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Environmental change induced by water engineering development dominates the global watershed sustainable development issues

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Introduction: Global watershed sustainable development has experienced world-wide threats from continuing anthropogenic stressors, and the need to deepen and broaden research encompassing the intersection in global environmental change as well as environmentally oriented watershed sustainable development (EOWSD) has been noticed. However, there is not yet a widely recognized cognition on the applicability and scope of various EOWSD issues, and the zoning of global EOWSD issues is remains uncertain despite it is crucial for achieving global watershed sustainable development.

Methods: This research was conducted to both clarify the zoning and evolution of various EOWSD issues around the world, and differentiate the relative impacts on EOWSD of climate change and human activities. The global EOWSD issues were summarized from 62 watersheds around the world as 6 categories associated with different aspects of global watershed sustainability. And the partition method, in which the spatial and temporal variations of global summer Normalized Difference Vegetation Index in summer were examined and the quantitative climate classification were conducted, indicates a clear and definite relationship between the zoning of EOWSD issues and 8 natural geographical zones. Meanwhile, we selected 34 watersheds either or both are the 100 most populous river basins and the 100 largest (by area) river basins in the world from the 62 watersheds to assess relative effects of human impact on watershed sustainability.

Results: Results from the numerical analyses of baseline water stress (BWS) values, which was used to provide a robust measure of human impact and evaluate the impact and relative importance of human-induced changes on watershed sustainability, indicate that the human activities do not affect the zoning of EOWSD issues at global scale while the environmental change induced by water engineering development should be certain to affect that on the long-term.

Discussion: Our findings present a new perspective to illustrate the relationship among global EOWSD, environmental change and human impacts, and will also provide a scientific basis on setting future emphasizes of global watershed sustainable development and furthering the related disciplines.

KEYWORDS

environmental change, sustainable development, zoning, climate change, human activities, watershed, global scale

1 Introduction

Global watershed sustainable development, which plays important and unique roles in the provision of ecological and economic services and advancement of human civilization (Postal and Carpenter, 1997; Covich et al., 2004; Wang et al., 2022), has experienced worldwide threats from continuing anthropogenic stressors. Thus, it is necessary to deepen and broaden research encompassing the intersection of watershed sustainable development and the evolution of global environmental change and water engineering development (Brinson and Malvarez, 2002; Malmqvist and Rundle, 2002; Covich et al., 2004). According to the most frequently quoted definition of sustainable development from Our Common Future (WCED, 1987), the Brundtland Report recognizes the dependency of humans on the environment to meet present and future needs and regards the environmentally oriented development issues as one of the two key concepts in sustainable development definition. Given that interactions with global change dynamics (Walker et al., 2009) and the development of water engineering (Vormoor, 2010) are not addressed, sustainable development is no longer possible, and promoting global watershed sustainable development requires research on a wide range of environmentally oriented watershed sustainable development issues, such as the potential impact of environmental changes and water engineering development on regional water supplies, biodiversity, food security, and feedback from watershed itself. Environmentally oriented watershed sustainable development (EOWSD) is of importance in meeting both economic development goals and global environmental risks, so many studies have been conducted on one specific drainage basin or part of it (Covich et al., 2004; Palmer et al., 2007). However, there is not yet a widely recognized cognition on the applicability and scope of various EOWSD issues, and the zoning of global EOWSD issues remains uncertain, although it is crucial for achieving global watershed sustainable development.

Furthermore, in addition to global warming and relevant changes in the hydrological cycle, which are likely to increase the frequency and severity of extreme climate events, the increase in human activities by way of water engineering, including cultivation, afforestation, irrigation, deforestation, and urbanization, has also resulted in changes to flow regimes, especially large-scale changes in land cover or management in watersheds (Bates et al., 2008; Milliman et al., 2008; Déry et al., 2009; Jung et al., 2012; Thompson, 2012). Meanwhile, the close connection between watershed sustainable development and water engineering development and its impact on socio-economic conditions has been demonstrated (Wang and Gao, 2002; Vormoor, 2010). Thus, understanding the impact and relative importance of water engineering development on EOWSD has recently drawn considerable concerns. Assessing the relative impact of climate change and human activities is important, both for understanding the mechanism of global watershed sustainability and for local water resources management as well as drought and flood protection (Ye et al., 2013; Luan et al., 2021; Ahmad et al., 2023).

Given the importance of setting future emphasis on global EOWSD and furthering the related disciplines, there is a clear need to clarify the zoning and evolution of various EOWSD issues around the world and distinguish the relative effects of human activities and climate change on EOWSD. In this study, we integrated the EOWSD issues from 62 watersheds located in different parts of the world (Figure 1). To study the distribution characteristics of these EOWSD issues and to explore the underlying evolutionary mechanisms, the zoning of global EOWSD issues, which is based on the assessment of environmental variables, including climate change and vegetation condition, was proposed by producing a global map of climate on the basis of observational data and examining the spatial and temporal variations of global summer vegetation conditions. Meanwhile, baseline water stress and similar withdrawal-to-availability indicators were quantitatively analyzed to provide a robust measure of human impact on the hydrological context at the catchment scale and evaluate the effect and relative importance of human-induced change on watershed sustainability and distribution of EOWSD issues. In addition, simulated climate data were obtained to predict the evolution of global EOWSD and address the future emphasis on global watershed sustainable development.

2 Materials and methods

2.1 Global data

As the existing research aiming to achieve EOWSD is highly fragmented and always focuses on one specific aspect, we have selected 62 watersheds for the unbiased collection and cataloging of global environmentally oriented watershed sustainability (Table 1). To investigate the interrelationship between environmental changes and watershed sustainable development at global scales, we categorized EOWSD issues according to the goals specified in the data source (Bernhardt et al., 2005) or based on key phrases in the title and description when the goals were not clearly articulated in the data source. We particularly avoided inferring the intent of a study or project from the data record.

