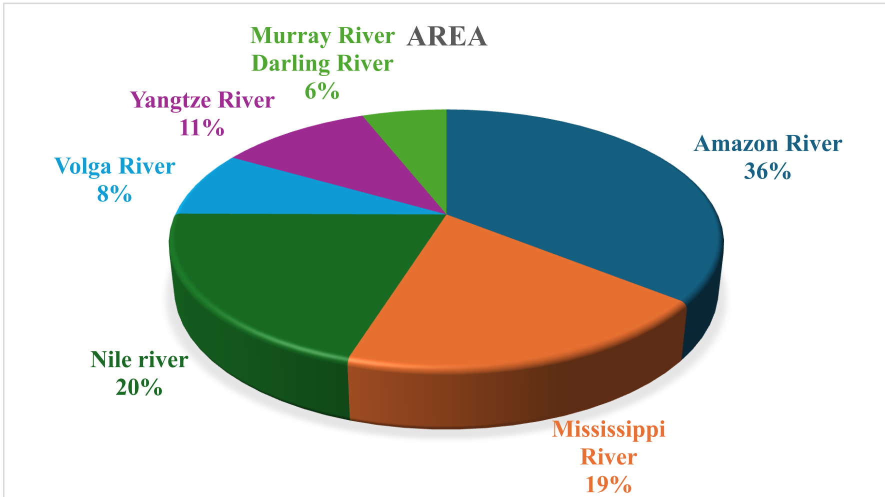

Fig. 7. Comparative representation of Global major watershed basins area.

River and Xingu River, drains various regions across south America, reflecting the basins vast scale and hydrological significance. Fig. 7 illustrates the relative size of the Amazon River compared to other major watershed basins in the world. As it highlights the Amazon River Basin as largest river basin in the global. Accounting for a key proportion of the world watershed area, focusing on its unparalleled role in hydrology and biodiversity.

The Amazon river basin receives almost 2,200 mm of precipitation per year [113]. This discharge of the Amazon River represents around 20% of total global river run-off [114]. However, deforestation and climate change in the Amazon River Basin caused significant impact on its hydrology. Forests losses to this basin disrupts the water cycle by reducing transpiration and altering rainfall patterns [115]. Cut down trees in the basin, experiences less evaporation and moisture release into the atmosphere, leading to mitigate rainfall and drier conditions. These variations in the precipitation affect river discharge, availability of water, and ecosystem stability. Further increasing frequency of droughts exacerbated by water scarcity, impacting ecological and agricultural systems [115].in addition, rapid growth of population, fires in the forest, mining, expansion of roads network, and land cover changes leading negative impact in the Amazon river basin. The Amazon basin is a significant components of global biodiversity as well as world water resource, energy, carbon cycle, ecosystem conservation, and plays a potential role in the global climate changes, through precipitation recycling and transformation of moisture to atmosphere [116]. To address these challenges and advance water resource management requires innovative approaches such as Reciprocal Watershed Agreements—referred to as ‘Watershed’ agreements within South America’s watershed regions—are grassroots-level conditional transfers that support land managers in upper watershed areas, encouraging sustainable management of forests and water resources. These agreements aim to create mutual benefits for both upstream stewards and downstream water users [117].

Additionally, the continent’s watersheds, which include the Amazon, Paraná, Northern Andes, Southern Andes, Mata Atlantica, Northeast Brazil, and Sao Francisco, have been comprehensively modeled. This extensive modeling has mapped over 5,400,000 kilometers of streams and more than 35,700 watershed units, providing a crucial framework for analyzing threats and assessing gaps in protected areas across South America [118]. The Colorado River Basin, while primarily located in the southwestern United States, also extends into northern Mexico, impacting regions in both countries. This river serves as a vital water source not only for seven U.S. states but also for the Mexican states of Baja California and Sonora, highlighting its cross-border importance in arid regions where water scarcity is an ongoing challenge [119].

