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# Bridging scales and borders on water availability and use in the transboundary Volta River Basin: A water accounting approach

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ABSTRACT

*Study region:* Volta Basin
*Study focus:* Water management in transboundary basins is challenging due to the interaction of natural and human factors across political borders. The Volta River Basin, shared by six West African countries, exemplifies this with variable water distribution and socio-economic pressures. This study presents a comprehensive multi-scale water accounting of the basin, assessing water flows and usage at basin-wide, sub-basin, and riparian country scales from 2003 to 2021.
*New hydrological insights for the region:* The results reveal average basin closure is 55 % with room for additional water allocation given that utilizable water in the basin is 20 km$^3$/year and almost 25 % of the basin's exploitable water is non-recoverable water (wastewater). Sub-basin analysis showed variations in average annual rainfall, ranging from 940 to 1250 mm/year, and groundwater recharge rates (18–64 mm/year), with southern sub-basins receiving more rainfall and having higher recharge rates. Similarly at the country level, variability in rainfall (630–1220 mm/year) and recharge rates (20–280 mm/year) were noted, with downstream countries benefiting from higher rainfall and significant inflows from upstream countries. The analysis underscored the interconnectedness of water use across the basin's riparian countries. The study's findings give insights for the strategic management of water resources and the crucial need for enhanced cooperation among riparian countries to address shared challenges and opportunities in the Volta Basin.

## 1. Introduction

Effective management of transboundary water resources is key for ensuring water security, fostering regional cooperation, and promoting sustainable development. In West Africa, the Volta River Basin is emblematic of the complex interplay between growing water demands, climatic variability, and the challenges of coordinating governance across multiple national borders. As pressures on

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water resources intensify due to population growth, economic development, and climate change, there is an urgent need for transparent, consistent, and policy-relevant assessments of water availability and use. This study responds to this need by applying a comprehensive, multi-scale water accounting approach to the Volta Basin, contributing to improved understanding and informed decision-making in one of Africa's most important transboundary river basins.

The Volta River Basin, located in West Africa (Fig. 1), is a major hydrological system draining into the Atlantic Ocean at the Gulf of Guinea. It serves as a home for approximately 29 million people and supports agricultural production, hydropower generation, fisheries, and urban water supply (Boubacar et al., 2005; Ntiamoa-Baidu et al., 2017; Williams et al., 2016). The basin has diverse landscapes ranging from savannas and grasslands to forests and wetlands including Ramsar sites in Ghana (Akpabey et al., 2017; Amoah and Ofori-Danson, 2012). Sustainable water management is crucial, as the basin faces pressures from climate variability, land use changes, population growth, and infrastructure development, alongside challenges like deforestation, land degradation, and pollution (Akpoti et al., 2016; Boubacar et al., 2005; Dembélé et al., 2022; Ekolu et al., 2022; Mahe et al., 2013). Climate change further compounds these challenges, altering precipitation patterns, increasing the frequency and severity of extreme weather events,


**Fig. 1.** The Volta basin with riparian countries: Burkina Faso, Ghana, Togo, Benin, Mali and Côte d'Ivoire; and subbasins: Black Volta, White Volta, Oti, and Lower Volta.

and contributing to the variability of water availability in the Volta Basin (Yeboah et al., 2022). Notably, all the opportunities and challenges in the Volta Basin are interconnected across the national boundaries of its six riparian countries, with the risk that competing demands for resources along with socioeconomic disparities could exacerbate conflicts between local communities and even the riparian countries (Gonzalez et al., 2021; Sullivan et al., 2016). The interdependency of ecosystems, communities, and economies across the basin's riparian countries underscores the need for enhanced cooperative approaches to water governance, aligning with global principles of integrated water resources management (IWRM).

Against this backdrop, the need for a holistic understanding of the water dynamics in the Volta Basin becomes pressing. One way to gain this understanding is through water accounting (WA), a systematic process of quantifying water resources by tracking the inflows, outflows, distribution, and utilization of water within an area over a defined period (Batchelor et al., 2016; Molden and Sakthivadivel, 1999). The primary objectives of WA are to support informed decision-making and promote efficient allocation and use of water in a consistent and transparent manner (Batchelor et al., 2016; Karimi et al., 2013a; Vardon et al., 2025). In the context of transboundary river basins like the Volta, water accounting becomes not just a tool for resource management but a bridge for dialogue and collaboration. By quantifying and clarifying water resources data, WA provides an independent factual basis for negotiations and shared decision-making among riparian states, facilitating equitable and efficient water distribution. To overcome data scarcity challenges of conducting WA studies at large scales, a version of WA called Water Accounting Plus (WA+) framework, which makes use of satellite remote sensing datasets and open access datasets was developed by International Water Management Institute (IWMI), IHE Delft, and the Food and Agriculture Organisation (FAO) (Karimi et al., 2013a). Through WA+ analyses, it is possible to identify the main drivers of water demand and identify trends, variations, and hotspots of water stress or scarcity in areas with relatively little in-situ data (FAO, IHE Delft, 2019; Karimi et al., 2013a). Water Accounting Plus has been successfully applied in the Litani Basin in Lebanon (FAO, IHE Delft, 2019), the Mahi Basin in India (Patle et al., 2023; Patle and Sharma, 2023) as well as the Indus Basin in Asia (Karimi et al., 2013b). For the Volta Basin, Dembélé et al. (2023) coupled a fully distributed hydrologic model and climate change scenarios with WA+ to forecast potential water resource challenges and suggest mitigation strategies. They found that there would be modest rise in net inflow due to climate change between 2021 and 2050 leading to a potential increase in exploitable water and total outflow from the basin (Dembélé et al., 2023).

Water accounting assessments are typically performed at the hydrologic scale, i.e. at the basin or subbasin level. However, water management decisions are typically made at political-administrative levels, which do not always align with hydrological boundaries. This misalignment often limits the effectiveness of national water governance, particularly in transboundary river basins with competing national interests from riparian countries. In this study, we apply a multi-scale WA methodology to the Volta Basin and the riparian countries. The concept of multi-scale WA involves assessing water inflows, outflows and use at various hierarchical levels, ranging from the entire basin down to smaller sub-basins and notably, riparian administrative regions for transboundary river basins such as Volta Basin. Herein lies the novelty of this study: WA analysis at non-hydrological scales, i.e.: country-level WA, which tends to be the scale at which national water resources are usually administered. The multi-scale approach allows for a more nuanced and policy-relevant understanding of water resources distribution and use, thus enabling targeted interventions and transparent and sustainable management practices. By promoting transparency and sharing of water-related data among riparian countries of the Volta, multi-scale WA+ can improve mutual understanding of water dynamics and facilitate informed decision-making. In this study, a multi-scale water accounting plus framework at an annual, 1 km spatial resolution was applied for the Volta Basin from 2003 to 2021 is undertaken to provide insights into the spatial and temporal patterns of water across: 1. the entire Volta Basin, 2. main subbasins, and 3. riparian countries. By examining water balances, trends, and variability across these different scales, we seek to identify areas of water stress, assess the impacts of human activities, and explore potential strategies for enhancing water security, transboundary cooperation, and resilience in the region.

## 2. Study Area

The Volta Basin extends from the Sahel to the Atlantic Ocean across six riparian countries: Burkina Faso, Ghana, Togo, Benin, Mali and Côte d'Ivoire. It stretches from approximately latitude 14°30'N in Mali to 5°30'N in Ghana and at its widest point, longitude 5°30'W in Burkina Faso to 2°00'E along the Togo-Benin border. Flowing in a north-southwards direction, the total length of the Volta River is about 1850 km and the drainage area of the basin is approximately 407,850 km$^2$ with parts of Burkina Faso making up about 42 %; Ghana, 41 %; Togo, 6 %; Mali, 4 %; Benin, 4 %, and Côte d'Ivoire, 3 % of the basin (Boubacar et al., 2005). The Volta Basin consists of four main sub-basins: the Black Volta (Mouhoun, in Burkina Faso), White Volta (Nakambé), Oti (Pendjari), and Lower Volta sub-basins. These subbasins make up 38 %, 27 %, 18 % and 17 % respectively of the basin.