2.2 Global climate and vegetation zoning

A zoning method, in which a global map of climate based on observational data was produced and spatial and temporal variations of the global normalized difference vegetation index (NDVI) in

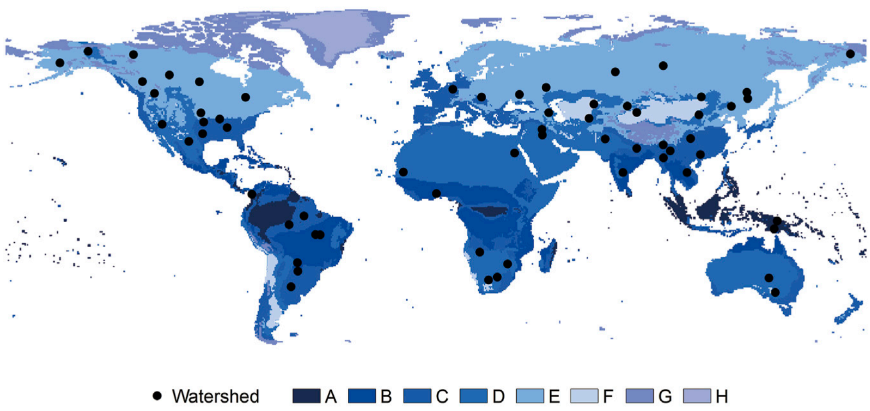

FIGURE 1
Eight natural geographical zones based on the Köppen–Geiger system and terrestrial vegetation, and the locations of the 62 watersheds. The letters in legends represent different natural geographical zones: A, humid tropical rainforest zone; B, tropical savanna climatic zone; C, humid evergreen broad-leaved forest zone; D, arid steppe-desert zone; E, humid and semihumid mixed broadleaf–conifer forest zone; F, arid and semiarid steppe zone; G, subpolar tundra zone; and H, polar ice sheet zone.

summer were examined, was used here to achieve a better understanding of the relationship between global climate and vegetation zoning and the distribution of EOWSD issues and to explore the underlying evolutionary mechanisms.

In order to assess the influence of climate change on global EOWSD issues, the Köppen–Geiger system was used to represent long-term mean climate conditions. There have been many modifications proposed to the Köppen system, but here we followed the criteria from Köppen's last publication about his classification system in the Köppen–Geiger Handbook (Köppen, 1936). The NCEP Reanalysis data for the period of 2001–2014 were downloaded from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). Data from the Community Earth System Model version 1 with the Community Atmosphere Model version 5 [CESM1 (CAM5)] (Hurrell et al., 2013), which is a single climate model of the Coupled Model Intercomparison Project Phase 5 (CMIP5), during 2041–2050 and 2091–2100 were both processed by the Köppen–Geiger system to examine the current status and evolution of emphasis on EOWSD in different parts of the world. The description and definition criteria for the Köppen climate symbols are listed in Table 2.

One series of 16-day NDVI data from a Moderate Resolution Imaging Spectroradiometer (MODIS) sensor at spatial resolutions of 1,000 m, which were downloaded from the Distribution Active Archive Center (DAAC) at the NASA Goddard Space Flight Center (GSFC) during the summer (June to August in the Northern Hemisphere and December to February in the Southern Hemisphere) of 2000–2014, was quantitatively analyzed using the EOF method to evaluate the influence of vegetation change on EOWSD issues around the world.

The EOF analysis is similar to the principal component analysis (PCA) commonly used for decorrelating a set of variables. The dataset of the observed parameter can be treated as a function $s(x, y, t)$ of spatial coordinates (x and y) and time t (Eq. 1). The EOF analysis basically decomposes $s(x, y, t)$ into a series of orthogonal functions f_i (x, y) of the spatial coordinates only. The temporal variation is captured in a series of temporal functions $g(t)$ such that

$$s(x,y,t) = \sum_{i=1}^{N} \int_i (x,y) g_{i(t)}, \tag{1}$$

where N is the total number of observations made in time t, which is taken for the 15-year period from 2000 to 2014 in this study. The orthogonal functions f_i (x, y) of EOF and their respective coefficients $g(t)$ can be determined by solving the eigenvalue equation constructed from the covariance matrix of $s(x, y, t)$. The orthogonal functions f_i (x, y) are arranged in decreasing order of the corresponding eigenvalues of the covariance matrix. Thus, the first few orthogonal functions usually account for most of the spatial variance that exists in the dataset.

2.3 The human impact: baseline water stress for 34 specific basin watersheds and numerical analyses

Based on the locations and ecosystem service value of watersheds, we have selected 62 watersheds to summarize their EOWSD issues, of which 34 watersheds, from either or both the 100 most populous river basins (Bernhard et al., 2008; CIESIN, 2010) and the 100 largest (by area) river basins (CIESIN, 2010) in the world, were chosen to assess the relative effect of human impact on watersheds. Baseline water stress (BWS), a commonly used indicator also known as relative water demand (Brown and Matlock, 2011), indicates the level of competition for available water and estimates the demand for freshwater (Gassert, 2013). The raw data of BWS we used here were obtained from the *Aqueduct Water Risk Atlas* (Aqueduct) (Reig et al., 2013), which is a publicly available, global database and interactive tool developed by the World Resources Institute (WRI). It evaluates, maps, and scores water risks globally based on 12 indicators, including baseline water stress. Baseline water stress measures the ratio of total annual water withdrawal (*Ut*) to average annual available blue water (*Ba*) (Eq. 2). It is important to note that most estimates of relative water demand do not account for upstream consumptive use as BWS here.

TABLE 1 Global EOWSD research cases.

Serial number	Name	Continent	Watershed location (latitude)	Watershed location (longitude)	Length (km)	Natural geographical zone	Reference
1	Yangtze River	Asia	30.13	106.48	6,300	C	Chen and Chen (2005); Zhong et al. (2003)
2	Yenisei River	Asia	60.50	95.00	5,539	G	Standring et al. (2009)
3	Kherlen River	Asia	47.50	111.00	5,498	G	Hideyuki et al. (2004)
4	Yellow River	Asia	40.00	110.00	5,464	E	Zhang and Sun (2005); Zhang et al. (2011)
5	Ob–Irtysh River	Asia	58.00	75.00	5,410	F	Guo et al. (2001); Deng et al. (2011)
6	Amur River	Asia	49.50	130.00	4,444	E	Wang and Chang (2006)
7	Mekong River	Asia	16.00	105.00	4,350	C	Ferguson et al. (2010)
8	Euphrates River	Asia	34.00	44.30	3,596	F	Al-Ansari and Knutsson (2011)
9	Indus River	Asia	30.00	70.80	3,180	C	Gosain et al. (2006)
10	Syr Darya–Naryn River	Asia	44.50	66.00	3,078	G	Karimov et al. (2010)
11	Nujiang River	Asia	25.00	98.00	3,060	C	Cai (2011)
12	Brahmaputra River	Asia	27.50	95.00	2,948	C	Phukan et al. (2012)
13	Amu Darya	Asia	38.60	64.00	2,620	G	Glantz (2005)
14	Ganges River	Asia	26.00	84.00	2,510	C	Sarkar et al. (2007)
15	Zhujiang River	Asia	23.46	110.60	2,200	C	Xia (1999)
16	Tarim River	Asia	41.06	84.00	2,100	D	Chen et al. (2003)
17	Tigris River	Asia	31.60	44.50	1,950	F	Al-Yamani et al. (2007)
18	Songhua River	Asia	46.81	130.37	1,927	E	Wang et al. (2013)
19	Ili River	Asia	43.70	80.00	1,400	D	Qiao et al. (2007); Wang (2007)
20	Kura River	Asia	40.93	47.18	1,364	C	Abbasov and Mahmudov (2009)
21	Liaohe River	Asia	43.58	123.50	1,345	E	Tu et al. (2013)
22	Krishna River	Asia	15.95	78.17	1,300	C	Venot et al. (2008)
23	Chindwin River	Asia	22.11	95.13	1,207	C	Goel et al. (2005)
24	Anadyr River	Asia	65.50	173.27	1,120	H	Alexander and Windom (1999)
25	Volga River	Europe	51.50	46.09	3,645	G	Liao et al. (2003)
26	Danube River	Europe	47.50	19.04	2,850	E	Sommerwerk et al. (2010); Tockner et al. (1998)
27	Dnieper River	Europe	48.51	34.87	2,287	E	Dubnyak and Timchenko (2000)
28	Rhine River	Europe	50.74	7.11	1,320	E	Rob et al. (2003)
29	Amazon River	South America	−2.11	−55.11	6,400	A	Braga et al. (2011); Coe et al. (2009)
30	La Plata Parana River	South America	−31.71	−60.51	5,578	C	Gottgens et al. (2001)
31	Rio Madeira	South America	−5.84	−61.34	3,350	A	Bastos et al. (2007)