3. Future research direction

Future research direction for watershed basin should emphasize understanding how climate change affects the availability of water, distribution of discharge and ecosystem services in these regions. It is critical to explore how changes in weather patterns and temperature increases impact strategies for water recourse management. In addition, developing better models that integrate social, economic and environmental factors will help to advance water management strategies, particularly in areas that share water resources across countries. For the Nile watershed basin, research should focus on the effects of land use on water resources and soil data improvement for better water management [22–25]. In Europe, future study could focus on development of hydropower impact and climate change on water quality, environmental and ecological conservation. The Danube and Rhine Basins, for instance, are facing challenges related to pollution and habitat fragmentation, which requires innovative holistic solutions for water resources management strategies [48, 74] In the same way research should focus on sustainable water management practices to investigate the unique challenges of each basin. The research should also emphasize climate change, deforestation, urbanization, and watershed health, particularly in developing rural regions. Mississippi River basin in northern parts of the United States requires research for integration of ecology with socio-ecologic factors to balance flood control with ecosystem health. And studies of effectiveness of water quality monitoring and adaptive management techniques are essential to reduce the impact of climate change on water resources and ecosystems services [26–30]. Ultimately, these research directions will contribute to developing effective, regional water management strategies, to ensure the sustainable management of water resources for both ecological health and human livelihoods.

4. Conclusion

The overview has provided a complete analysis of major watershed basins all around the world, focusing on their hydrological, environmental, and socio-economic importance. As the global need for water continues to rise due to growth of population, urbanization, and climate change, the management of water basins has become increasingly crucial. These watershed basins are fundamental for sustainability of biodiversity, supporting production of agriculture, providing freshwater for communities, and managing climate patterns. Although, they face numerous challenges, including overallocation of water, pollution, climate change effects, and loss of biodiversity, which threaten their extended sustainability. The major basins examined including the Murray-Darling, Yangtze, Volga, Nile, Mississippi, and Amazon illustrate water management complexity across various continents. Each watershed basin has unique characteristics, yet all share common challenges related to water scarcity, degradation of ecosystem, and competing population needs. In specifically, the Mississippi and Nile basins exemplify the tension among development of human and environmental preservation, underscoring the demand for more integrated and adaptive management techniques. Future research should prioritize addressing these challenges by highlighting climate resilience, improving water quality control, and adopting sustainable water usage approaches that balance ecological health with human demands.

This review of literature also highlighted the importance of transboundary cooperation, as many of the major universal watershed basins are shared across national borders. Effective management in these shared basins needs not just technological and scientific advances but in addition the establishment of collaborative frameworks that include several stakeholders, involving governments, localized communities, and the non-public sector. Policymaking must be grounded in an understanding of both the characteristics of hydrological watersheds and the social, economic, and political contexts in which they operate. The European Union's Water Framework Directive and India's National Mission for Clean Ganga provide vital models for collaborative and participatory management techniques that could be adapted to other Globalized watershed basins.

Despite progress made in understanding the dynamics of the major watershed basins, significant research gaps remain, specifically in the integration of natural and social sciences to better understand human-water interactions. focus of the future study should be on enhancing monitoring and collection of data, developing more sophisticated hydrological models, and exploring the effect of socio-economic factors on watershed health. Moreover, there is an urgent demand for targeted research on the future viability of watershed basins such as Nile and Mississippi, which confront significant stress from over-extraction, pollution, and climate change impact. Sustainable management strategies, informed by scientific study and local knowledge, will be crucial to maintaining the health and resilience of these critical hydrological systems.

Ultimately, the sustainable management of watershed basins is critical due to water security for future generations. By concluding these challenges identified in the review and fostering interdisciplinary research review and global cooperation, it is possible to develop more effective management approaches that will safeguard these essential resources for both population and ecosystems. Continued research, coupled with strong policy frameworks and collaborative techniques, will be necessary in mitigating the growing challenges of water faced by many of the world's most critical watershed basins.

Conflict of interest

The authors declare no conflict of interest to any party.

