TERRESTRIAL BIOSPHERE WATER BALANCE ANALYSIS: A MATHEMATICAL MODEL TO PREDICT THE IMPACTS OF CLIMATE CHANGE ON NET WATER BUDGET ON GLOBAL SCALE

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Abstract. The industrial revolution triggered increased greenhouse gas emissions, disrupting the water cycle, and raising global temperatures by 2°C. This shift has induced extreme weather, rising sea levels, altered precipitation, and high evaporation rate. Since agriculture, soil, and health of ecosystems are impacted adaptation and mitigation strategies are crucial. To investigate net water budget (NWB) changes in ecosystems, this study employed the Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset to assess NWB distribution. Global Land Evaporation Amsterdam Model (GLEAM) database analyzes global land evaporation, revealing a gradual NWB increase since 1980 with sporadic drops during severe droughts. Positive shifts are noted in tropics and mountains, while Egypt, Iraq, Russia, Canada, and Australia suffer declines. NWB variability is the highest in the tropics, temperate, and cold regions, necessitating adaptable water management. Coefficient of variation identifies sensitive zones like tropical and transition climate areas. Latitudinal NWB trends show rising inputs and outputs. Most affected is the "First Tropical Lowland Rain Forest" biome, experiencing significant shifts since 2000 due to input and climate changes. The tropics and transition zones of boreal and temperate climate zones have high sensitivity to NWB change, which is attributed to their unique climatic conditions and ecological characteristics. The sensitivity of most continents is also approximately 40%. The change in the latitudinal average of the NWB between 1980 and 2015 is significant, with inputs and outputs in the NWB increasing over time.

Keywords: *mathematical modeling, black box model, industry, water availability, vulnerability*

Introduction

Water is the most important substance in every ecosystem. It exists in three states (gas, liquid, and solid) in the biosphere, cycles between terrestrial-marine ecosystems and the atmosphere, and sustains life on Earth. Since the industrial revolution, the anthropogenic impacts on greenhouse gas (GHG) emissions have increased, altering the equilibrium of the atmosphere (Keeling et al., 2010; de Vicente, 2021). This change in atmospheric equilibrium has resulted in modifications to the water cycle, which has affected the net water budget. As GHG emissions continue to rise, it is essential to comprehend and mitigate their impact on the global water cycle in order to ensure the sustainability of ecosystems and the health of all living organisms (Esser et al., 2011).

The increase in greenhouse gas emissions caused a temperature increase of nearly 1.5°C above the global average temperature, and if GHGs emission into the atmosphere continues to rise as it did in the last century, a 2°C increase in the global annual average temperature is expected for the next 30 years (Roudier et al., 2015; Jacob et al., 2018). This increase in temperature will lead to more intense and frequent extreme weather events, such as droughts and floods, further disrupting the water cycle. Additionally, the

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melting of glaciers and polar ice caps due to higher temperatures will contribute to sea level rise, posing a threat to coastal communities and ecosystems. It changes the surface energy balance and raises the evaporation rate from the soil surface. Especially arid and semi-arid regions have been negatively affected by it. Furthermore, the increase in temperature can also have detrimental effects on agriculture, as it can lead to reduced crop yields and increased vulnerability to pests and diseases (Balkovic et al., 2018). Additionally, higher temperatures can exacerbate air pollution and worsen respiratory conditions, impacting human health in both urban and rural areas. The vulnerability of semi-arid and arid regions to climate change is quite high in the short and long term. In various studies, mitigation and adaptation strategies have been developed to reduce the impacts of climate change on the water cycle in different types of ecosystems (Piao et al., 2010; Carvalhais et al., 2014).

Since the Industrial Revolution, climate change has influenced not only the temperature but also all types of precipitation (Wan et al., 2021). This has resulted in changes to the distribution of precipitation, with some regions experiencing more frequent and intense rainfall events and others experiencing protracted droughts. The variations in precipitation can have substantial effects on water availability, agriculture, and ecosystem health as a whole (Vicente-Serrano et al., 2010). Changes in the Earth's surface temperature have the greatest influence on the cumulative amount of precipitation and its global distribution (Shakib and Shojarastegari, 2017; Xiang et al., 2019; Abatzoglou et al., 2022). Precipitation is the primary input flux of the Earth's water budget, and its global distribution is primarily affected by the change in the Earth's surface temperature (Zang et al., 2019). Previous research indicates that the Earth's surface temperature will rise by approximately 5°C by 2100, compared to the current global annual average temperature (Sherwood et al., 2014; Wang et al., 2021). The rise in temperature is predominantly attributable to the emission of greenhouse gases, such as carbon dioxide and methane, into the atmosphere as a result of human activities such as burning fossil fuels and deforestation. The greenhouse gases capture heat from the sun, causing a rise in global temperatures and consequently altering the patterns and intensities of precipitation worldwide. More moisture and water evaporate from terrestrial and marine ecosystems into the atmosphere as a result of the warming of the Earth's surface (Ritter, 2006). The greatest quantity of heat transfer into the atmosphere occurs over tropical oceans, resulting in most of the precipitation and evaporation from and into the terrestrial biosphere (Trenbert and Fasullo, 2013; Li and Xie, 2014). Due to the fact that changes in rainfall distribution are not uniformly disseminated across the globe, the number of dry months may increase in certain crucial regions. The changing rainfall pattern and associated impacts in semi-arid and arid regions of the continents have had an impact on the farm industry, agriculture, livestock industry, etc. (Huho et al., 2012). These variations in the distribution of precipitation can also result in droughts, which can have detrimental effects on crop yields and livestock productivity. In addition, the increased aridity in these regions can contribute to soil degradation and desertification, thereby compounding the negative effects on agriculture and the local economy.