(Continued on following page)

TABLE 1 (*Continued*) Global EOWSD research cases.

Serial number	Name	Continent	Watershed location (latitude)	Watershed location (longitude)	Length (km)	Natural geographical zone	Reference
32	Tocantins River	South America	−10.06	−48.38	2,699	A	Costa et al. (2003)
33	Araguaia River	South America	−9.90	−50.26	2,627	A	Coe et al. (2011)
34	Parana River	South America	−21.69	−57.89	2,549	B	Agostinho et al. (2013)
35	Pilcomayo River	South America	−25.26	−57.73	2,500	A	Smolders et al. (2002)
36	Atrato River	South America	6.92	−76.94	700	A	Mosquera-Machado and Ahmad (2007)
37	Nile River	Africa	24.10	32.89	6,650	D	Kim and Kaluarachchi (2009); Kassas (1971)
38	Orange River	Africa	−28.89	22.00	2,092	B	Conley and Niekerk (2000)
39	Limpopo River	Africa	−22.22	29.97	1,800	B	Hanjra and Francis (2008)
40	Senegal River	Africa	16.13	−13.59	1,641	B	Barreteau et al. (2001)
41	Volta River	Africa	7.14	0.19	1,600	B	Hanjra and Francis (2008)
42	Okavango River	Africa	−17.23	18.31	1,600	D	Mbaiwa (2004)
43	Vaal River	Africa	−27.67	25.64	1,210	E	Braune and Rogers (1987)
44	Murray–Darling River	Oceania	−34.11	141.91	3,750	D	Thoms and Sheldon (2000)
45	Cooper River	Oceania	−28.09	139.25	1,420	D	Arthington et al. (2005)
46	Fly River	Oceania	−7.59	141.40	1,290	A	Swales (2002)
47	Sepik River	Oceania	−4.22	142.68	1,126	A	Dudgeon and Smith (2006)
48	Mississippi River	North America	38.34	−90.37	6,275	C	Schoenholtz et al. (2001); Day et al. (2007)
49	Mackenzie River	North America	65.16	−126.43	4,241	H	Morris and de Loë (2014)
50	Yukon River	North America	66.57	−145.39	3,184	H	Hay and Mccabe (2010)
51	Nelson–Saskatchewan River	North America	53.83	−98.84	2,570	G	Cutlac and Horbulyk (2010)
52	Arkansas River	North America	37.05	−97.06	2,348	G	Gober and Wheater (2013)
53	Colorado River	North America	36.14	−114.43	2,333	D	Christensen et al. (2004)
54	Columbia River	North America	49.00	−117.63	2,250	E	Naiman et al. (2012)
55	Platte River	North America	40.87	−98.28	1,594	F	Supalla et al. (2000)
56	Grande River	North America	28.99	−103.26	1,438	C	Pinheiro et al. (2004)
57	Fraser River	North America	53.92	−122.71	1,368	E	Martins et al. (2010)
58	Brazos River	North America	32.13	−97.50	1,352	E	Vogl and Lopes (2009)
59	Ottawa River	North America	47.40	−79.55	1,271	F	Newton et al. (2007)
60	Athabasca River	North America	56.74	−111.40	1,231	G	Seitz et al. (2013)

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TABLE 1 (*Continued*) Global EOWSD research cases.

Serial number	Name	Continent	Watershed location (latitude)	Watershed location (longitude)	Length (km)	Natural geographical zone	Reference
61	Kuskokwim River	North America	61.70	−157.18	1,050	G	Gisclair (2009)
62	Tennessee River	North America	34.76	−87.29	1,049	C	Wang et al. (2016)

Note: The letters in legends represent different natural geographical zones: A, humid tropical rainforest zone; B, tropical savanna climatic zone; C, humid evergreen broad-leaved forest zone; D, arid steppe-desert zone; E, humid and semihumid mixed broadleaf–conifer forest zone; F, arid and semiarid steppe zone; G, subpolar tundra zone; and H, polar ice sheet zone.

TABLE 2 Description of Köppen climate symbols and defining criteria.

First	Second	Third	Description	Criteria[a]
A			Tropical	$T_{cold}\geq18$
	Af		Rainforest	$P_{dry}\geq60$
	Am		Monsoon	$P_{dry}<60$ and $P_{dry}\geq(100–MAP/25)$
	Aw		Savannah	$P_{dry}<60$ and $P_{dry}<(100–MAP/25)$
B			Arid	$MAP<10^{a}P_{th}$
	BS		Steppe	$MAP\geq5^{a}P_{th}$
	BW		Desert	$MAP<5^{a}P_{th}$
		h	Hot	$MAT\geq18$
		k	Cold	$MAT<18$
C			Temperate	$T_{hot}>10$ and $0<T_{cold}<18$
	Cs		Dry summer	$P_{sdry}<40$ and $P_{sdry}<P_{wwet}/3$
	Cw		Dry winter	$P_{wdry}<P_{swet}/10$
	Cf		Without dry season	Not (Cs) or (Cw)
		a	Hot summer	$T_{hot}\geq22$
		b	Warm summer	$T_{hot}<22$ and $T_{mon10}\geq4$
		c	Cold summer	Not (a or b) and $1\leq T_{mon10}<4$
D			Cold	$T_{hot}>10$ and $T_{cold}\leq0$
	Ds		Dry summer	$P_{sdry}<40$ and $P_{sdry}<P_{wwet}/3$
	Dw		Dry winter	$P_{wdry}<P_{swet}/10$
	Df		Without dry season	Not (Ds) or (Dw)
		a	Hot summer	$T_{hot}\geq22$
		b	Warm summer	$T_{hot}<22$ and $T_{mon10}\geq4$
		c	Cold summer	$T_{cold}\geq-38$ and $T_{mon10}<4$
		d	Very cold winter	Not (a or b) and $T_{cold}<-38$
E			Polar	$T_{hot}<10$
	ET		Tundra	$T_{hot}>0$
	EF		Frost	$T_{hot}\leq0$