References

1. S. Giri, "Water quality prospective in Twenty First Century: Status of water quality in major river basins, contemporary strategies and impediments: A review," *Environ. Pollut.*, vol. 271, p. 116332, 2021.
2. C. He, C. P. Harden, and Y. Liu, "Comparison of water resources management between China and the United States," *Geogr. Sustain.*, vol. 1, no. 2, pp. 98–108, 2020.
3. I. Haddeland, *et al.*, "Global water resources affected by human interventions and climate change," *Proc. Natl. Acad. Sci.*, vol. 111, no. 9, pp. 3251–3256, 2014.
4. D. Vanham, *et al.*, "Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4. 2 'Level of water stress,'" *Sci. Total Environ.*, vol. 613, pp. 218–232, 2018.
5. M. M. Mekonnen and A. Y. Hoekstra, "Four billion people facing severe water scarcity," *Sci. Adv.*, vol. 2, no. 2, pp. e1500323–e1500323, Feb. 2016. doi: 10.1126/sciadv.1500323.
6. V. P. Singh and D. A. Woolhiser, "Mathematical modeling of watershed hydrology," *J. Hydrol. Eng.*, vol. 7, no. 4, pp. 270–292, 2002.
7. E. B. Daniel, J. V. Camp, E. J. LeBoeuf, J. R. Penrod, J. P. Dobbins, and M. D. Abkowitz, "Watershed modeling and its applications: A state-of-the-art review," *Open Hydrol. J.*, vol. 5, no. 1, 2011.
8. Z. H. Doost and Z. M. Yaseen, "Allocation of reservoirs sites for runoff management towards sustainable water resources: Case study of Harirud River Basin, Afghanistan," *J. Hydrol.*, vol. 634, p. 131042, 2024.
9. R. I. McDonald, *et al.*, "Water on an urban planet: Urbanization and the reach of urban water infrastructure," *Glob. Environ. Chang.*, vol. 27, pp. 96–105, 2014.
10. W. Paterson, *et al.*, "Water footprint of cities: A review and suggestions for future research," *Sustainability*, vol. 7, no. 7, pp. 8461–8490, 2015.
11. M. E. Assessment, *Ecosystems and human well-being*, vol. 5. Island press, Washington, DC, 2005.
12. J. Garcia-Moreno, *et al.*, "Sustaining freshwater biodiversity in the Anthropocene," *Glob. water Syst. Anthr. Challenges Sci. Gov.*, pp. 247–270, 2014.
13. B. M. Crowder, "Economic costs of reservoir sedimentation: A regional approach to estimating cropland erosion damage," *J. soil water Conserv.*, vol. 42, no. 3, pp. 194–197, 1987.
14. R. I. McDonald, K. F. Weber, J. Padowski, T. Boucher, and D. Shemie, "Estimating watershed degradation over the last century and its impact on water-treatment costs for the world's large cities," *Proc. Natl. Acad. Sci.*, vol. 113, no. 32, pp. 9117–9122, 2016.
15. M. A. Giordano, *International river basin management: Global principles and basin practice*. Oregon State University, 2002.
16. Z. H. Doost, M. Alsuwaiyan, and Z. M. Yaseen, "Runoff Management based Water Harvesting for better water resources sustainability: A comprehensive review," *Knowledge-Based Eng. Sci.*, vol. 5, no. 1, pp. 1–45, 2024.
17. F. Mushtaq, H. Rehman, U. Ali, M. S. Babar, M. S. Al-Suwaiyan, and Z. M. Yaseen, "An investigation of recharging groundwater levels through river ponding: New strategy for water management in Sutlej River," *Sustain*, 2023. doi: 10.3390/su15021047.
18. C. Revenga and T. Tyrrell, "Major river basins of the world," in *The Wetland Book II: Distribution, Description, and Conservation*, Springer Nature, pp. 109–124, 2018. doi: 10.1007/978-94-007-4001-3_211.
19. J. Alcamo, P. Döll, F. Kaspar, and S. Siebert, "Global change and global scenarios of water use and availability: an application of WaterGAP 1.0," *Cent. Environ. Syst. Res. Univ. Kassel, Kassel, Ger.*, 1997.
20. Z. M. Yaseen, *et al.*, "Hourly river flow forecasting: Application of emotional neural network versus multiple machine learning paradigms," *Water Resour. Manag.*, vol. 34, no. 3, pp. 1075–1091, 2020. doi: 10.1007/s11269-020-02484-w.
21. P. Nagamuthu, "Climate change impacts on surface water resources of the Northern Region of Sri Lanka," *Knowledge-Based Eng. Sci.*, vol. 4, no. 2, pp. 25–50, 2023.
22. C. Onyutha, H. Tabari, M. T. Taye, G. N. Nyandwaro, and P. Willems, "Analyses of rainfall trends in the Nile river basin," *J. Hydro-Environment Res.*, vol. 13, pp. 36–51, 2016. doi: 10.1016/j.jher.2015.09.002.
23. R. F. Digna, Y. A. Mohamed, P. Van Der Zaag, S. Uhlenbrook, and G. A. Corzo, "Nile river basin modelling for water resources management–a literature review," *Int. J. River Basin Manag.*, vol. 15, no. 1, pp. 39–52, 2017.
24. Y. T. Dile, *et al.*, "Advances in water resources research in the Upper Blue Nile basin and the way forward: A review," *J. Hydrol.*, vol. 560, pp. 407–423, May 2018. doi: 10.1016/J.JHYDROL.2018.03.042.
25. M. M. Deribe, A. M. Melesse, B. B. Kidanewold, S. Dinar, and E. P. Anderson, "Assessing international transboundary water management practices to extract contextual lessons for the Nile river basin," *Water*, vol. 16, no. 14, p. 1960, 2024.
26. D. A. Goolsby and W. A. Battaglin, "Long-term changes in concentrations and flux of nitrogen in the Mississippi river basin, USA," *Hydrol. Process.*, vol. 15, no. 7, pp. 1209–1226, 2001.
27. N. D. Walker, W. J. Wiseman Jr, L. J. Rouse Jr, and A. Babin, "Effects of river discharge, wind stress, and slope eddies on circulation and the satellite-observed structure of the Mississippi River plume," *J. Coast. Res.*, vol. 21, no. 6, pp. 1228–1244, 2005.
28. P. J. DuBowy, "Mississippi river ecohydrology: Past, present and future," *Ecohydrol. Hydrobiol.*, vol. 13, no. 1, pp. 73–83, 2013.
29. S. A. Changnon, "The historical struggle with floods on the Mississippi River basin: Impacts of recent floods and lessons for future flood management and policy," *Water Int*, vol. 23, no. 4, pp. 263–271, 1998.
30. Q. Guo, "Strategies for a resilient, sustainable, and equitable Mississippi river basin," *River*, 2023.
31. K. Schwabe, J. Albiac, J. D. Connor, R. M. Hassan, and L. M. González, *Drought in arid and semi-arid regions: A multi-disciplinary and cross-country perspective*. Springer, 2013.
32. J. Wang, Y. Wu, Z. Hu, and J. Zhang, "Remote Sensing of Watershed: Towards a New Research Paradigm," *Remote Sensing*, vol. 15, no. 10. MDPI, p. 2569, 2023.
33. B. T. Hart, "The Australian Murray–Darling Basin plan: challenges in its implementation (part 1)," *Int. J. Water Resour. Dev.*, vol. 32, no. 6, pp. 819–834, 2016.