The primary outputs of the water cycle are evaporation and transpiration from the earth's surface. The primary drivers of evaporation and transpiration fluxes (evapotranspiration) are climate parameters such as temperature, radiation, precipitation, humidity, wind, etc. (Guo et al., 2017). These fluxes play a vital role in regulating the climate of the Earth and sustaining the water balance in various ecosystems. They also have significant effects on agriculture, as evapotranspiration directly affects crop water

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demands and irrigation requirements. Understanding and accurately estimating these output fluxes is crucial for water resource management and sustainable agricultural practices (Stephens et al., 2012; Moderow et al., 2020). Thus, the extreme variations in the Earth's climate have had varying effects on the ecosystems' incoming and outgoing water fluxes. The magnitude of the change is largely determined by the type of ecosystem, land use, greenhouse gas emissions, etc. Due to variations in the latent heat of the boundary layers, the Earth's energy balance is the most affected by these changes. The outgoing water cycle fluxes may have both cooling and warming effects on Earth's ecosystems. In tropical rainforests, for instance, increased evaporation and transpiration rates caused by higher temperatures can have a chilling effect as the water consumes heat from the surrounding environment. In arid regions, however, decreased evaporation and transpiration can have a warming effect because there is less water available to chill the surface via evapotranspiration. Changes in the water cycle can have significant effects on the ability of ecosystems to regulate their overall temperature and adapt to climate change (Diffebaugh and Giorgi, 2012; Hoerling et al., 2012).

Changes in the global net water budget are among the most significant aspects of climate change and have a substantial effect on ecosystems water use efficiency (WUE). Recent research demonstrates the effects of climate change on the total and net primary productions of the biosphere's terrestrial ecosystems (Schlenker and Roberts, 2009; Lobell and Gourdji, 2012). These studies indicate that as temperatures rise, evapotranspiration rates increase, resulting in a decrease in plant water availability. This can reduce photosynthesis and productivity, ultimately impacting the health of ecosystems as a whole. Moreover, alterations in precipitation patterns brought on by climate change can exacerbate these effects on primary production and water use efficiency.

In this study, we intended to investigate the change in number of arid months, net water budget, and water use efficiency on the terrestrial biosphere by analyzing the major in- and out-fluxes of the water cycle. In accordance with our hypothesis, the net quantity of water in terrestrial ecosystems will progressively decrease as the effects of climate change on the world differ across regions and the global temperature continues to rise at a rapid rate. This will negatively impact the ecosystem's water use capacity and biomass production. Moreover, owing to the varying effects of climate change on various vegetation zones, we anticipate that the net water budget in these regions will vary. In this study, one of the focal points will be determining the spatial and temporal distribution of NWB in terrestrial ecosystems and analyzing the effects of climate change on the availability of water resources. By comprehending the spatial and temporal distribution of NWB, we can evaluate the sensitivity of various ecosystems to climate change and devise efficient water resource management strategies. Moreover, researching the effects of climate change on NWB will contribute to our comprehension of how ecosystems adapt and respond to environmental changes, thereby assisting us in making informed decisions for sustainable development.

Material and Method

Precipitation

Multi-Source Weighted-Ensemble Precipitation (MSWEP) is a global precipitation dataset with a 0.1° spatial resolution and a 3 hourly temporal resolution that spans 1979 to 2015. The database was validated on a global scale utilizing approximately 70.000

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observational data and approximately 9000 hydrological modelling data (Beck et al., 2017, 2019). This dataset provides researchers with valuable information on precipitation patterns and trends, enabling them to assess the impact of climate change on water resources and ecosystems. By comprehending how precipitation varies over time and space, the water availability can be predicted and managed for various industries, including agriculture, energy, and urban planning. In addition, the validation of this dataset with a large quantity of observational and modeling data increases its dependability and utility for scientific studies and decision-making processes.

Evapotranspiration

GLEAM Version 3.7a (Global Land Evaporation Amsterdam Model) database includes parameters about transpiration, bare-soil evaporation, interception loss, sublimation, and open-water evaporation, which are generated by a set of algorithms that separately estimate the different components of the parameters (Martens et al., 2016, 2017). These algorithms are based on various input data sources, such as satellite observations, meteorological data, and land surface characteristics for a time period 1980-2022. The combination of these different data sources allows for a more accurate estimation of evapotranspiration and provides valuable information for studying the water cycle and managing water resources.

GLEAM V3.7a Database includes data for following fluxes:

$$E = Et + Eb + Ew + Ei + Es \quad \text{(Eq.1)}$$

where *E* is for Actual evaporation (mm/day), *Et* for Transpiration (mm/day), *Es* for Snow sublimation (mm/day), *Eb* for Base-Soil evaporation (mm/day) and *Ew* for Open-Water evaporation (mm/day).

Since the MSWEP database has data from 1979 to 2015 and GLEAM has data from 1980 to 2022, we used data from 1980 to 2015 in this study to capture the time window in both datasets.