[a] MAP, mean annual precipitation (mm); MAT, mean annual temperature (°C); T_{hot}, temperature of the hottest month; T_{cold}, temperature of the coldest month; T_{mon10}, number of months where the temperature is above 10; P_{dry}, precipitation of the driest month; P_{sdry}, precipitation of the driest month in summer; P_{wdry}, precipitation of the driest month in winter; P_{swet}, precipitation of the wettest month in summer; P_{wwet}, precipitation of the wettest month in winter; P_{th}, varies according to the following rules (if 70% of MAP occurs in winter, then $P_{th} = 2 \times MAT$; if 70% of MAP occurs in summer, then $P_{th} = 2 \times MAT + 28$; otherwise, $P_{th} = 2 \times MAT + 14$). Summer (winter) is defined as the warmer (cooler) 6-month period of ONDJFM and AMJJAS.

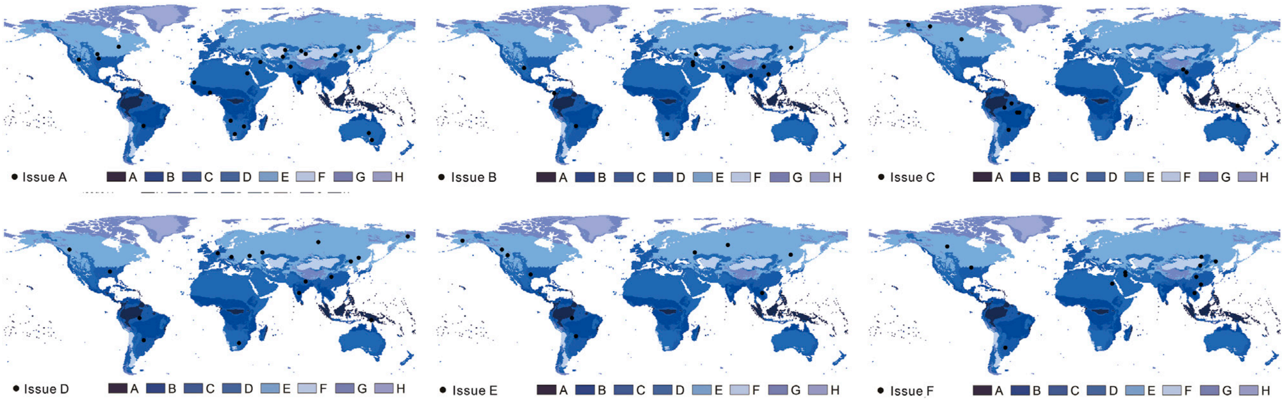

FIGURE 2
Global distribution of EOWSD issues. The six categories of the issues are as follows: (A) Water scarcity and allocation of water resources. (B) Floods and water resource allocation. (C) Interaction between the watershed itself and the potential impact of environmental changes and human behaviors on watershed sustainable development. (D) Prevention and control of water quality deterioration. (E) Prevention and control of damage to habitats and fishery resources. (F) Changes in biodiversity. The letters in legends represent different natural geographical zones: A, humid tropical rainforest zone; B, tropical savanna climatic zone; C, humid evergreen broad-leaved forest zone; D, arid steppe-desert zone; E, humid and semihumid mixed broadleaf–conifer forest zone; F, arid and semiarid steppe zone; G, subpolar tundra zone; and H, polar ice sheet zone.

A long time series of supply (1950–2010) were used to reduce the effect of multi-year climate cycles and to ignore complexities of short-term water storage (e.g., dams and floodplains) for which global operational data are nonexistent (Beek et al., 2011; Wada et al., 2011). Baseline water stress thus measures chronic stress rather than drought stress.

$$r_{BWS} = \frac{Ut_{2010}}{mean_{[1950,2010]\,(Ba)}}. \tag{2}$$

We masked catchments with less than 0.012 m/m^2/year of withdrawal and 0.03 m/m^2/year of available blue water as "arid and low water use" since catchments with low values were more prone to error in estimates of BWS.

The BWS values were then mapped to thresholds and normalized to a score between 0 and 5 such that scores 0–1 correspond to the lowest category and scores 4–5 correspond to the highest category. The general function for mapping indicators like BWS, whose thresholds are on a logarithmic scale (Eq. 3), is

$$\min\left(5,\ \max\left(0,\left(\frac{\ln r - \ln t_1}{\ln base} + 1\right)\right)\right), \tag{3}$$

where r is the raw value, t_1 is the lowest category's upper threshold, and *base* is the rate of increase between thresholds. Values greater than 5 or less than 0 are truncated to remain within the range of 0–5. For BWS, $t1 = 0.1$ and $base = 2$. The threshold method of indicator normalization has several advantages. Foremost is it creates clear categories and enables scores to be matched with guidelines. Relative to purely mathematical or statistical methods of normalization, thresholds are unaffected by extreme values. They allow for comparison even when using new sources of data.

The subprogram discriminant in SPSS 16.0 was used to perform the descriptive statistics, bivariate analysis, discriminant analysis, and hierarchical cluster analysis of BWS scores in order to examine whether human activities affect the distribution of environmentally oriented watershed sustainable development issues at a global scale.