34. J. Pittock and D. Connell, "Australia demonstrates the planet's future: water and climate in the Murray–Darling Basin," *Int. J. Water Resour. Dev.*, vol. 26, no. 4, pp. 561–578, 2010.
35. J. D. Koehn, S. R. Balcombe, and B. P. Zampatti, "Fish and flow management in the Murray–Darling Basin: Directions for research," *Ecol. Manag. Restor.*, vol. 20, no. 2, pp. 142–150, 2019.
36. F. Yu, Z. Chen, X. Ren, and G. Yang, "Analysis of historical floods on the Yangtze River, China: Characteristics and explanations," *Geomorphology*, vol. 113, no. 3–4, pp. 210–216, 2009.
37. V. G. Ferreira, *et al.*, "Characterization of the hydrogeological regime of Yangtze River basin using remotely-sensed and modeled products," *Sci. Total Environ.*, vol. 718, p. 137354, 2020.
38. A. Y. Sidorchuk, A. V. Panin, and O. K. Borisova, "Morphology of river channels and surface runoff in the Volga River basin (East European Plain) during the Late Glacial period," *Geomorphology*, vol. 113, no. 3–4, pp. 137–157, 2009.
39. E. Nikitina, F. Wefering, and S. Rupprecht, "CABRI-Volga Future Research Agenda".
40. K. R. Olson and S. S. Chernyanskii, "The Volga River is Russia's lifeline and in need of maintenance, mitigation and restoration," *Open J. Soil Sci.*, vol. 14, no. 3, pp. 159–179, 2024.
41. E. M. Latrubesse, *et al.*, "Damming the rivers of the Amazon basin," *Nature*, vol. 546, no. 7658, pp. 363–369, 2017.
42. M. J. Lathuillière, M. T. Coe, and M. S. Johnson, "A review of green-and blue-water resources and their trade-offs for future agricultural production in the Amazon Basin: what could irrigated agriculture mean for Amazonia?," *Hydrol. Earth Syst. Sci.*, vol. 20, no. 6, pp. 2179–2194, 2016.
43. S. Dalby, S. Horton, R. Mahon, and D. Thomaz, "Achieving the sustainable development goals," *Glob. Gov. Challenges. Routledge Taylor Fr. New York*, 2019.
44. S. Athayde, *et al.*, "Mapping research on hydropower and sustainability in the Brazilian Amazon: advances, gaps in knowledge and future directions," *Curr. Opin. Environ. Sustain.*, vol. 37, pp. 50–69, 2019.
45. H. Zhang, *et al.*, "Impacts of future climate change on water resource availability of eastern Australia: A case study of the Manning river basin," *J. Hydrol.*, vol. 573, pp. 49–59, 2019.
46. W. Magrath and J. B. Doolette, *Strategic issues for watershed development in Asia*, vol. 30. World Bank Policy Planning and Research Staff, Environment Department, 1990.
47. X. Wang, Y. Chen, Z. Li, G. Fang, and Y. Wang, "Development and utilization of water resources and assessment of water security in Central Asia," *Agric. Water Manag.*, vol. 240, p. 106297, 2020.
48. G. Duarte, P. Segurado, G. Haidvogl, D. Pont, M. T. Ferreira, and P. Branco, "Damn those damn dams: Fluvial longitudinal connectivity impairment for European diadromous fish throughout the 20th century," *Sci. Total Environ.*, vol. 761, p. 143293, 2021.
49. F. Karamage, *et al.*, "Spatial relationship between precipitation and runoff in Africa," *Hydrol. Earth Syst. Sci. Discuss.*, vol. 2018, pp. 1–27, 2018.
50. Z. Zahmatkesh, S. Kumar Jha, P. Coulibaly, and T. Stadnyk, "An overview of river flood forecasting procedures in Canadian watersheds," *Can. Water Resour. Journal/Revue Can. des ressources hydriques*, vol. 44, no. 3, pp. 213–229, 2019.