The population of the Volta Basin is largely rural and is projected to increase from 29 million to over 56 million by 2050- more than double what it was in 2010 (United Nations Environmental Program UNEP, 2023; Williams et al., 2016). Economic activity is largely reliant on natural resources, particularly water resources, with agriculture, fisheries and livestock rearing being the dominant activities (Williams et al., 2016). Hydropower is an important source of electricity in the basin and major hydropower plants in the basin are the Akosombo (1020 MW), Bui (400 MW) and Kpong (160 MW) dams in Ghana, and the Bagre Dam (16 MW) in Burkina Faso which have historically provided most of the riparian nations' electricity (Ntiamoa-Baidu et al., 2017; Tsikata, 2008).

The basin's climate is influenced by the dry North-East and the wet South-West trade winds, which converge to form the Inter-Tropical Convergence Zone (ITCZ). The movement of the ITCZ over the basin, typically from March to October, corresponds with the rainy season of the regions falling south of it at any time. This leads to the emergence of three distinct climatic zones: the humid southern region with two well-defined rainy seasons in southern Ghana, the transitional tropical zone with closely spaced rainfall seasons, and the northern tropical climate with a single rainy season peaking in August in Burkina Faso and Mali (Oguntunde et al., 2017). Given this climate, Burkina Faso in the relatively dry northern part of the basin has built many small dams for irrigation while Ghana, with more abundant water resources, relies on inflows from the north for its large hydropower dams (De Fraiture et al., 2014; Dye, 2020).

Water governance in the Volta Basin is based on statutory and customary laws, both recognized in the constitutions of the six riparian countries (Williams et al., 2016). Water resources are governed by statutory laws—Ghana's Water Resources Act and the Water Codes in the other five countries—which place ownership, control, and regulation under state authority (UNEP-GEF Volta Project, 2013; Williams et al., 2016). However, traditional leaders and community water user groups continue to play a significant role in water rights, reflecting historical perceptions of water as a communal resource (Dorm-Adzobu and Ampomah, 2014; UNEP-GEF Volta Project, 2013). Each country has a national apex body responsible for water management, typically housed within the main ministry overseeing water resources, except in Ghana, where it functions as an independent commission (UNEP-GEF Volta Project, 2013).

Efforts to formalize transboundary water management in the Volta Basin began in the 1990s and culminated in the 2007 Convention on the Status of the Volta River and the Establishment of the Volta Basin Authority (VBA) (Buskop, 2022; Volta Basin Authority, 2018). The convention took effect in August 2009 after ratification by four countries (Togo, Mali, Ghana and Burkina Faso), with all six completing the process by 2012 (Volta Basin Authority, 2018; Word Bank Group and CIWA, 2017). The VBA's mandate is to facilitate permanent consultation and the sustainable development of water resources, fostering cooperation among riparian states to ensure equitable and efficient water management (Volta Basin Authority, 2018). A Transboundary Diagnostic Analysis (TDA) of the Volta Basin found that, despite the Volta Basin Authority's (VBA) strong mandate, cooperation on water resource management remains limited with riparian countries continuing unilateral water development (UNEP-GEF Volta Project, 2013). Limited financial contributions, information sharing, and resource constraints further impede progress. In response, a Strategic Action Programme (SAP) was developed to guide five-year Strategic Plans (UNEP-GEF Volta Project, 2014). One of the priorities of the Volta Basin SAP is strengthening governance and improving information quality for resource management, a goal that multiscale water accounting can support (UNEP-GEF Volta Project, 2014).

## 3. Data and methods

The underlying theory, inputs and outputs of multi-scale water accounting builds upon the approach of WA+ for river basins and subbasins. The reader is referred to Karimi et al. (2013a) and Dembélé et al. (2023) for a detailed description of WA+ framework. In this section, only a brief overview of the theory, inputs and the main WA+ outputs are presented. This is followed by a description of multi-scale WA+ with an emphasis on WA+ within non-hydrological boundaries.

### 3.1. *Water Accounting Plus*

WA+ uses a mass water balance method whereby for a given time and space:

$$P - ET - QP - QS = \Delta SM \tag{1}$$

where: $P$ represents precipitation, $ET$ is actual evapotranspiration, $QP$ is deep percolation, $QS$ is surface runoff, $\Delta SM$ is the change in soil moisture at a pixel scale defined within the rootzone depth. $QP$ is derived as an exponential function of the soil moisture and $QS$ is derived using an adjusted version of the Soil Conservation Service runoff method (FAO, IHE Delft, 2019);

In WA+ , $ET$ is further partitioned into green or rainfall $ET$ ($ET_g$) and blue or incremental $ET$ ($ET_b$). The former refers to the portion of precipitation that is absorbed by soil and used by plants for transpiration, as well as the moisture that evaporates directly from soil and plant surfaces, while the latter is evapotranspiration of water from surface and groundwater sources that have been supplied to the land, typically through irrigation (Falkenmark and Rockström, 2006). Thus $ET_b$ is calculated simply as a residual of soil moisture

**Table 1**
Remote sensing datasets used in this study.

| | Data | Units | Product | Reference |
|---|---|---|---|---|
| Dynamic data | Daily and monthly precipitation | mm | CHIRPS v2 | Funk et al. (2015) |
| | Monthly Actual ET | mm | SSEBop v5 | Senay et al. (2020) |
| | Monthly Potential ET | mm | GLEAM v3.6a | Martens et al. (2017) |
| | Monthly Leaf area index (LAI) | $m^2/m^2$ | MOD15A2H | Myneni et al. (2015) |
| | Monthly net primary production (NPP) | $kg\ m^{-2}\ yr^{-1}$ | MOD17A3HGF.061 | Running and Zhao (2021) |
| | Monthly gross primary production (GPP) | $kg\ m^{-2}\ yr^{-1}$ | MOD17A2HGF.061 | Running and Zhao (2021) |
| | Monthly net dry matter (NDM) | kg/ha | Derived from GPP and NPP | - |
| | Annual landcover | - | CCI LC V2 | ESA CCI (2015) |
| Static data | Digital elevation map (DEM) | m | Hydrosheds (90 m) | Lehner et al. (2008) |
| | Saturated soil moisture | $m^3/m^3$ | Hihydrosoils v2.0 | Simons et al. (2020) |
| | Irrigated areas | % | Global map of irrigated areas (GMIA) | Siebert et al. (2013) |
| | Reserved flow | - | Environmental water requirement | Smakhtin et al. (2009) |
| | Grey water footprint | - | Water pollution levels (WPL) | Liu et al. (2012) |
| | Population | pop/ha | WorldPop - 2015 (adjusted) | Lloyd et al. (2019) |
| Vector | Discharge | $m^3$/month | VegDischarge | Akpoti et al. (2024) |

balance for a given timestep ($t$):

$$ET_b = \begin{cases} 0, & if\ SM_t \geq 0 \\ SM_t \times -1, & if\ SM_t < 0 \end{cases} \quad (2)$$

This assumes that if soil moisture exceeds precipitation, the extra water must be coming from another source such as rivers, lakes, or groundwater (van Eekelen et al., 2015). $ET_g$ is then calculated as:

$$ET_g = ET - ET_b \quad (3)$$

### 3.2. Input data

The WA+ framework uses remote sensing data to monitor water flows and storages over large areas and extended periods. In this study, the spatial resolution of the input remote sensing data used were resampled to 1 km (Table 1). All water balances were calculated at monthly timestep aggregated to derive annual water accounts for the entire basin, subbasins and riparian countries.