3 Results

3.1 Global distribution of EOWSD issues

A great deal of research aiming to achieve global EOWSD has attracted significant attention all over the world. In the tropical region, EOWSD issues mainly focus on rainforest recovery and restoration and maintenance of natural ecosystem functions (Dudgeon and Smith, 2006; Coe et al., 2009; Laura et al., 2016; Richard et al., 2022). The impact of human activities, which has led to the introduction of chemical pollutants, altered flows, and system instability (Wang and Chang, 2006; Sarkar et al., 2007), is a crucial part of EOWSD in mid-latitude regions, which is the origin of many ancient civilizations and also has the world's important economic belts. The primary issue of EOWSD in the polar regions is how to deal with the effects of global warming (Westmacott and Burn, 1997; Hay and Mccabe, 2010; Lin et al., 2019), while a rational allocation of water resources is an essential component in regions of water scarcity and flood (Richardson et al., 2005; Karimov et al., 2010). The main global EOWSD issues were summarized into six categories associated with different aspects of watershed sustainable development to explore the interrelations of environmental changes and watershed sustainable development at global scales (Supplementary Figures S1–S8). The six categories of EOWSD issues are as follows (Figure 2): A) water scarcity and allocation of water resources, which exists in Central Asia, the southern tip and northern tip of Africa, Central and southern Australia, and the mid-east of North America. B) Floods and water resource allocation could mainly be found in Central and Western Asia. In South America, northern North America, and South Asia, there exists the issue of C) interaction between the watershed itself and the potential

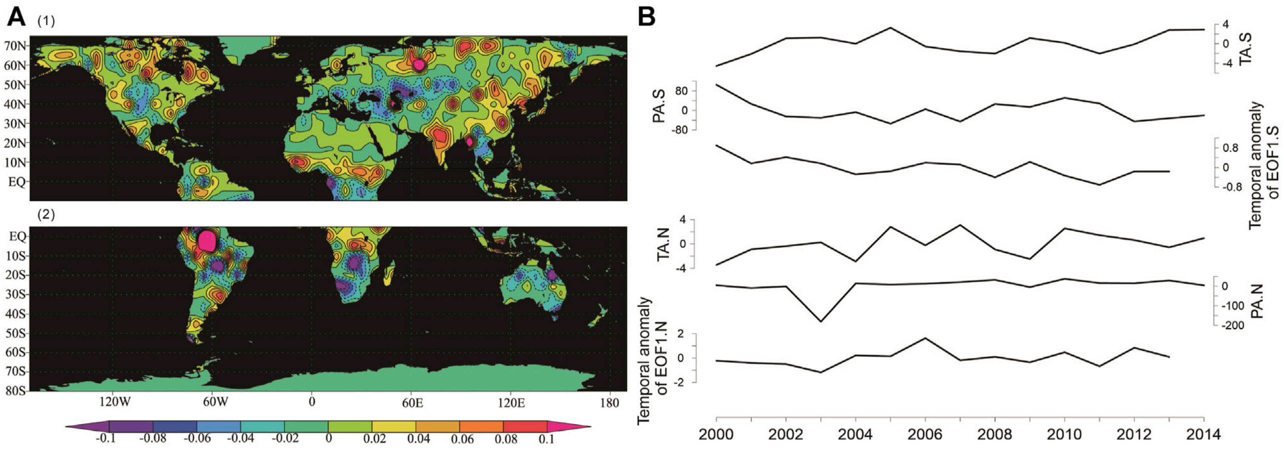

FIGURE 3
Spatial and temporal variations of the global NDVI in summer. **(A)** First EOF mode of the global NDVI in the summer (June to August in the Northern Hemisphere (1) and December to February in the Southern Hemisphere (2)) during 2000–2014. **(B)** Temporal anomaly of EOF1, temperature anomaly, and precipitation anomaly (Bernhard et al., 2008) in the Northern Hemisphere and Southern Hemisphere (Harris et al., 2014). TA.N, temperature anomaly in the Northern Hemisphere; TA.S, temperature anomaly in the Southern Hemisphere; PA.N, precipitation anomaly in the Northern Hemisphere; PA.S, precipitation anomaly in the Southern Hemisphere.

impact of environmental changes and human behaviors on watershed sustainable development. D) Prevention and control of water quality deterioration particularly occurs in Europe and some plain areas of Asia. E) Prevention and control of damage to habitats and fishery resources mainly exists around 50° north latitude. F) Changes in biodiversity concentrate in Eastern and Western Asia.

3.2 The relationship between the zoning of global EOWSD issues and climate and vegetation zoning

In order to examine the influence of climate and vegetation changes on the distribution of global EOWSD issues, the global NDVI in the summer of 2000–2014 was quantitatively analyzed using the EOF method (Figure 3A; Supplementary Figure S9). The first three EOF modes account for 21.64%, 14.03%, and 11.17% of the total variance in the Northern Hemisphere and 20.49%, 12.60% and 10.33% of the total variance in the Southern Hemisphere, respectively. Since there is a distinct correspondence between EOF modes and distribution of the main sustainable development issues and the global vegetation growth is mainly dominated by climate change, a partition method based on the Köppen–Geiger system and terrestrial vegetation was used to achieve a better understanding of the distribution of global EOWSD issues and to verify their applicability and scope. The first three temporal EOFs show that the responses of vegetation to climate change in different parts of the world have consistency even though the responsiveness varies, as shown in the associated EOF modes (Figure 3B). Ultimately, a clear and definite relationship between the distribution of the main EOWSD issues and different natural geographical zones is shown (Figure 2). In the humid tropical rainforest zone (A), issue C exists in six of all eight rivers, issues B and E occur in one river each, and three rivers have issue D. All five rivers in the tropical savanna climatic zone (B) have issue A, while two rivers have issue B, and one river has issue E. Issue A–F all exist in the humid evergreen broad-leaved forest zone (C), whilst the numbers of theories are various. Issue A is the main watershed sustainable development issue in the arid steppe-desert zone (D), and the sustainable development practices implemented in the Nile also led to issue F. Issue D can be found in most rivers in the humid and semihumid mixed broadleaf–conifer forest zone (E), which is the origin of many ancient civilizations and also has many of the world's important economic belts. Issues A and E are also obvious in this area. The main watershed sustainable development issues in the arid and semiarid steppe zone (F) concentrate on issues A, B, E, and F, while issues A, C, D, E, and F are found in the subpolar tundra zone (G). The main watershed sustainable development issues in the polar ice sheet zone (H) are issues C and D. It is worth noting that using the NDVI as a standard for global analyses has its limitations, especially in tropical regions, and should be improved in subsequent studies.

3.3 Evaluation of watershed human impacts on the zoning of global EOWSD issues

In the context of global climate change and anthropogenic pressures, intensified regional environmental change and human water engineering efforts have been identified as two factors influencing EOWSD. Here, we selected 34 watersheds from 62 watersheds, from the 100 most populated watersheds globally (Bernhard et al., 2008; CIESIN, 2010) and the 100 largest watersheds globally (in terms of area) (CIESIN, 2010), in order to assess the relative impacts of human activities on watersheds (Table 3). When evaluating the influence and relative importance of human impact on watersheds (Vörösmarty et al., 2000), it is particularly important to understand baseline water stress (BWS), which measures total annual water withdrawals expressed in percentage of total available flow. Two variables determine baseline water stress: water supply

TABLE 3 BWS scores of 34 watersheds from either or both the 100 most populous river basins and the 100 largest (by area) river basins in the world from the 62 watersheds.