Net Water Budget

To model the terrestrial Net Water Budget (NWB), we used a black box model-based methodology. Black-box models refer to systems that are analyzed only based on their input and output characteristics, without any understanding or awareness of their underlying workings. These models often use deterministic data to generate predictions or make judgments by analyzing patterns and data. By adopting a black box approach, it enables the efficient examination and exploitation of the model's functionalities without necessitating a comprehensive understanding of its internal workings. Following equation was used to determine the NWB in each grid cell for respectively time steps.

$$NWB_i = \sum_{t=1} Rainfall_t - E_t \quad \text{(Eq.2)}$$

where NWB_i is Net Water Budget for each grid cell, *Rainfall* is for input fluxes, i.e. precipitation, snow etc. from MSWEP and *E* is the actual evaporation components from the GLEAM databases at each *t* time step, respectively.

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Vegetation

In order to take into account the distribution of vegetation groups, which are among the most important factors affecting the water cycle, we digitized the distribution of 176 vegetation groups established by Schmithüsen (1976) and classified them into 31 biome groups based on their functional characteristics (see *Table 1*). The methodology of this study can be found in Esser et al. (2011). Excluding the Antarctic continent, we calculated the total amount of NWB corresponding to the individual 31 biome groups on 62483 grids with 0.5ºx0.5º resolution, the standard deviation within each biome group and the sensitivity rate under climate change, which we will describe in the next section.

$$NWB_{biome(i)} = \sum_{i=1}^{62483} \sum_{t=1} NWB_{i,t} \quad \text{(Eq.3)}$$

Table 1. *The biome groups that were aggregated from the Schmithuesen (1976) vegetation formations. Schmithuesen database includes 176 vegetation formations at global scale. Number of grids shows the number of 0.5º gridcells for each biome group at global scale*

Biome Nr.	Biome Type Name	Nr. of Grids (0.5º)
1	Tropical Lowland Rain Forests	5478
2	Tropical Lowland Dry Forests	2038
3	Tropical Mountain Forests	862
4	Tropical Savannas	1853
5	Tropical paramo woodlands	140
6	Tropical paramo grasslands	18
7	Puna steppes	148
8	Subtropical evergreen forests	1062
9	Subtropical deciduous forests	109
10	Subtropical savannas	4276
11	Subtropical halophytic formations	296
12	Subtropical steppes and grasslands	306
13	Temperate steppes and grasslands	3847
14	Subtropical semideserts	5427
15	Xeromorphic formations	1372
16	Deserts (tropical, subtropical, cold)	6421
17	Mediterranean sclerophyllous forests	440
18	Mediterranean woodlands and shrub formations	1166
19	Temperate evergreen forests	540
20	Temperate deciduous forests	4465
21	Temperate woodlands	2056
22	Temperate shrub formations	1476
23	Cool-temperate bogs	67
24	Boreal evergreen coniferous forests	5881
25	Boreal deciduous forests	2805
26	Boreal woodlands	2866
27	Boreal shrub formations	237
28	Shrub tundras	4691
29	Forbs tundras	1193
30	Azonal formations	641
31	Mangrove	303

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Vulnerability

Our primary objective is to analyze the change in NWB over the last 36 years (1980-2015) and identify vulnerable areas. The following phase involved classifying the NWB into biome groups and calculating the total quantity, standard deviation, and sensitivity ratio (CV=Coefficient of Vulnerability to Climate Change) for each group. By analyzing the change in NWB in the last climate span over a period of 36 years, we can obtain insight into how climate change has affected various regions. This information is essential for identifying vulnerable regions and devising targeted water resource management strategies for those regions. In addition, by calculating the total amount, standard deviation, and sensitivity ratio within biome groups, we can gain a deeper understanding of the variability and susceptibility of various ecosystems to climate change.

$$CV_{NWB_i} = \frac{\sigma_{NWB_i}}{NWB_i} \quad \text{(Eq.4)}$$

where *CV* is for vulnerability of NWB that is expressed as the coefficient of variation (CV) of NWB from 1980-2015, to climate change.

Results

The global change in NWB over the past 36 years exhibited a modest upward trend. The results of the analysis indicate that there is no cyclical change in the NWB (see *Figure 1*). This suggests that climate change has had a consistent impact on biome productivity over the past 36 years, with a progressive increase in productivity. It is important to note, however, that additional research is required to determine the specific drivers of this trend and to assess the potential long-term effects on ecosystem health and stability. NWB experienced its greatest and least significant transformations in last 10 years (1995-2015). Although the linear trend indicates an increase, between 1984–87, 1988–92, and 2013–15, significant decreases were observed (see *Figure 1*). There were severe droughts during this time period. These droughts had a significant impact on the availability of water resources and caused a decline in plant cover and animal populations. In addition, the protracted drought spells exacerbated soil erosion and increased the risk of wildfires, thereby exacerbating the detrimental impacts on ecosystem health and stability.