51. M. A. Habermehl, "The evolving understanding of the Great Artesian Basin (Australia), from discovery to current hydrogeological interpretations," *Hydrogeol. J.*, vol. 28, no. 1, pp. 13–36, 2020.
52. J. Peng, *et al.*, "The conflicts of agricultural water supply and demand under climate change in a typical arid land watershed of Central Asia," *J. Hydrol. Reg. Stud.*, vol. 47, p. 101384, 2023.
53. W. Brack, *et al.*, "Towards the review of the European Union Water Framework Directive: recommendations for more efficient assessment and management of chemical contamination in European surface water resources," *Sci. Total Environ.*, vol. 576, pp. 720–737, 2017.
54. G. Wang, *et al.*, "Integrated watershed management: evolution, development and emerging trends," *J. For. Res.*, vol. 27, pp. 967–994, 2016.
55. P. S. Lake and N. R. Bond, "Australian futures: freshwater ecosystems and human water usage," *Futures*, vol. 39, no. 2–3, pp. 288–305, 2007.
56. G. E. Amirthanathan, M. A. Bari, F. M. Woldemeskel, N. K. Tuteja, and P. M. Feikema, "Regional significance of historical trends and step changes in Australian streamflow," *Hydrol. Earth Syst. Sci.*, vol. 27, no. 1, pp. 229–254, 2023.
57. M. Leblanc, S. Tweed, A. Van Dijk, and B. Timbal, "A review of historic and future hydrological changes in the Murray-Darling Basin," *Glob. Planet. Change*, vol. 80, pp. 226–246, 2012.
58. S. Beare and A. Heaney, "Climate change and water resources in the Murray Darling Basin, Australia," in *Conference paper*, 2002, pp. 1–33.
59. J. Bellamy, B. W. Head, and H. Ross, "Crises and institutional change: Emergence of cross-border water governance in Lake Eyre Basin, Australia," *Soc. Nat. Resour.*, vol. 30, no. 4, pp. 404–420, 2017.
60. J. Davis, *et al.*, "When trends intersect: The challenge of protecting freshwater ecosystems under multiple land use and hydrological intensification scenarios," *Sci. Total Environ.*, vol. 534, pp. 65–78, 2015.
61. R. P. Yadav, *Agricultural research in Nepal: resource allocation, structure, and incentives*, vol. 62. Intl Food Policy Res Inst, 1987.
62. L. Bharati, B. R. Sharma, and V. Smakhtin, *Ganges River Basin*, Taylor & Francis, 2016.
63. X. Wang, Y. Chen, Z. Li, G. Fang, F. Wang, and H. Hao, "Water resources management and dynamic changes in water politics in the transboundary river basins of Central Asia," *Hydrol. Earth Syst. Sci.*, vol. 25, no. 6, pp. 3281–3299, 2021.
64. J. D. Milliman and J. P. M. Syvitski, "Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers," *J. Geol.*, vol. 100, no. 5, pp. 525–544, 1992.
65. H. Wang, Y. Saito, Y. Zhang, N. Bi, X. Sun, and Z. Yang, "Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia," *Earth-Science Rev*, vol. 108, no. 1–2, pp. 80–100, 2011.
66. Y. Chen, W. Li, G. Fang, and Z. Li, "Hydrological modeling in glacierized catchments of central Asia–status and challenges," *Hydrol. Earth Syst. Sci.*, vol. 21, no. 2, pp. 669–684, 2017.
67. X. Liu, *et al.*, "Microbiome analysis in Asia's largest watershed reveals inconsistent biogeographic pattern and microbial assembly mechanisms in river and lake systems," *iScience*, 2024.
68. S. Yin, Y. Yi, Q. Liu, Q. Luo, and K. Chen, "A review on effects of human activities on aquatic organisms in the Yangtze River Basin since the 1950s," *River*, vol. 1, no. 1, pp. 104–119, 2022.