Natural geographical zone	Name	All sector	Sd	Agricultural	Domestic	Industrial
C	Indus River	4.30	1.21	4.31	4.08	4.14
D	Colorado River	4.18	1.28	3.97	4.24	4.48
E	Liaohe River	4.00	0.72	4.14	3.86	3.50
E	Yellow River	4.00	1.03	4.07	3.91	3.87
F	Tigris and Euphrates	3.54	1.15	3.60	3.35	2.98
C	Ganges–Brahmaputra	3.39	1.61	3.43	2.89	3.24
C	Kura River	3.26	0.97	3.36	2.96	2.90
C	Krishna River	3.08	1.07	3.08	3.12	3.07
F	Ob (Tobol) River	2.83	0.90	3.00	2.81	2.79
E	Columbia River	2.78	1.98	3.07	1.74	2.13
B	Limpopo River	2.69	1.39	2.53	3.00	2.80
C	Mississippi River	2.44	1.76	3.35	1.69	1.76
G	Amur River	2.38	1.41	2.40	2.38	2.33
B	Orange River	1.91	1.53	2.07	1.70	1.66
C	Yangtze River	1.62	1.48	1.69	1.57	1.36
E	Rhine River	1.48	0.96	1.70	1.26	1.53
C	Ganges River	1.46	1.55	1.57	1.01	0.71
G	Volga River	1.12	1.36	0.97	1.51	0.99
B	Parana River	0.96	1.37	1.21	0.79	0.60
E	Dnieper River	0.92	0.99	0.86	0.82	0.98
D	Nile River	0.86	1.25	0.90	0.69	0.66
E	Danube River	0.78	0.98	0.46	0.71	0.85
G	Yenisei River	0.65	1.64	0.57	0.69	0.67
A	Amazonas River	0.53	0.78	0.71	0.29	0.35
C	Mekong River	0.34	0.44	0.34	0.38	0.37
B	Senegal River	0.11	0.41	0.13	0.04	0.01
B	Volta River	0.00	0.07	0.00	0.00	0.00
E	Brazos River	3.88	1.49	4.56	2.76	2.79
D	Murray River	3.73	1.27	3.74	3.37	3.31
G	Nelson River	1.94	1.28	2.68	1.96	1.65
D	Okavango River	0.59	1.61	0.15	1.10	0.47
H	Mackenzie River	0.58	1.07	0.38	0.50	0.59
E	Fraser River	0.39	0.68	0.25	0.66	0.28
A	Tocantins River	0.00	0.00	0.00	0.00	0.00

Note: A, humid tropical rainforest zone; B, tropical savanna climatic zone; C, humid evergreen broad-leaved forest zone; D, arid steppe-desert zone; E, humid and semihumid mixed broadleaf–conifer forest zone; F, arid and semiarid steppe zone; G, subpolar tundra zone; and H, polar ice sheet zone.

availability and demand for that water. Water supply estimates are obtained from a model that considers a wide variety of variables, including temperature, precipitation, wind speed, and soil moisture absorption. The demand for water is computed by adding the total annual withdrawals from municipal, industrial, and agricultural sources based on a series of reported and modeled global datasets (Gassert et al., 2013). Water withdrawals of the three sectors (agricultural, domestic, and industrial) are used as a weight to

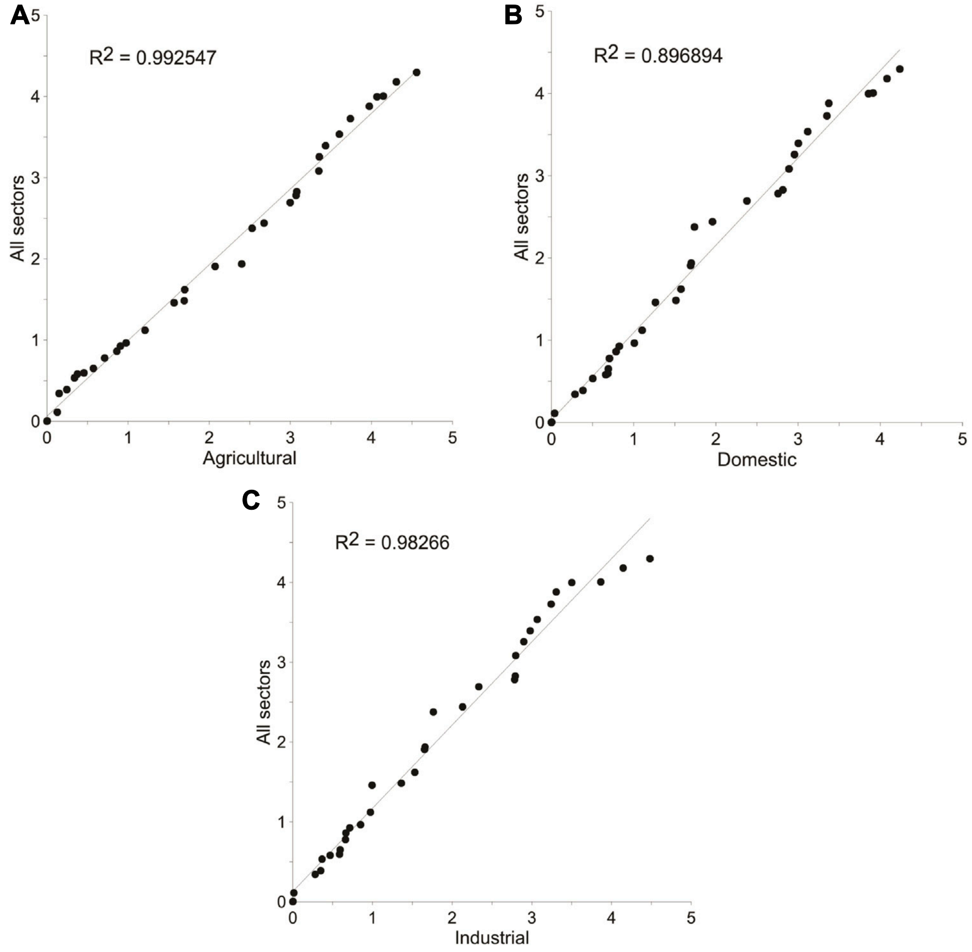

FIGURE 4
Quantile–quantile plots of the total baseline water stress vs **(A)** agricultural, **(B)** domestic, and **(C)** industrial (AID) scores in the 34 watersheds.

measure the exposure of each sector's water users to BWS (Figure 4), which allows us to explore the internal characteristics in specific river basins. The baseline water stress of all 34 river basins was used in the numerical analyses.