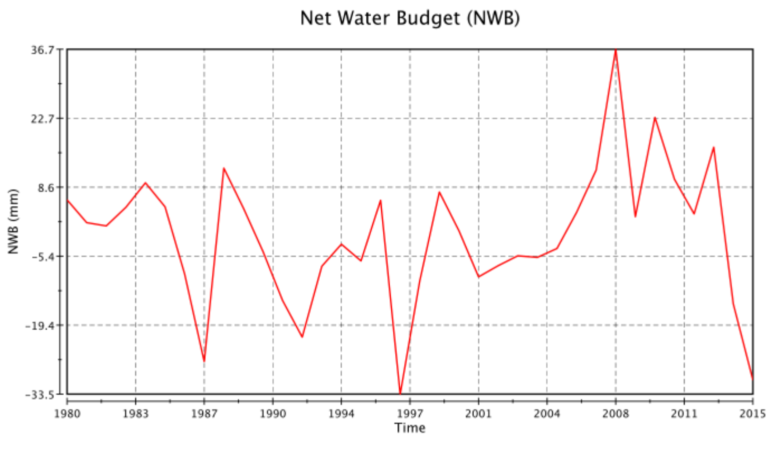

Figure 1. *The change of the global average Net Water Budget between 1980 and 2015*

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Figure 2 shows the spatial distribution of the 36-year average of the NWB. The highest positive change is observed in tropical regions and mountainous highlands. This indicates that these areas have experienced an increase in water availability over the 36-year period. This could be attributed to factors such as increased rainfall or improved water management practices in these regions. Over the last 30 years, water input to the terrestrial ecosystem has been greater than water output in this region. The change here exceeds 2700 mm on average. In Egypt, Iraq, eastern Russia, Central Canada and small areas in Australia, the NWB has decreased by up to 300 mm.

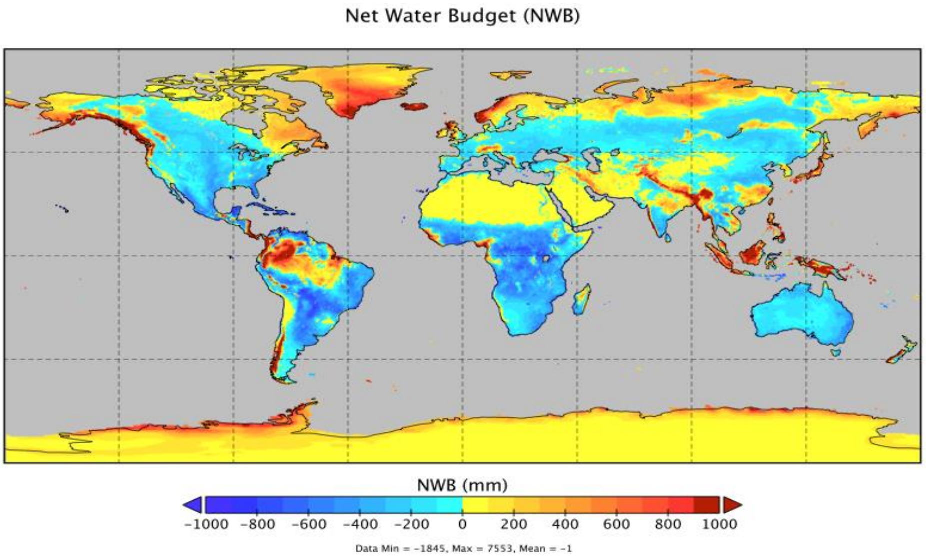

Figure 2. *Distribution of time averaged (1980-2015) Net Water Budget at global scale*

Standard deviation analyses are among the analyses that best express the dynamic rate of change of a parameter in a region. The standard deviation analysis of the NWB at the global level, based on the years 1980-2015, revealed that the standard deviation is higher in the tropics, where the outflow of water from the ecosystem is higher than the input (see *Figure 3*). This indicates that the tropics experience more variability in their water flow, which can have significant implications for both the natural ecosystem and the human populations that depend on it. These findings highlight the need for further research and monitoring to better understand and manage these dynamic ecosystems. After the tropics, regions in the temperate climate zone also have high standard deviations, while the rest of the regions have a more stable input-output relationship compared to these two regions. Understanding and managing the variability in water flow in tropical regions is crucial for preserving biodiversity and ensuring sustainable water resources for local communities. Additionally, the high standard deviations observed in temperate regions suggest the potential for more unpredictable water availability, emphasizing the importance of adaptive management strategies in these areas as well. In addition, in cold regions with low evaporation, the standard deviation is almost as high as in the tropics. This highlights the need for effective water management practices in cold regions as well, to mitigate the potential impacts of unpredictable water availability on ecosystems and local communities. Moreover, understanding the factors contributing to the high standard deviations in these regions can aid in developing targeted strategies for sustainable water resource management.