69. H. Zhang, *et al.*, "Rapid change in Yangtze fisheries and its implications for global freshwater ecosystem management," *Fish Fish*, vol. 21, no. 3, pp. 601–620, 2020.
70. X. Liu, *et al.*, "Impact of land use on shallow groundwater quality characteristics associated with human health risks in a typical agricultural area in Central China," *Environ. Sci. Pollut. Res.*, vol. 28, pp. 1712–1724, 2021.
71. S. Shrestha, D.-H. Bae, P. Hok, S. Ghimire, and Y. Pokhrel, "Future hydrology and hydrological extremes under climate change in Asian river basins," *Sci. Rep.*, vol. 11, no. 1, p. 17089, 2021.
72. M. L. Tan, P. W. Gassman, R. Srinivasan, J. G. Arnold, and X. Yang, "A review of SWAT studies in Southeast Asia: Applications, challenges and future directions," *Water*, vol. 11, no. 5, p. 914, 2019. doi: 10.3390/w11050914.
73. M. Achouri, "Preparing the next generation of watershed management programmes," *Prep. NEXT Gener. WATERSHED Manag. Program. Proj.*, p. 11, 2005.
74. M. Flörke and J. Alcamo, "European outlook on water use," *Cent. Environ. Syst. Res. Univ. Kassel, Final Report, EEA/RNC/03/007*, vol. 83, 2004.
75. M. Schletterer, *et al.*, "The Volga: Management issues in the largest river basin in Europe," *River Res. Appl.*, vol. 35, no. 5, pp. 510–519, 2019.
76. A. Kalugin, "Hydrological and meteorological variability in the Volga River basin under global warming by 1.5 and 2 degrees," *Climate*, vol. 10, no. 7, p. 107, 2022.
77. S. G. Dobrovolski, "The issue of global warming and changes in the runoff of Russian rivers," *Water Resour*, vol. 34, pp. 607–618, 2007.
78. EEA, "European waters—assessment of status and pressures. EEA Report No 7/2018." EEA Copenhagen, 2018.
79. B. Grizzetti, *et al.*, "Ecosystem services for water policy: Insights across Europe," *Environ. Sci. Policy*, vol. 66, pp. 179–190, 2016.
80. J. Pokrývková, Ľ. Jurík, and R. Hanzlík, "Water retention in urban areas in the Danube Region: Study on facts, activities, measures and their financial assessment." Slovak University of Agriculture Nitra, Slovkia, 2020.
81. T. Botterweg and D. W. Rodda, "Danube River Basin: progress with the environmental programme," *Water Sci. Technol.*, vol. 40, no. 10, pp. 1–8, 1999.
82. B. Bisselink, *et al.*, "Impact of a changing climate, land use, and water usage on water resources in the Danube river basin," *EUR 29228EN, Publ. Off. Eur. Union, Luxembg.*, 2018.
83. U. F. Uehlinger, K. M. Wantzen, R. S. Leuven, and H. Arndt, "The Rhine river basin," 2009.
84. M. Pfeiffer and M. Ionita, "Assessment of hydrologic alterations in Elbe and Rhine Rivers," Germany," *Water*, vol. 9, no. 9, p. 684, 2017.
85. L. Palmeri, G. Bendoricchio, and Y. Artioli, "Modelling nutrient emissions from river systems and loads to the coastal zone: Po River case study, Italy," *Ecol. Modell.*, vol. 184, no. 1, pp. 37–53, 2005.
86. H. U. Sverdrup, L. L. Frolova, and A. E. Sverdrup, "Using a system dynamics model for investigating potential levels of antibiotics pollution in the Volga River," *Water, Air, Soil Pollut*, vol. 231, pp. 1–32, 2020.
87. A. M. Negm, *The Nile River*. Springer, 2017.
88. M. K. Gumma, B. Z. Birhanu, I. A. Mohammed, R. Tabo, and A. M. Whitbread, "Prioritization of watersheds across Mali using remote sensing data and GIS techniques for agricultural development planning," *Water*, vol. 8, no. 6, p. 260, 2016.