With respect to the dynamic data inputs, precipitation is the primary source of water to a basin while actual ET represents the total water loss through evaporation from soil and water bodies, and transpiration from plants. Potential ET indicates the potential water loss under ideal conditions, serving as a benchmark for comparing actual water usage (actual ET) and helping assess irrigation needs and water stress. LAI refers to the leaf area per unit ground area, used to estimate plant transpiration rates and water usage, as plants with higher LAI generally require more water. Saturated soil moisture represents the maximum water-holding capacity of the soil and is important to determine runoff or infiltration of water into the soil. NPP reflects the amount of carbon assimilated by plants after accounting for respiration while GPP measures the total carbon fixed by plants through photosynthesis. As such, NPP is the portion of GPP that remains after subtracting the energy used by plants for respiration, representing the net biomass available for growth and consumption. NPP and GPP are used in calculating NDM which is the total biomass produced by plants, excluding water. It represents the accumulation of organic material in plants over a certain period and is used to assess agricultural productivity, crop yield, and the efficiency of water use in ecosystems (Running and Zhao, 2021). Landcover describes the types of vegetation and land use (forests, agriculture, urban areas) across the basin, which is crucial for estimating water usage, runoff patterns, and the impact of land management on water resources.

The static data inputs include the DEM which is a digital representation of the earth's surface elevation used to delineate slope and drainage patterns. Saturated soil moisture represents the maximum water content a soil can hold when all its pore spaces are completely filled with water, affecting processes such as saturation excess runoff. Reserved flow is the water required to maintain ecosystem health and downstream water needs, such as for aquatic habitats, wetlands, and human uses. Reserved flow data is critical for ensuring sustainable water allocation while protecting environmental water needs (Bunn and Arthington, 2002). Grey Water Footprint represents the volume of water required to assimilate pollutants and maintain water quality. It helps assess the environmental impact of water pollution and the capacity of a basin to handle wastewater from domestic, and agricultural sources (Liu et al., 2012). The population data is used to estimate water demand for domestic consumption while the map of irrigated area shows formal irrigation areas in the study area.

Discharge data is a timeseries dataset showing inflows and outflows to the basin (Akpoti et al., 2024).

#### 3.2.1. Land cover and land use classification

Water use in WA+ is summarised based on four main land use types, referred to as Land Use for Water Accounting (LUWA) classes: protected land use (PLU), utilized land use (ULU), modified land use (MLU), and managed water use (MWU) (Karimi et al., 2013a). Each class represents a distinct way in which land and water resources are managed, reflecting different priorities and thus impacts on the hydrological cycle:

- **Protected land use (PLU)** includes areas allocated for protection to ensure minimal human interference and includes locations like national parks, coastal dunes, wildlife reserves, and Ramsar-designated wetlands. PLU areas play a crucial role in maintaining natural hydrological processes, supporting groundwater recharge, and mitigating flood risks.
- **Utilised land use (ULU)** classification includes regions providing diverse ecosystem services with little to no human alteration. Encompassing ecosystems like grasslands, savannas, and forests, this category delivers returns in the form of fuel, wildlife, aquatic birds, and mineral resources. ULU areas help regulate the water cycle by supporting groundwater recharge, sustaining river base flows, and stabilizing local climates. However, activities like over grazing, logging, and mining can disrupt these functions, affecting water availability and ecosystem health. Balancing conservation with resource use is key to protecting biodiversity and water security.
- **Modified land use (MLU)** category refers to regions extensively changed by human actions for farming, fuel generation, infrastructure, and recreational activities. Activities within this category, including deforestation, rainfed agriculture, and urban expansion, affect evapotranspiration rates, infiltration rates, surface runoff and groundwater replenishment, thus altering water availability and flow in downstream areas.
- **Managed water use (MWU)** group includes types of land use where man-made infrastructure, such as pumps, dams, and canals, intentionally modify the natural water cycle for purposes like irrigation, drinking water provision, and hydropower generation. MWU play a major role in water security and economic development but can also lead to conflicts over water allocation, especially in transboundary basins where upstream water use affects downstream availability.

For the Volta Basin, MLU dominates the other LUWA classes in the northern part of the basin, while in the south, ULU is the major LUWA class (Fig. 2). In total, ULU covers 45 %; MLU, 39 %, PLU,14 % and MWU 2 % of the basin area. The implications of these land-use categories for water management strategies are significant. For instance, increasing the extent of MLU without sustainable land-use practices can exacerbate water scarcity and soil degradation. Similarly, expanding MWU through increased irrigation or dam construction requires careful planning to balance agricultural productivity with ecosystem conservation and downstream water needs.

### *3.2.2. Overall Water Resources Assessment*

The WA+ resource base sheet (Fig. 5) provides information on the overall water resource status by detailing all inflows and outflows from a basin, and linking them to different land use and water management activities (Karimi et al., 2013a). The net inflow to a basin is calculated by adjusting the gross inflow from precipitation, surface, groundwater and desalination sources by the change in storage. A portion of net inflow is lost to natural evaporation (landscape ET) as green and blue water evaporation across the different landcover classes. The net inflow left over once landscape evapotranspiration (ET) has been deducted constitutes exploitable water, which is essentially the blue water that has not evaporated and is available for use. This exploitable water is categorized into utilized outflow; non-utilizable outflow, and non-recoverable outflow which is grey water that is often lost to the system due to contamination or discharge into sinks where it cannot be readily reused (Liu et al., 2011); reserved flow which includes allocations for downstream use, navigation, and ecological preservation (Arthington et al., 2018; Smakhtin et al., 2009); and utilizable outflow which is water that can be further used. These three outflows, utilizable, reserved, and non-utilizable outflows, are the non-consumed water which together with the non-recoverable flow portion of utilized flows make up outflows from the study area. The remainder of the utilized flows along with the landscape evapotranspiration (ET) is identified as depleted water, consumed in the basin through ET. It is important to note that wastewater treatment and reuse strategies can reclaim a portion of non-recoverable flows for irrigation, industrial use, or even potable supply, depending on the level of treatment, thereby reducing outflows (Tortajada, 2020).

Additional WA+ indicators may be calculated to assess the water dynamics within the Volta Basin (Karimi et al., 2013a). In this paper we mainly use the Basin Closure Fraction (BCF) indicator as this evaluates the extent of water utilization within the basin, providing insight into the pressure on water resources due to consumption. A basin becomes "closed" when all of its water is allocated, and no additional water is available for new uses without reducing allocations to existing water users including the environment (Falkenmark and Molden, 2008). High BCF values, above 70 % especially, indicate that water demand is close to consuming all water supply, indicating water stress or scarcity and signifying that the basin is nearing over-allocation or full closure (Falkenmark and Molden, 2008).

It is calculated as:

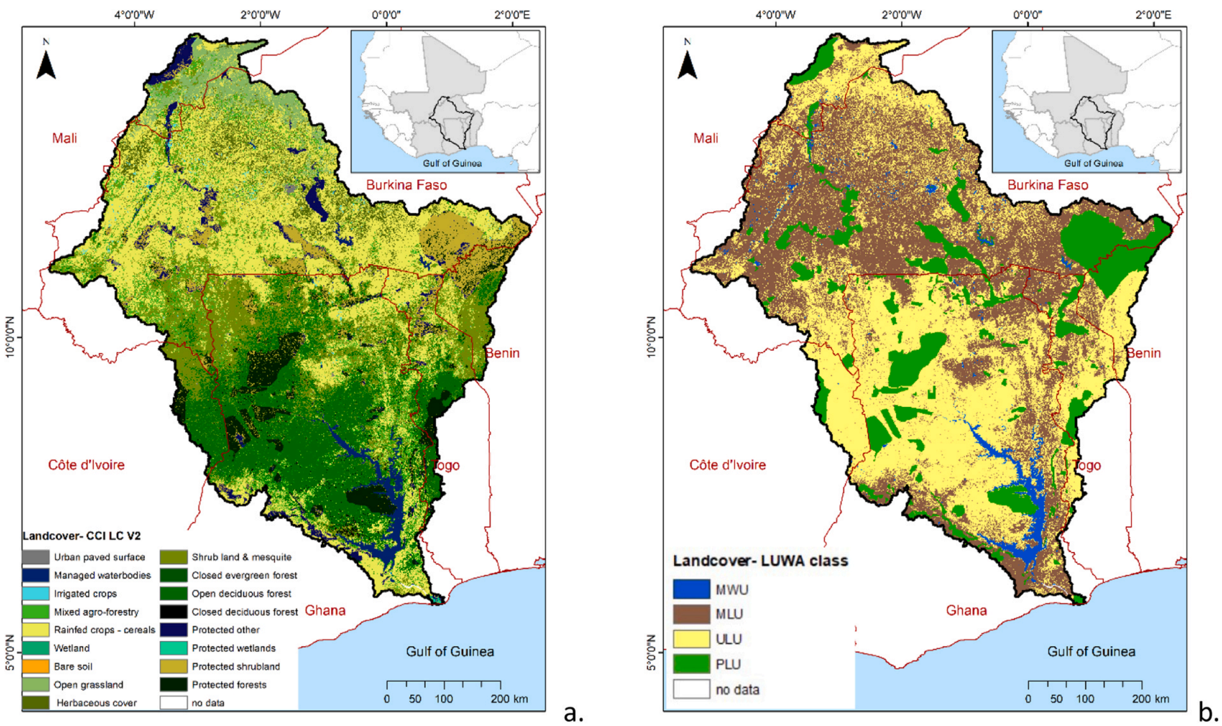



**Fig. 2.** a. Volta Basin landcover (Climate Change Initiative Land Cover, version 2 (CCI LC V2) b. Volta basin land use/landcover categorised into the four land use for water accounting (LUWA) classes: Managed water use (MWU), Modified land use (MLU), Utilised land use (ULU), and Protected land use (PLU).

$$BCF = Utilized\ flow + Reserved\ flow / Exploitable\ water \quad (4)$$

### 3.3. Multi-scale water accounting

For the Volta Basin and its upstream sub-catchments (Black Volta, White Volta and Oti), there are no natural inflows across hydrological boundaries and outflow occurs at just the outlet. However, in carrying out WA+ at non-hydrological scales, consideration must be given to the flows (inflows and outflows) across these boundaries. Using multiscale water accounting approach (Fig. 3), water accounts can be generated consistently for any boundary - basin, subbasin, country or county- for analysis. The annual multi-scale water accounts presented in this study were scaled by first conducting a WA+ run for the whole Volta Basin. This was followed by scaling and extracting data for subsequent subbasins and country portions of the basin. Establishing multiple hydrological models or conducting separate water accounting analyses for each sub-scale would be more resource-intensive and less efficient. This approach would require computational efforts for each individual sub-scale unit including estimating relative flows for multiple river segments crossing sub-units, posing a particular challenge for country-level (non-hydrological) analyses (Vardon et al., 2025). In the case of the Volta River Basin, this would mean running ten additional models and estimating relative inflows and outflows— for each of the four sub-basins and six riparian countries. The multiscale water accounting allows for a harmonized water accounting assessment that ensures comparability across scales, facilitating transboundary cooperation and decision-making. The multiscale WA+ framework for the Volta Basin consists of the following modules:

- A data extraction module which extracts WA+ input and output remote sensing data for any boundary within the larger water account region.
- A discharge extractor which extracts inflows and outflows crossing the boundary of the area under study. The inflows and outflows are derived from VegDischarge v1, an advanced discharge model of Africa (Akpoti et al., 2024). VegDischarge is based on satellite data and on-site measurements in a VegET hydrological model (Senay et al., 2023) and mizuRoute routing framework (Mizukami et al., 2021, 2016), thereby generating intricate hydrological representations of over 64,000 river segments in Africa, and 923 segments for the Volta Basin.
- WA+ indicator generation module which calculates WA+ indicators
- WA+ resource base sheet extractor module which generates WA+ sheets for the region under study.

The multiscale WA+ framework follows a structured workflow to process hydrological data and generate comprehensive water accounts for the Volta subbasins and riparian countries. The key steps are detailed in Fig. 3 and Table 2.

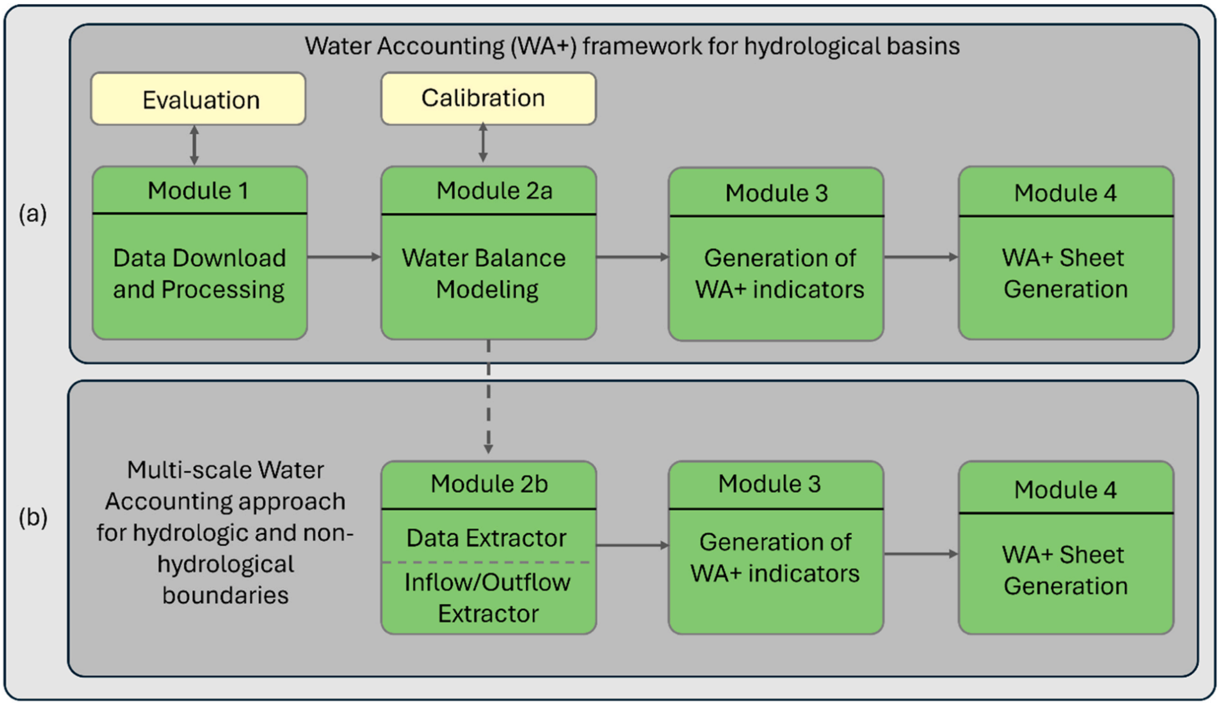



**Fig. 3.** Multi-scale water accounting for Volta Basin. The conventional WA+ (a) was applied for the Volta Basin area and multi-scale WA+ (b) was applied for Volta Basin sub-catchments and riparian countries.