The ternary diagram shows that the distribution and variability of the agricultural/industrial/domestic (AID) withdrawals in the 34 watersheds (Figure 5A) do not suggest an evident relationship between the composition features of AID and the different natural geographical conditions since there is no obvious centrality of watersheds from each natural geographical zone. The raw BWS values are then mapped to thresholds (low (<10%); low to medium (10%–20%); medium to high (20%–40%); high (40%–80%); and extremely high (>80%)) using continuous functions and normalized to a score between 0 and 5 on account of thresholds that are unaffected by extreme values and allow for comparison even when using new sources of data relative to purely mathematical or statistical methods of normalization. Descriptive statistics and bivariate analysis were used to characterize scores of agricultural, industrial, domestic, and total baseline water stress and to examine whether the human impact could be well represented by the AID scores (Table 4). The results of the discriminant analysis confirm that the normalized scores of the 34 watersheds do not exhibit distinctive spatial signatures, as represented by the 8 natural geographical zones (Figure 5B). Meanwhile, two major groupings are indicated by hierarchical cluster analysis based on the BWS scores, and the clustering results are very different from the groups divided according to various natural geographical conditions of watersheds (Figure 5C). Therefore, human activities do not affect the distribution of EOWSD issues on a global scale, even though water engineering development may have significant influences on watershed sustainable development in each specific natural geographical zone.

4 Discussion

Environmental change and human activities are the two major factors that affect watershed sustainable development (Zhang et al., 2023). According to the zoning of global EOWSD issues in eight different natural geographical zones, it is quite evident that EOWSD issues vary under different natural geographical conditions and that the scientific basis of watershed sustainable development issues in identical natural geographical zones is always unified (Fu et al., 2019; Qi et al., 2020; Zhou et al., 2023). Meanwhile, under the condition that the number and magnitude of water engineering activities are growing rapidly (Postal and Carpenter, 1997; Malmqvist and Rundle, 2002),

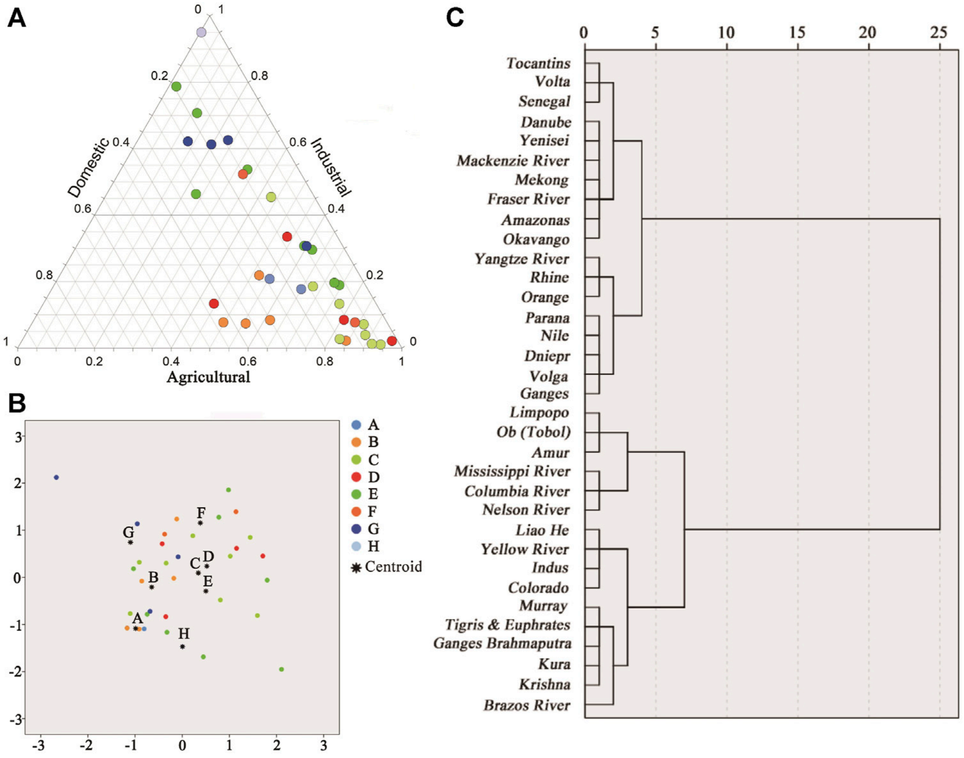

FIGURE 5
Numerical analyses of BWS values. **(A)** Ternary diagram of the agricultural/industrial/domestic withdrawals in the 34 watersheds. **(B)** Discriminant analysis of total baseline water stress scores. **(C)** Hierarchical cluster analysis of total baseline water stress scores. The solid circles in subgraph A and subgraph C represent different natural geographical zones as shown in the figure: A, humid tropical rainforest zone; B, tropical savanna climatic zone; C, humid evergreen broad-leaved forest zone; D, arid steppe-desert zone; E, humid and semihumid mixed broadleaf–conifer forest zone; F, arid and semiarid steppe zone; G, subpolar tundra zone; and H, polar ice sheet zone.

TABLE 4 Descriptive statistics and bivariate analysis of agricultural, industrial, domestic, and total baseline water stress.

		Agricultural			Industrial			Domestic		
		M = 2.037	S = 1.499		M = 1.760	S = 1.335		M = 1.819	S = 1.312	
All Sectors	M = 1.963	PCC	Sig	Cov	PCC	Sig	Cov	PCC	Sig	Cov
	S = 1.403	0.984	0.000	2.071	0.979	0.000	1.834	0.971	0.000	1.788

Note: M, mean; S, standard deviation; PCC, Pearson's correlation coefficient; Sig, significance; Cov, covariance.

human activities were thought to be the main factor that threatens watershed sustainable development. However, our results based on BWS scores of 34 river basins and related numerical analyses suggest that water engineering development does not affect the distribution of EOWSD issues at a global scale directly, even though it may have significant influences on watershed sustainable development in each specific natural geographical zone. Nevertheless, environmental change induced by water engineering activities (Vörösmarty et al., 2010; Schewe et al., 2014) should be certain to affect the distribution of EOWSD issues in the long term. Therefore, as demonstrated in this paper, each natural geographical zone has a principal EOWSD issue, which provides the scientific basis for watershed sustainable development governance.