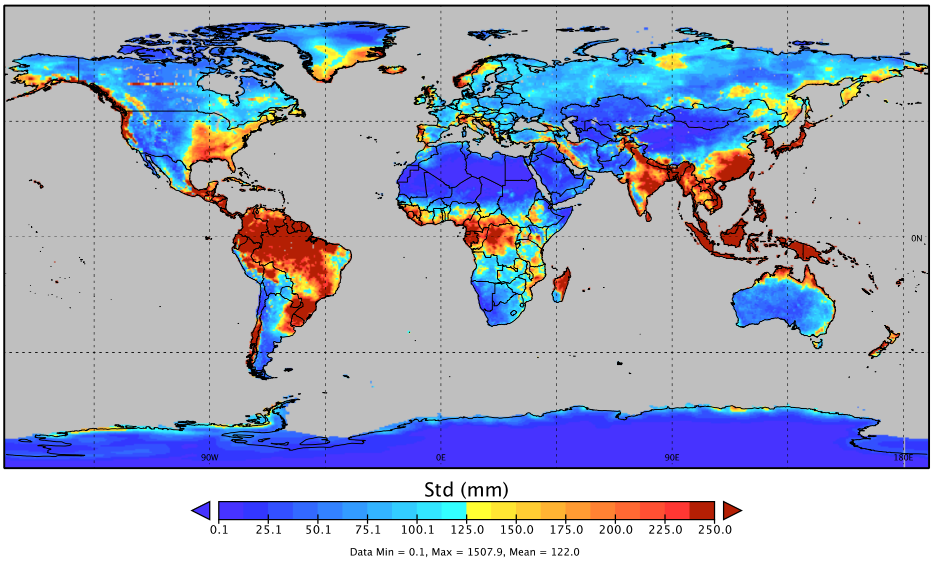

Figure 3. *Standard deviation (std) (1980-2015) of Net Water Budget at global scale*

Although the temporal average or standard deviation of a variable in a region provides information about the character of the variable in that region, the best information about the sensitivity of the region with respect to this variable is obtained by dividing these two outputs by each other (see *Eq. 4*). This ratio, known as the coefficient of variation, provides a measure of the relative variability of the variable in different regions. By comparing the coefficients of variation across regions, we can identify which regions are more sensitive to changes in the variable and prioritize them for targeted interventions. *Figure 4*, which shows the results of this process, shows more clearly the locations of vulnerable regions that may be affected by climate change. Especially in the tropics and in the transition zones of the boreal and temperate climate zones, the sensitivity to NWB change is very high compared to other regions. This high sensitivity in these regions can be attributed to their unique climatic conditions and ecological characteristics. The tropics, for example, are known for their high biodiversity and delicate ecosystems, making them particularly vulnerable to changes in the environment. Similarly, the transition zones between boreal and temperate climate zones experience significant shifts in temperature and precipitation patterns, further increasing their sensitivity to NWB change. The CV indicates that the sensitivity coefficient in these regions exceeds approximately 200%. The sensitivity of the majority of continents is also approximately 40%. These high sensitivity coefficients highlight the need for effective conservation and management strategies in these regions. Additionally, understanding the specific factors driving these shifts in temperature and precipitation patterns is crucial for developing targeted mitigation and adaptation measures to protect these delicate ecosystems.

The change in the latitudinal average of the NWB between 1980 and 2015 is shown in *Figure 5*. In many areas, especially in the equatorial region, inputs have been greater than outputs in the NWB over time. This indicates a net increase in water availability, which can have significant implications for local ecosystems and human communities. However, it is important to note that this trend may not be sustainable in the long term, as climate change continues to impact precipitation patterns and water resources in these regions. Therefore, careful monitoring and management of water resources are essential

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to ensuring the resilience and sustainability of these delicate ecosystems. The situation is similar in the subtropical latitude zone in the southern hemisphere, but the amount of change is smaller. At other latitudes, the temporal variation of the NWB in the latitudinal belt is much lower than in the equatorial and subtropical belts. In these other latitudes, the impact of climate change on precipitation patterns and water resources is relatively minimal. However, it is still important to maintain monitoring and management practices to ensure the long-term sustainability of water resources in these regions. Additionally, understanding the differences in temporal variation across latitudinal belts can help inform more targeted conservation efforts in areas with higher vulnerability to climate change impacts.