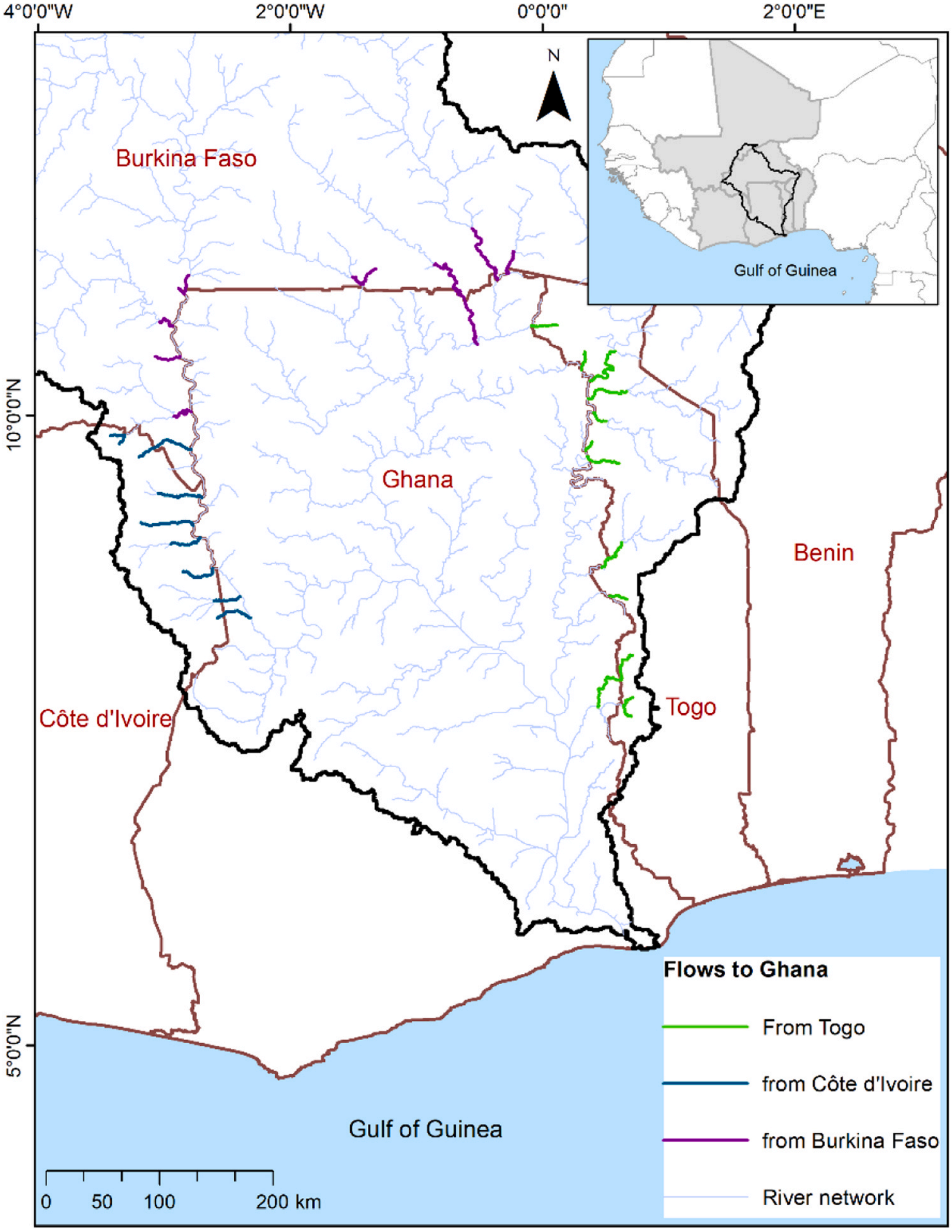



**Fig. 4.** Inflows to Ghana from adjacent riparian countries in the Volta basin.

### 3.4. Validation of inputs

Validation of remote sensing products is important to ensure accuracy, reliability, and trustworthiness for informed decision-making. The references in Table 1, provide details on how each product used in this study was derived and validated. In this section, additional information on the performance of the two main remote sensing inputs: precipitation (CHIRPS) and actual evapotranspiration (SSEBop); and also the discharge model, VegDischarge (Akpoti et al., 2024) used in the multi-scale Volta WA study is presented.

#### 3.4.1. Precipitation

As the principal flux in the hydrological cycle, numerous remote sensing products have been developed for precipitation (Beck et al., 2019; Funk et al., 2015; Herman et al., 2010; Maidment et al., 2015). In a review of eight of these products covering Africa, Mekonnen et al. (2023) evaluated their performance using independent, quasi-dependent and dependent datasets derived from in-situ measurements and Global Summary of the Day (GSOD) precipitation database. They concluded that the Climate Hazards Group

**Table 2**
Multiscale water accounting plus (WA+) steps, processes and outputs for the Volta Basin.

| Step | Process | Output |
|---|---|---|
| 1: WA+ run for Volta Basin | Running the WA+ model for the entire Volta River Basin (Karimi et al., 2013a). WA+ model utilizes dynamic and static geospatial data (Table 1) as inputs and has the following main steps:<br>• Data download and pre-processing<br>• Pixel-based water balance analysis for the root zone of various land classes<br>• Calculation of water accounts by summarizing all the key variables and fluxes at annual time scales.<br>• Generation of water accounting resource base sheets using a pre-designed template. | WA+ resource base sheet (Fig. 5) and output raster layers (Karimi et al., 2013a) for the Volta basin.<br>The results from the WA+ run for the Volta Basin are stored and become the input data for the multiscale WA+ run for the subbasins and riparian countries. |
| 2: Basin data extractor module | Given shapefiles of sub-units, this module clips data from the Volta Basin WA+ input and output layers. | WA+ input and output raster layers for the sub-unit/boundary under consideration |
| 3: Inflows and outflows extractor module | Overlays the sub-unit's shape onto the VegDischarge (Akpoti et al., 2024) river network and detects stream segments that cross its boundary by analysing their start and end nodes. For border rivers—those serving as natural boundaries between countries—50 % of the river flow is assigned to each adjacent country. | Vector shapefiles of the identified inflow and outflow stream segments for the sub-unit, along with a monthly time series of flow through these segments.<br>The vector shapefiles of inflows to Ghana are shown in Fig. 4 |
| 4: WA+ indicators generation | Calculates WA+ indicators | WA+ indicators on inflows, water use and outflows |
| 5: WA+ resource base sheet extractor module | Summarizes all the key variables and fluxes at annual time scales for the selected sub-unit. | Water accounting resource base sheets for the sub-unit. |

InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015) generally performed well at both daily and monthly timescales (Mekonnen et al., 2023). Specifically, for the Volta Basin, CHIRPS had a median correlation value of 0.90 with in situ observations and was recommended for hydrologic modelling studies, flood and drought monitoring (Mekonnen et al., 2023). In Burkina Faso, studies have found that accuracy of remote sensing precipitation products, including CHIRPS, improved with longer time steps, showing good to excellent agreement with observed rainfall at monthly and annual scales. CHIRPS also demonstrated a strong correlation with Standardized Precipitation Index (SPI) across monthly timescales (Dembélé and Zwart, 2016; Garba et al., 2023; Yonaba et al., 2024). Similarly, to avoid the risk of validating products with ground truth data that may have been used for bias correction, Poméon et al. (2017) conducted a hydrological evaluation of precipitation products in West Africa. Their findings identified CHIRPS as one of the better-performing precipitation products in the region with a Nash-Sutcliffe Efficiency (NSE) of 0.64 (Poméon et al., 2017). As such, CHIRPS was selected as the rainfall product to be used in this study.

### *3.4.2. Evapotranspiration*

Previous studies (Jung et al., 2019; Weerasinghe et al., 2020) have shown that while remote sensing products effectively capture the temporal dynamics of evapotranspiration (ET) over West Africa, significant variations in monthly estimates stem from differences in model structure, parameters, and input data uncertainties. Weerasinghe et al. (2020) used three approaches to evaluate the accuracy of eight actual ET products over Africa: first, a comparison of ET products to annual ET calculated from the water balance of basins; then comparison of the annual ET to potential ET ($ET_o$) ratios for water bodies (expected $ET/ET_o = 1$) and for irrigated areas (expected $ET/ET_o = k_c$, where $k_c$ is the average crop coefficient for the irrigated crop as estimated by FAO); and then finally, by plotting $ET_o/P$ and ET/P against the Budyko curve and estimating the difference (Weerasinghe et al., 2020). They concluded that three products, the CSIRO MODIS ReScaled EvapoTranspiration (CMRSET) (Guerschman et al., 2009), Water Productivity through Open access of Remotely sensed derived data (WaPOR) actual ET (FAO, 2018) and Simplified Surface Energy Balance (SSEBop) (Senay et al., 2007) consistently performed best with good spatial distribution and relatively little bias as compared to the other products. Consequently, SSEBop was used as the representative ET product for this study.