89. T. J. Baker and S. N. Miller, "Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed," *J. Hydrol.*, vol. 486, pp. 100–111, 2013.
90. P. J. Ferraro, "Regional review of payments for watershed services: Sub-Saharan Africa," *J. Sustain. For.*, vol. 28, no. 3–5, pp. 525–550, 2009.
91. A. Bodian, A. Dezetter, L. Diop, A. Deme, K. Djaman, and A. Diop, "Future climate change impacts on streamflows of two main West Africa river Basins: Senegal and Gambia," *Hydrology*, vol. 5, no. 1, p. 21, 2018.
92. J. A. Adesina, J. Jiang, and T. Xiaolan, "Integrated watershed management framework and groundwater resources in Africa: A review of West Africa sub-region," 2021.
93. N. Pacini and D. M. Harper, "Hydrological characteristics and water resources management in the Nile Basin," *Ecohydrol. Hydrobiol.*, vol. 16, no. 4, pp. 242–254, 2016.
94. S. Wang, D. W. McKenney, J. Shang, and J. Li, "A national-scale assessment of long-term water budget closures for Canada's watersheds," *J. Geophys. Res. Atmos.*, vol. 119, no. 14, pp. 8712–8725, 2014.
95. S. Dumanski, J. W. Pomeroy, and C. J. Westbrook, "Hydrological regime changes in a Canadian Prairie basin," *Hydrol. Process.*, vol. 29, no. 18, pp. 3893–3904, 2015.
96. T. A. Stadnyk and S. J. Déry, "Canadian continental-scale hydrology under a changing climate: A review," *Water*, vol. 13, no. 7, p. 906, 2021.
97. W. Greaves, "Climate change and security in Canada," *Int. J.*, vol. 76, no. 2, pp. 183–203, 2021.
98. P. H. Whitfield and A. J. Cannon, "Recent variations in climate and hydrology in Canada," *Can. water Resour. J.*, vol. 25, no. 1, pp. 19–65, 2000.
99. R. R. Shrestha, M. A. Schnorbus, A. T. Werner, and A. J. Berland, "Modelling spatial and temporal variability of hydrologic impacts of climate change in the Fraser River basin," British Columbia, Canada," *Hydrol. Process.*, vol. 26, no. 12, pp. 1840–1860, 2012.
100. A. M. Bartolai, L. He, A. E. Hurst, L. Mortsch, R. Paehlke, and D. Scavia, "Climate change as a driver of change in the Great Lakes St. Lawrence River basin," *J. Great Lakes Res.*, vol. 41, pp. 45–58, 2015.
101. D. Lee and J. Veizer, "Water and carbon cycles in the Mississippi river basin: Potential implications for the Northern Hemisphere residual terrestrial sink," *Global Biogeochem. Cycles*, vol. 17, no. 2, 2003.
102. S. J. Cohen, K. A. Miller, A. F. Hamlet, and W. Avis, "Climate change and resource management in the Columbia River Basin," *Water Int*, vol. 25, no. 2, pp. 253–272, 2000.
103. J. M. Volkman, "*A river in common: the Columbia River, the salmon ecosystem, and water policy*." *Western Water Policy Review Advisory Commission*, 1997.
104. J. W. Parcher, D. G. Woodward, and R. A. Durall, "A Descriptive Overview Of The Rio Grande–Rio Bravo Watershed," *J. Transbound. water Resour.*, vol. 1, pp. 159–178, 2010.
105. S. J. Déry, T. A. Stadnyk, M. K. MacDonald, K. A. Koenig, and C. Guay, "Flow alteration impacts on Hudson Bay river discharge," *Hydrol. Process.*, vol. 32, no. 24, pp. 3576–3587, 2018.
106. C. Lant, "Watershed governance in the United States: The challenges ahead," *Water Resour. Updat.*, vol. 126, pp. 21–28, 2003.
107. J. Dyer, "Snow depth and streamflow relationships in large North American watersheds," *J. Geophys. Res. Atmos.*, vol. 113, no. D18, 2008.