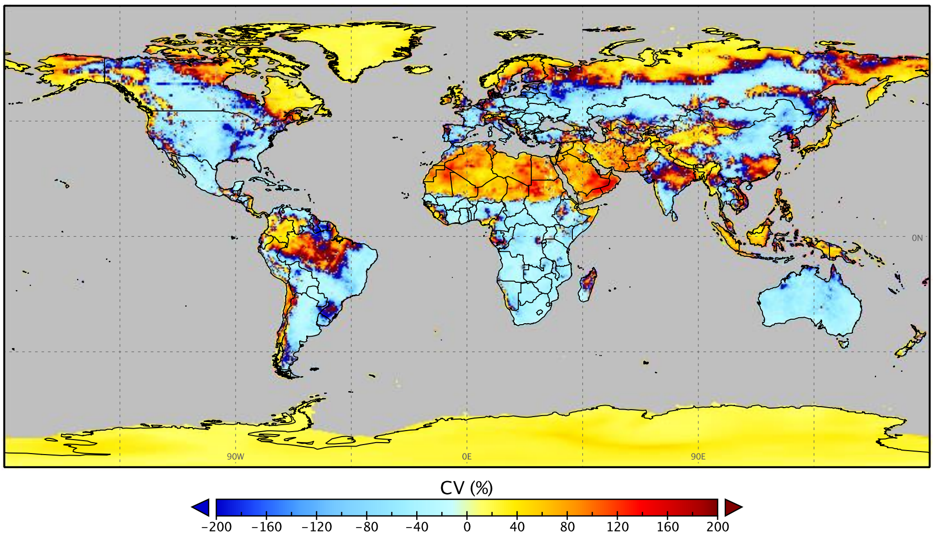

Figure 4. *Vulnerability coefficient (CV) for Net Water Budget at global scale*

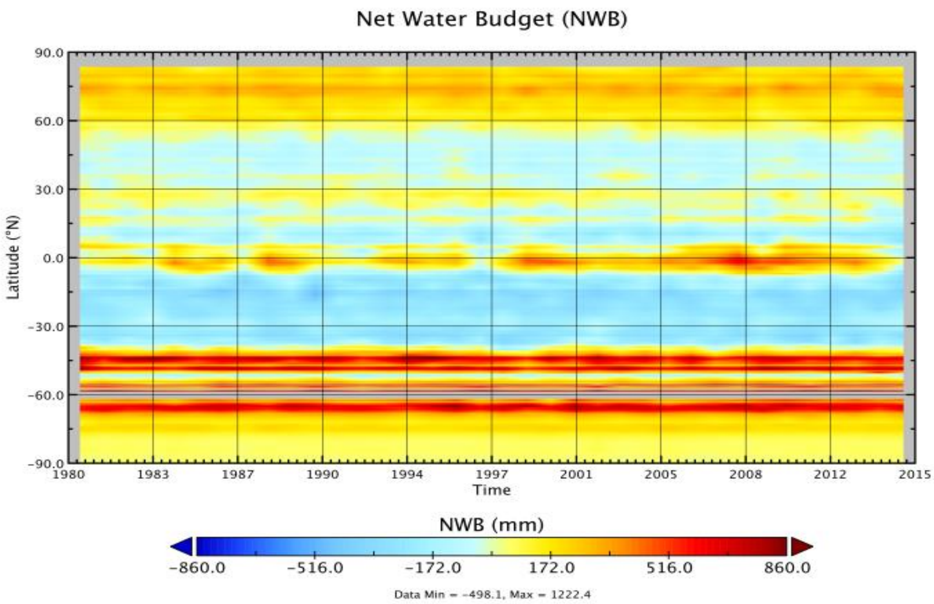

Figure 5. *Zonal mean of the Net Water Budget (NWB in mm) from 1980 to 2015*

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Plants play a very important role in the majority of the processes that make up the inputs and outputs of the NWB. In their methodology, Esser et al. (2011) grouped the 176 vegetation groups of Schmithüsen (1976) on a global scale into 31 biome groups. The distribution of these biome groups on a global scale at 0.5ºx0.5º spatial resolution is shown in *Figure 6*. The number of grids per biome group at the same scale is shown in *Table 1*. In this study, we classified the NWB according to biome groups, averaged them, and analyzed their temporal changes. These results are shown in *Figure 6.* In a total of 62483 0.5º grids around the world (excluding the Antarctic continent), the most common desert biome group is deserts (tropical, subtropical, and cold) with 6421 grids. In second place are the groups distributed in boreal regions, and in third place are the groups distributed in tropical regions.

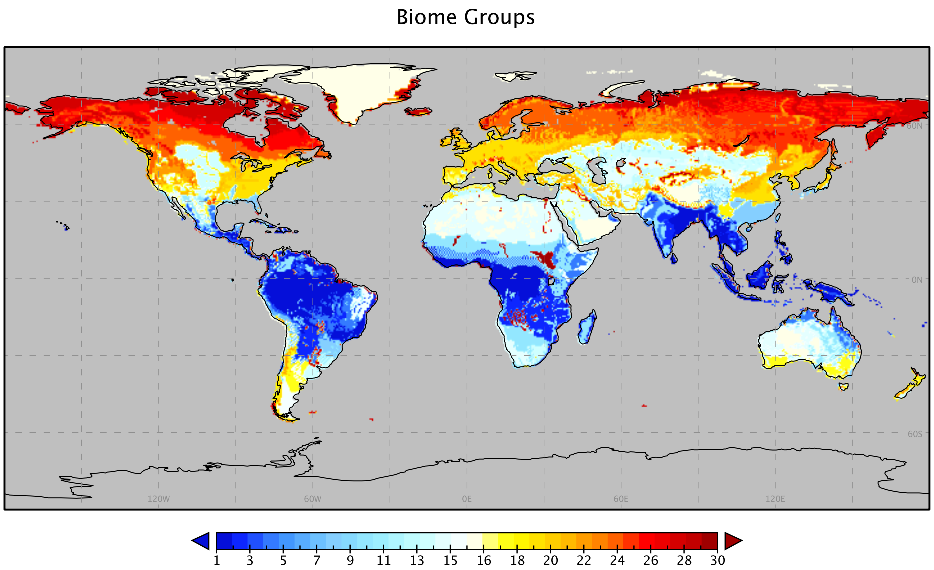

Figure 6. *Distribution of the 31 biome groups on 0.5º at global scale*

The mean, standard deviation, and CV of NWB classified according to biome groups are shown in *Figure 7*, *Figure 8* and *Figure 9*. These figures provide a comprehensive overview of the variability in NWB across different biome groups. The mean NWB values range from the highest in the desert biome group to the lowest in the tropical biome group. The standard deviation and coefficient of variation (*CV*) also show considerable variation within each biome group, indicating the heterogeneity of NWB within these regions.