### *3.4.3. Discharge*

Hydrological modelling and water accounting studies in Africa frequently encounter obstacles due to data limitations, characterized by the scarcity of high-quality, spatially distributed, and long-term hydrological data (Ndehedehe, 2019). This is overcome by using the VegDischarge model to estimate discharge in the multiscale analysis for Volta. In VegDischarge, remote sensing data on precipitation and Normalized Difference Vegetation Index (NDVI) phenology was used to improve the representation of hydrological variability in space and time (Akpoti et al., 2024). This integration of remote sensing data helps overcome limitations associated with data scarcity and quality, resulting in a more dependable hydrological model for Africa (Akpoti et al., 2024). For the Volta Basin, the NSE for VegDischarge was 0.76 while the Kling-Gupta Efficiency (KGE) was 0.74 when compared to observed data (Akpoti et al., 2024).

## 4. Results

### 4.1. Basin-wide WA+ results

The WA+ resource base sheet (in km$^3$/year), averaged for 2003–2021 for the entire Volta Basin is presented in Fig. 5. For this period, average annual rainfall over the basin was approximately 410 km$^3$/year (1000 mm/year), actual ET was 350 km$^3$/year (860 mm/year) while the average annual flow out of the basin was 41 km$^3$/year (1300 m$^3$/s). Out of the average net inflow of 391 km$^3$/year, about 90 % of inflows is consumed in the basin as ET with 10 % flowing out as runoff. Overall, from 2003 to 2021, the basin is recharging surface and groundwater storage at an average rate of 17 km$^3$/year.

The exploitable fraction of net inflows is about 12 % and out of this (47 km$^3$/year), about 21 % is reserved for the environment, 23 % is non-recoverable and < 1 % is non-utilizable. This shows that water quality issues are leading to the 'loss' of a considerable proportion of the exploitable water in the basin.

An average basin closure of 55 % indicates that approximately 45 % of the Volta Basin's water is not already allocated or consumed on an annual basis. As such, there is capacity for further water allocation given the utilizable flow of approximately 20 km$^3$/year, but seasonal and spatial variations must be considered as these may add further constraints (Fig. 6a and b). The Volta Basin receives the bulk (approximately 75 %) of its annual rainfall during the wet season from May to October. This period is characterized by cooler temperatures, cloudy skies and reduced evaporative demand resulting in relatively low evapotranspiration across the basin. Consequently, there is a surplus of water during this wet season and thus a positive water yield over much of the basin (Fig. 6a). Conversely, in the dry season, with low rainfall, clear skies, high temperatures and arid conditions prevailing, evapotranspiration rates increase significantly, depleting both the dry season precipitation and the surplus from the wet season thus resulting in negative water yield over much of the basin (Fig. 6b).

Fig. 7 and Fig. 8 illustrate annual inflows, outflows, and exploitable flow in the Volta Basin from 2003 to 2021, highlighting periods of both low and high water availability. Notably, 2004–2006 and 2013–2016 experienced generally low water availability, as seen in the constrictions (Fig. 7) and dips (Fig. 8) in the graphs. During these periods, groundwater resources are tapped to supplement limited surface water. In the WA+ framework, this is considered a gain for the basin, and is thus depicted as a positive storage change relative to the basin. Conversely, in years such as 2010 and 2019–2020, water availability was high. In 2010, for instance, excessive inflows resulted in emergency spilling from the Akosombo Dam. During such high-water periods, excess surface water recharges groundwater, which in WA+ is considered a loss from the basin and is therefore depicted as a negative storage change relative to the basin.

Green ET (rainfall-based ET) makes up about 80 % of actual ET from the basin. For both green and blue ET, ULU and MLU (natural and rainfed landscapes, respectively) are the major landcovers consuming water (Fig. 9a and b) although with respect to blue ET, MWU (irrigated and managed water bodies) particularly, the lakes formed by dams are also an abundant source of blue ET consumption (Fig. 10a and b).

### 4.2. Subbasin WA+ results

The WA+ resource base sheets, averaged for 2003–2021 for each subbasin can be found in Appendix A (supplementary material).