108. W. Buytaert and L. Breuer, "Water resources in South America: sources and supply, pollutants and perspectives," *Proc. IAHS-IAPSO-IASPEI Assem. Gothenburg, Sweden*, pp. 106–113, 2013.
109. C. Campuzano, *et al.*, "Water resources assessment," *Water food Secur. wellbeing Lat. Am. Caribb. Soc. Environ. Implic. a Glob. Econ. Abingdon Routledge*, pp. 27–54, 2014.
110. L. N. Rigacci, A. D. N. Giorgi, C. S. Vilches, N. A. Ossana, and A. Salibián, "Effect of a reservoir in the water quality of the Reconquista River," Buenos Aires, Argentina," *Environ. Monit. Assess.*, vol. 185, pp. 9161–9168, 2013.
111. M. M. C. Bustamante, *et al.*, "Nitrogen management challenges in major watersheds of South America," *Environ. Res. Lett.*, vol. 10, no. 6, p. 65007, 2015.
112. J. C. E. Villar, *et al.*, "Contrasting regional discharge evolutions in the Amazon basin (1974–2004)," *J. Hydrol.*, vol. 375, no. 3–4, pp. 297–311, 2009.
113. J. Bouchez, *et al.*, "River mixing in the Amazon as a driver of concentration-discharge relationships," *Water Resour. Res.*, vol. 53, no. 11, pp. 8660–8685, 2017.
114. L. Nagy, B. R. Forsberg, and P. Artaxo, *Interactions between biosphere, atmosphere and human land use in the Amazon basin*, vol. 227. Springer, 2016.
115. M. Guimberteau, *et al.*, "Impacts of future deforestation and climate change on the hydrology of the Amazon Basin: a multi-model analysis with a new set of land-cover change scenarios," *Hydrol. Earth Syst. Sci.*, vol. 21, no. 3, pp. 1455–1475, 2017.
116. O. Bagheri, Y. Pokhrel, N. Moore, and M. S. Phanikumar, "Groundwater dominates terrestrial hydrological processes in the Amazon at the basin and subbasin scales," *J. Hydrol.*, vol. 628, p. 130312, 2024.
117. N. Asquith, "*Reciprocal agreements for watershed conservation in South America*," *JSTOR*, 2018.
118. P. Petry and L. Sotomayor, "Mapping Freshwater Ecological Systems with Nested Watersheds in South America," *Nat. Conserv.*, 2009.
119. H. Salehabadi, *et al.*, "The future hydrology of the Colorado River Basin," *Futur. Color. River Proj. White Pap. No. 4. Logan, UT Utah State Univ. Quinney Coll. Nat. Resour. Cent. Color. River Stud. 71 p.*, 2020.