We used *Eq. 3* to model NWB per biome. According to *Figure 7*, the biome group in which the NWB has undergone the most change is the "First Tropical Lowland Rain Forest." The NWB inputs to this biome group have increased progressively since 2000. The 16th (Deserts (tropical, subtropical, and frigid)) and 28th (Shrub tundra) biome groups have the highest NWB in the positive plane. The inputs (precipitation) of the NWB are greater than the outputs (evaporation, sublimation, evapotranspiration, etc.) because the majority of grids in these regions are in the cool climate zone. This is since cool climate zones typically receive more precipitation than they lose through evaporation and other processes. Additionally, the NWB inputs to the "First Tropical Lowland Rain Forest" biome group have likely increased due to factors such as deforestation and climate

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change. Tropical lowland forests (Biome 1) have the maximum standard deviation of the NWB biome categories (see *Figure 8*). This indicates that there is a high variability in the amount of precipitation received within this biome group. The increased inputs from the NWB could further contribute to this variability, potentially leading to more extreme rainfall events in these tropical lowland forests. In the remaining categories, the ranges of approximately 0-30 mm, 30-60 mm, and 80-130 mm are separated into three groups. The first group (0-30 mm) represents arid regions with low precipitation levels, while the second group (30-60 mm) includes areas with moderate rainfall. The third group (80-130 mm) consists of regions with higher precipitation levels, such as tropical rainforests and temperate forests. These distinct categories help to better understand the distribution and variability of precipitation across different biomes.

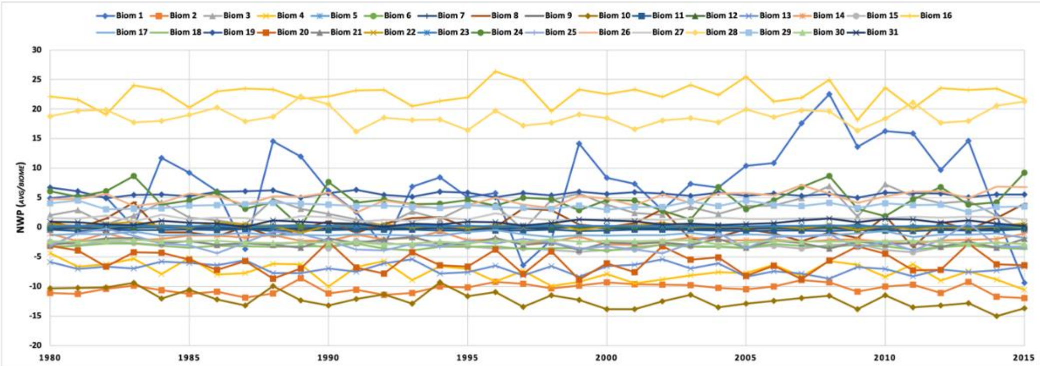

Figure 7. *Global avarage of Net Water Budget per biome (NWP) group from 1980 to 2015*

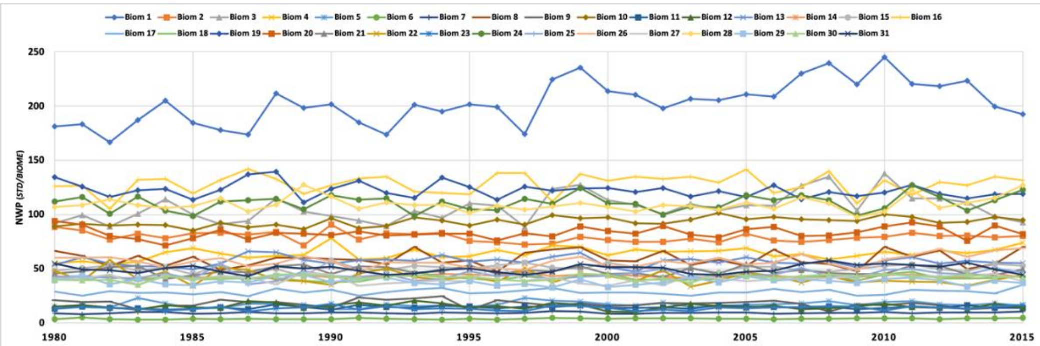

Figure 8. *Standard deviation of Net Water Budget per biome group (NWP) from 1980 to 2015*

According to the change in *CV*, the 22nd "Temperate shrub formations" biome group is the most vulnerable to climate change (see *Figure 9*). This is likely due to the fact that temperate shrub formations are highly dependent on specific precipitation levels, and any significant changes in rainfall patterns could have a detrimental impact on their growth and survival. Additionally, the vulnerability of this biome group highlights the importance of monitoring and mitigating climate change effects to protect these ecosystems and their associated biodiversity. Between 1980 and 2015, this region was one of the most susceptible to oscillations in the NWB. In addition, the sensitivity of the NWB is frequently more variable in the fifth biome group, "Tropical Paramo Woodlands" than in other biome groups.

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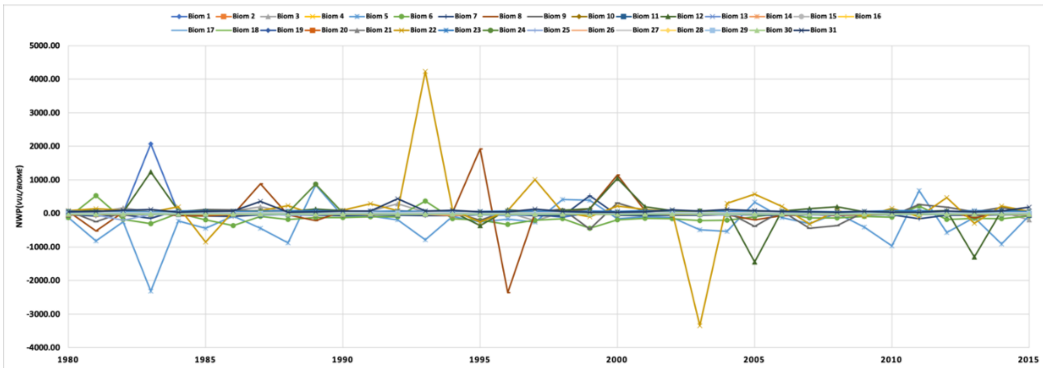