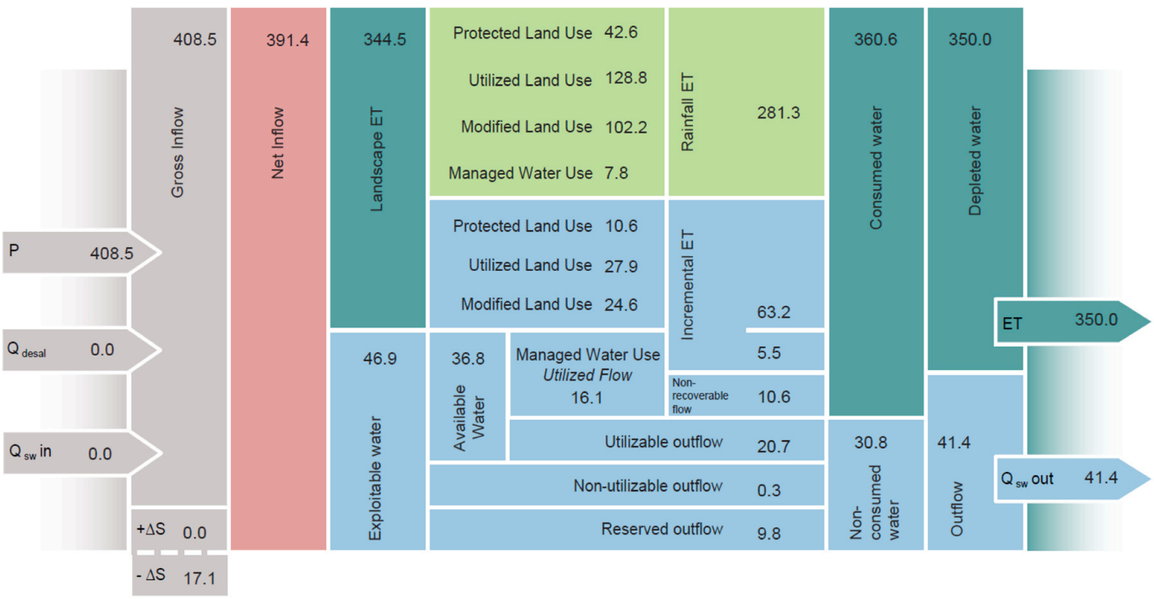



**Fig. 5.** WA+ resource base sheet for Volta basin for 2003–2021 (km$^3$/year).

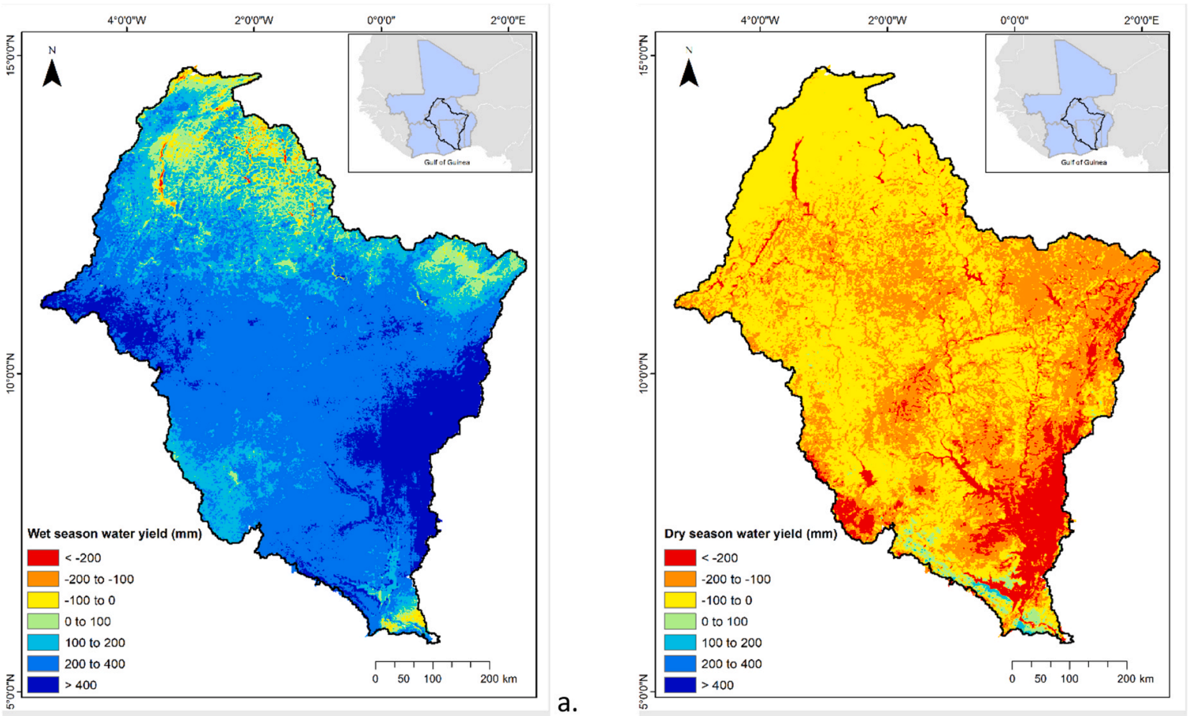



**Fig. 6.** a. Wet season water yield over the Volta Basin (May to October)- abundant rainfall, cooler temperatures, and reduced evaporative demand result in a positive water yield across much of the basin; b. Dry season water yield over the Volta Basin (November to April) - limited rainfall, high temperatures, and increased evapotranspiration lead to negative water yield, as water stored from the wet season is depleted.

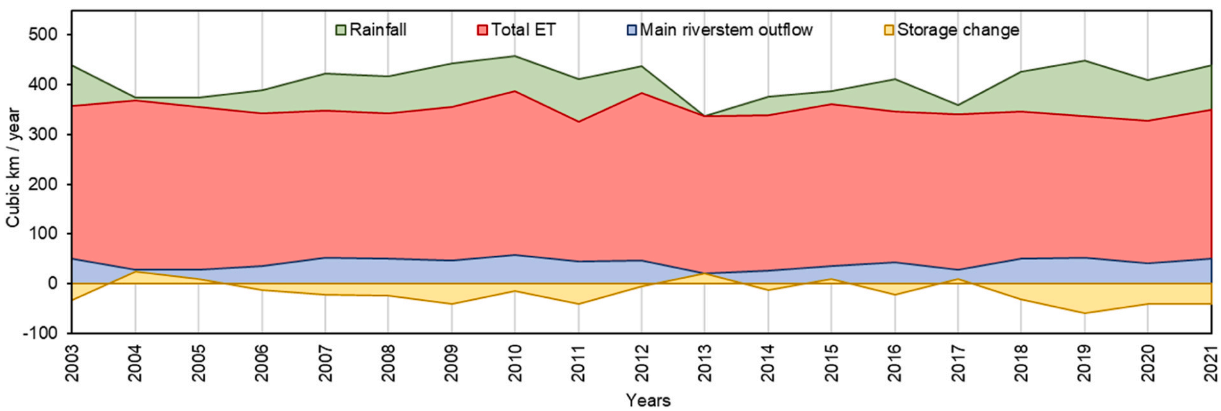



**Fig. 7.** Annual inflows and outflows from the Volta Basin from 2003–2021. NB: Negative storage change implies that water is leaving in the basin's rivers, lakes, or reservoirs and recharging groundwater. Conversely, positive storage change suggests that groundwater contributions are increasing water availability in the basin.

As expected, subbasins with a larger proportion in the southern part of the basin have higher average annual rainfall so that the subbasins in order of increasing average annual rainfall over 2003–2021 are White Volta, Black Volta, Oti and Lower Volta with 940, 945, 1113 and 1247 mm/year of average rainfall respectively (Fig. 11a). The Volta Basin is recharging groundwater at an average annual rate of 42 mm/year and this ranges from a high of 63 mm/year in Oti to 18 mm/year in the White Volta (Fig. 11b).

For green ET, over the entire basin and separately for each of the four basins, MWU consumes the least followed by PLU, MLU and ULU (Fig. 12a). Owing to the Volta Lake, which is the largest manmade lake by surface area globally (8502 $km^2$ at full capacity), for blue ET, MWU in the Lower Volta consumes the highest per year at 213 mm/year (Fig. 12b).

With respect to flow generated internally, the Black Volta generated the highest flows from 2003–2021 with about 13 $km^3$/year. This was followed by White Volta, Oti and Lower Volta with 10, 8.7 and 8.5 $km^3$/year, respectively.

Considering the three upper subbasins, the average exploitable fraction of net inflows is about 11 % while for the Lower Volta the

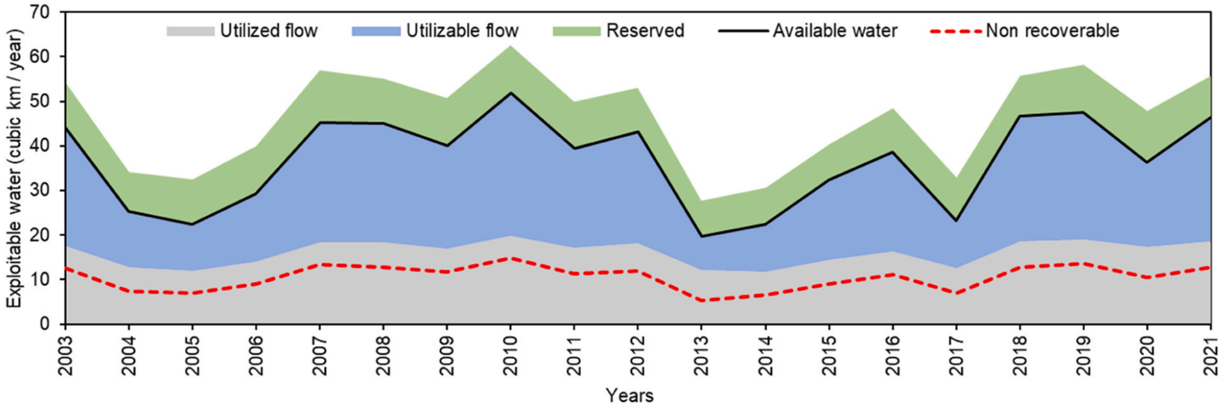



**Fig. 8.** Exploitable flows from 2003–2021 showing reserved, utilizable, utilized and non-recoverable flows. The black line is available water which is made up of utilized and utilizable flow. The red dashed line shows non-recoverable flows (wastewater).