Research indicates that unabated climate change will exacerbate environmental risks and affect watershed sustainable development across the world (Brooks and Lake, 2007); hence, two maps of the eight natural geographical zones during 2041–2050 and 2091–2100 from simulated climate data were produced to predict the evolution of global watershed sustainability and address the future emphasis on sustainable development (Figure 6). There is an obvious change in the ranges of natural geographical zones, which presents various change trends in different parts of the world. The tropical savanna climatic zone (B) will increase by 9.11% (2.40 million km^2) of its previous area, while the area of humid and semihumid mixed broadleaf–conifer forest zone (E) will decrease by approximately 1.07 million km^2 from 2041–2050 to 2091–2100, as indicated by the simulated results. Therefore, water engineering aimed at water scarcity and water resource allocation will become even more important in the future, and the applicability and scope of the principal EOWSD issues of the areas in which the

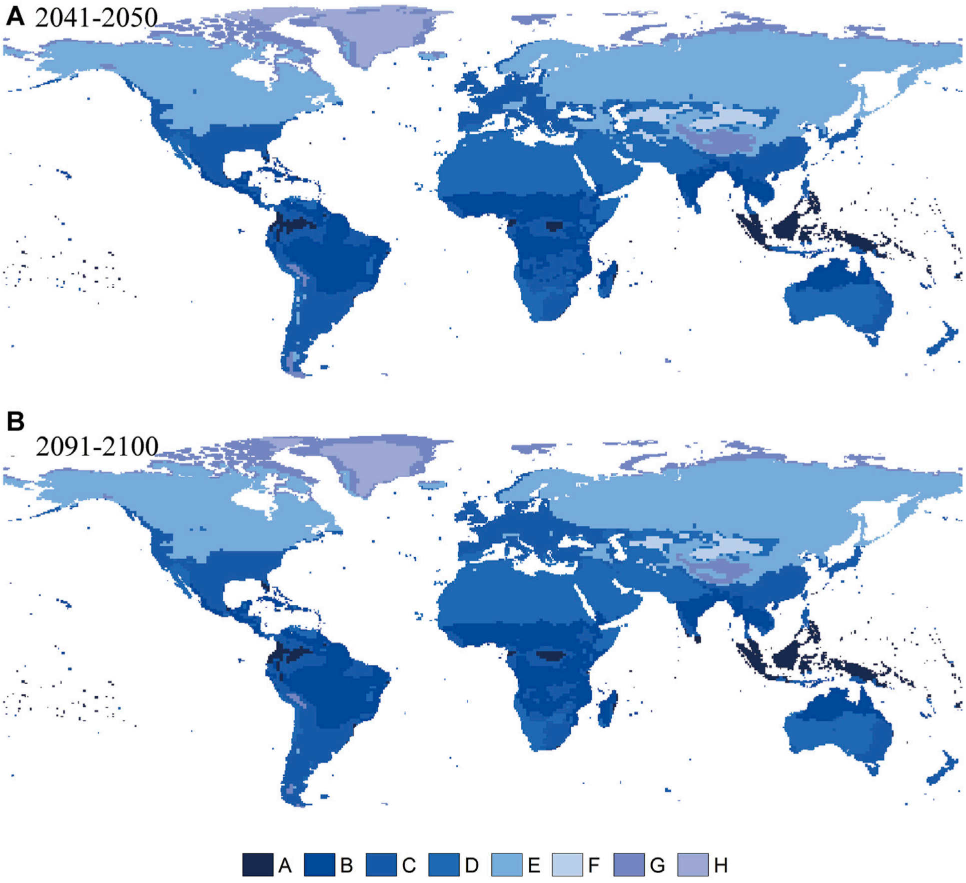

FIGURE 6
Evolution of the eight natural geographical zones during **(A)** 2041–2050 and **(B)** 2091–2100 from simulated climate data that follows the RCP 4.5 scenario. As indicated by the simulated results, the humid tropical rainforest zone (A), the tropical savanna climatic zone (B), and the arid steppe-desert zone (D) will increase by 9.55% (0.54 million km^2), 9.11% (2.40 million km^2), and 0.44% (0.13 million km^2) of their previous area, while the area of the humid evergreen broad-leaved forest zone (C), the humid and semihumid mixed broadleaf–conifer forest zone (E), the arid and semiarid steppe zone (F), the subpolar tundra zone (G), and the polar ice sheet zone (H) will decrease by 0.12% (0.04 million km^2), 2.57% (1.07 million km^2), 25.97% (0.61 million km^2), 14.90% (0.87 million km^2), and 24.02% (0.48 million km^2) from 2041–2050 to 2091–2100.

type of natural geographical zone will change should be appropriately adjusted.

The recognition of the natural and social importance of watershed sustainability has resulted in a massive increase in efforts toward and research on watershed sustainable development. However, promoting sustainable development requires research on a wide range of social, economic, cultural, institutional, and environmental issues, and research dominated by the natural sciences must transition toward research involving the full range of sciences and humanities (Reid et al., 2010). Despite considerable consensus on the urgent need to improve watershed health and enhance ecological sustainability and the importance of understanding how to achieve watershed sustainability (Lake, 2005; Palmer et al., 2005), there is little evidence for a mechanism or a theory for guiding the practice of watershed sustainable development (Palmer et al., 1997; Lake, 2001; Bond and Lake, 2003; Brooks and Lake, 2007). The objectives and emphasis of global EOWSD efforts are multifarious since there are obvious differences in EOWSD issue types in various locations of the world, so it is essential for effective watershed sustainable development to ascertain the zoning of global EOWSD issues and identify the priorities of these issues as sustainable development emphasis could vary broadly. In this study, we made attempts, in which the distribution and evolution of various EOWSD issues were clarified and the relative impacts of environmental change and human activities on watershed sustainability were distinguished, to provide the scientific basis for setting future emphasis on global watershed sustainable development and furthering the related disciplines.

5 Conclusion

The zoning of global EOWSD issues suggested that EOWSD issues vary under different natural geographical conditions, while the scientific basis of EOWSD issues in identical natural geographical zones is always unified. Meanwhile, human activities do not affect the distribution of EOWSD issues at a global scale directly, even though they may have significant influences on watershed sustainability in each specific natural geographical zone, and environmental change induced by water engineering development should be certain to affect the distribution of EOWSD issues in the long term. Furthermore, water engineering aimed at water scarcity and the allocation of water resources will become even more important in the future according to simulated climate data, and the applicability and scope of the principal EOWSD issues of the areas in which the type of natural geographical zone will change should be appropriately adjusted. In light of these results, the zoning of global EOWSD issues presents a new perspective to understand the relationship between global EOWSD, human impacts, and environmental change, and our findings will also provide the scientific basis for setting future emphasis on global watershed sustainable development and furthering the related disciplines.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

ZM: conceptualization, formal analysis, funding acquisition, methodology, and writing–original draft. ZC-Q: conceptualization, formal analysis, methodology, and writing–original draft. FQ: conceptualization, methodology, project administration, supervision, and writing–review and editing. ZJ-T: methodology, validation, and writing–review and editing. LW: conceptualization, methodology, project administration, supervision, and writing–review and editing. WL-G: data curation, methodology, validation, and writing–review and editing. XY-Y: methodology, validation, and writing–review and editing. SY-Q: data curation and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1322308/full#supplementary-material

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