Figure 9. *Vulnerability of Net Water Budget per biome group (NWP) from 1980 to 2015*

Discussion

In most regions, Trenberth et al. (2006) global water budget modeling investigation using the ERA-40 dataset yielded similar results to this study. Trenberth et al. (2006) reported the most positive water budget (Input Fluxes > Output Fluxes), particularly in the Tropics and the Arctic, where the most positive NWB is observed. In addition, input and output fluxes are considered annual totals in this study. This study also found that the water budget in these regions is heavily influenced by precipitation, which is the main input flux. The results suggest that understanding and monitoring precipitation patterns is crucial for accurately predicting and managing water resources in these vulnerable biomes. Trenberth et al. (2006) employed daily mean values as opposed to annual total values. This causes significant losses in the study's value. Because taking the daily average values eliminates the impact of the highest and lowest values on the NWB. By using daily mean values instead of annual total values, Trenberth et al. (2006) may have overlooked the extreme precipitation events that can have a significant impact on the water resources in these vulnerable biomes. Incorporating the highest and lowest values could provide a more comprehensive understanding of the hydrological dynamics in these regions.

Anthropogenic climate change is known to significantly affect physical processes such as temperature transfer between the atmosphere and the terrestrial ecosystem, which in turn affects the amount of water available in the terrestrial ecosystem, surface runoff, precipitation amount and frequency, and evapotranspiration (Doll, 2002; Wada et al., 2013). The vulnerability of irrigation seasons in South Korea has increased considerably due to climate change, according to a study on altering irrigation seasons caused by regional climate change (Nam et al., 2017). Our research also revealed evidence supporting this conclusion. This study indicates that the net water budget on the Korean peninsula is vulnerable by more than 200 percent (see *Figure 4*). This vulnerability is primarily driven by a significant decrease in precipitation amount and frequency, as well as an increase in evapotranspiration. These changes in the water budget pose a major challenge for maintaining sustainable irrigation practices and ensuring food security in South Korea. Additionally, the findings highlight the urgent need for adaptive measures and strategies to mitigate the impacts of climate change on water resources in the region. Oki and Kanae (2006) discuss global hydrological cycles and world water resources. Similar findings were made to those in our study, and they emphasize the need to lessen current vulnerability to get ready for water resource changes that are expected. Li et al.

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(2018) explore the vulnerability of global terrestrial ecosystems to climate change. They also highlighted the importance of estimating the spatial distribution of ecosystem vulnerability to climate change to develop optimal adaptive strategies by considering water availability. Hotchkiss et al. (2015) investigated the sources and processes controlling CO_2 emissions in streams and rivers. They place a strong emphasis on the role inland waters play in various ecologies as well as the significance of knowing the rates and forces that govern carbon cycling in the availability of running water. The difference between the results of our study and their based on the using of different vegetation database. Kayiranga et al. (2020) focus on the evaluation of Africa's ecohydrological resilience to ecosystem transformations. They discovered similar results to ours in African regions and emphasized the potential ecohydroclimatic disturbances that can occur as a result of drought and moisture intensity, which can impact terrestrial ecosystems and pose threats to cereal production and food security (Ruwanza et al., 2022; Theron et al., 2023). These studies provided valuable insights into the vulnerability of terrestrial ecosystems according to the water budget. They discussed the importance of reducing vulnerability, estimating ecosystem vulnerability to climate change, understanding carbon cycling in running waters, and assessing ecohydrological resilience in the face of climate disturbances, which also matched the founding of our study. Tropical Paramo Woodlands are particularly sensitive to climate change due to their high elevation and unique ecological characteristics (Cuesta et al., 2013; Verral et al., 2023). These ecosystems are already experiencing changes in temperature and precipitation patterns, which can disrupt the delicate balance of species interactions and lead to shifts in vegetation composition. Therefore, it is crucial to prioritize conservation efforts and implement strategies that reduce greenhouse gas emissions to safeguard the future of these vulnerable biomes (Mosquera et al., 2023).

Several studies shed light on the analysis of terrestrial water budgets, the role of vegetation in water cycling, the effects of climate change on vegetation dynamics and water storage, and the techniques for ensuring the closure of water budgets (Dirmeyer et al., 2006; Lanning et al., 2019; Deng et al., 2021, 2022; Luo et al., 2023). They contributed to our comprehension of the interactions between types of water and vegetation on land and pointed to similar findings.

Conclusion

By considering the findings and recommendations from our study about the modeling of terrestrial net water budgets, policymakers and conservationists can develop effective strategies for managing and protecting vulnerable areas in terrestrial ecosystems. These strategies can include implementing sustainable water management practices, such as rainwater harvesting and reforestation efforts, to enhance water storage and regulate vegetation dynamics. Additionally, understanding the interactions between water and vegetation can inform land-use planning decisions, ensuring that vulnerable areas are preserved and protected for future generations.

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