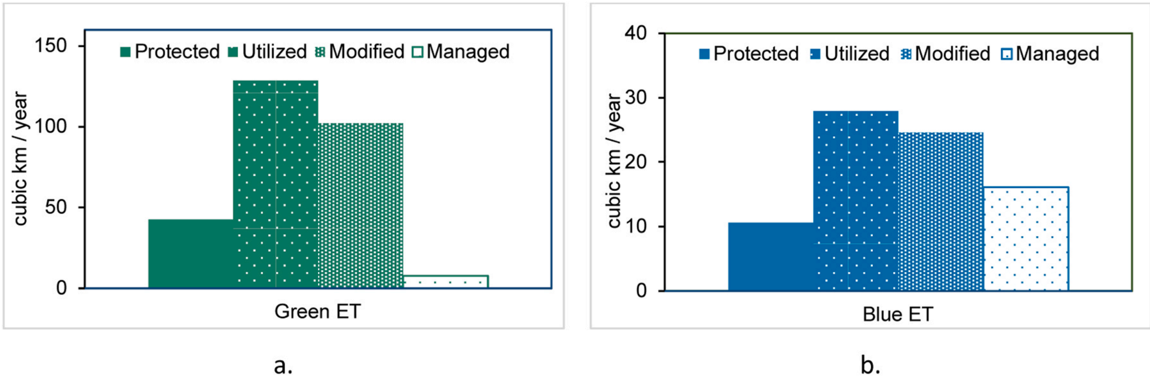



**Fig. 9.** Average green ET (a) and blue ET (b) across four main landcover classes from 2003 to 2021.

exploitable fraction is 39 %. Non-recoverable flows make up an average of 22 % of exploitable flows, ranging from 23 % in the Lower Volta and Oti to 25 % in the Black Volta (Fig. 13). This shows high variability over the years as does available water (Fig. 14). The pattern of water availability across the subbasins is similar and some years stand out as years with low water availability (dry years like 2013) or vice versa (wet years like 2010). The average basin closure for the three upstream subbasins is 47 % with average utilizable flow of 5 km$^3$/year. For the Lower Volta, which is the most downstream subbasin, basin closure is 54 % but with a utilizable flow equivalent to that of the entire basin at 20 km$^3$/year.

### 4.3. Riparian country water accounts

The WA+ resource base sheets, averaged for 2003–2021 for each riparian country can be found in Appendix A (supplementary material). Similar to subbasins, riparian countries with a larger area in the southern part of the basin have higher average annual rainfall. The riparian countries in order of decreasing average annual rainfall over 2003–2021 are Togo, Ghana, Côte d'Ivoire, Benin, Burkina Faso and Mali with 1221, 1116, 1052, 959, 840 and 630 mm/year of rainfall respectively (Fig. 15a). On recharge to groundwater and surface storage, Togo, in particular is increasing storage at a high average rate of 284 mm/year over 2003 2021. This is followed by Benin at 69 mm/year with the slowest recharge rate occurring in Burkina Faso at 23.7 mm/year (Fig. 15b).

For Ghana, Togo and Mali, average green ET across the four landscape types is similar to the subbasins whereby MWU contributes the least followed by PLU, MLU and ULU. Comparing Burkina Faso and Ghana which together make up about 80 % of the Volta Basin, blue ET and green ET across the four types of landcovers highlights differences in landcover and water use between the two main riparian countries (Fig. 16): while MLU makes up the greatest share of both green and blue ET in Burkina Faso, ULU is the major water user in Ghana, only exceeded by MWU for blue ET due to the presence of large dams such as Akosombo, Bui and Kpong dams.

The flows generated within the riparian basin (Table 3) were 17 km$^3$/year from Ghana, 14 km$^3$/year from Burkina Faso, and a total of 2.5 km$^3$/year from Benin, Côte d'Ivoire and Togo and Mali. Basin closure in the part of the countries in the Volta is highest in Ghana at 55 % and lowest in Mali at 39 % while the utilizable flow ranges from 0.6 km$^3$/year in Côte d'Ivoire to 20 km$^3$/year in Ghana.

Focusing on the largest two riparian countries, Burkina Faso has the slightly larger area, making up about 42 % of the basin area while Ghana makes up 41 %. In terms of exploitable water this slight difference is inversed over the study period as Ghana continues to

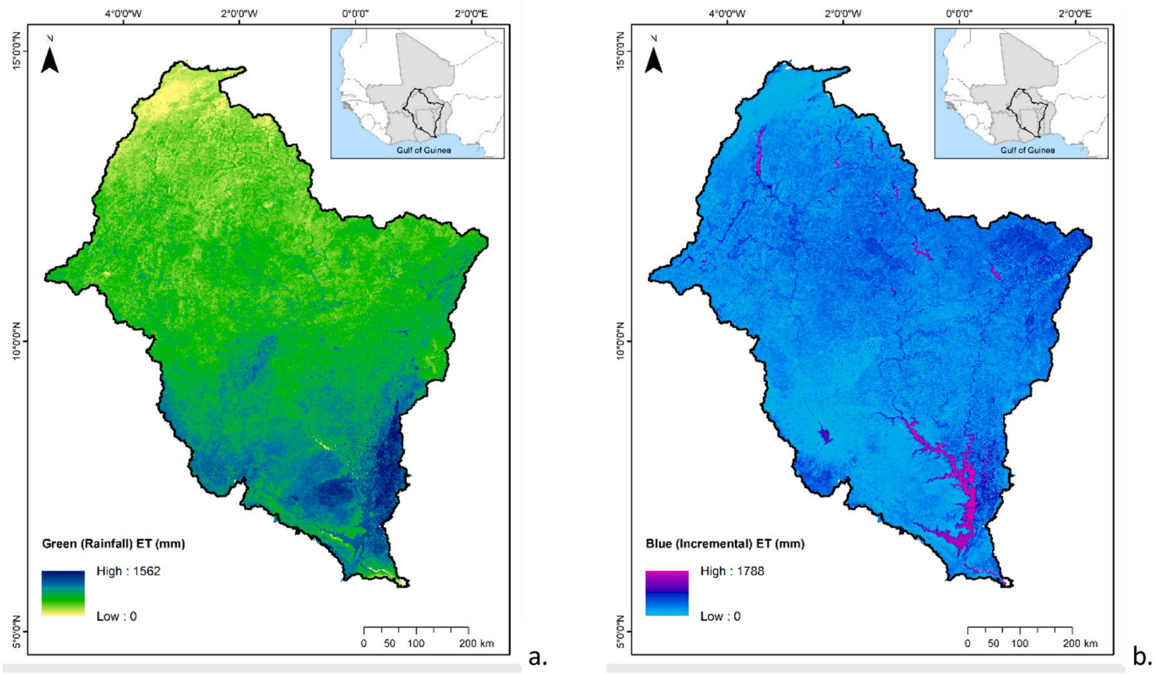



**Fig. 10.** Average green ET (a) and blue ET (b) over Volta basin from 2003 to 2021.

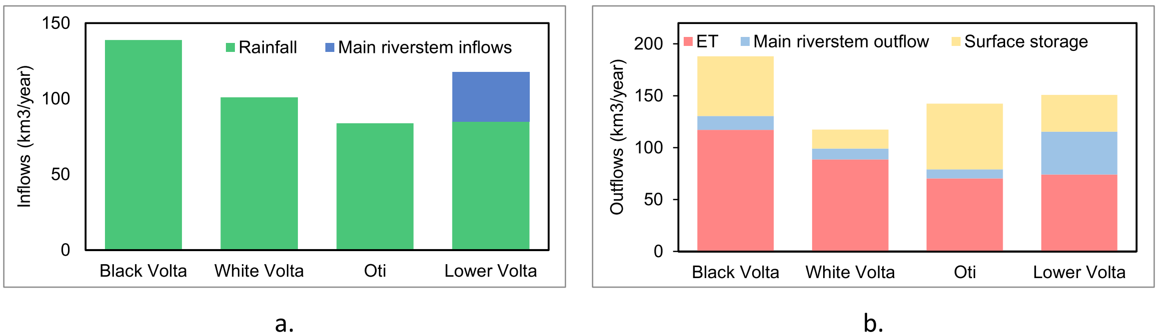



**Fig. 11.** Average inflows (a) and outflows (b) from 2003 f to 2021 for the subbasins (2003 – 2021).

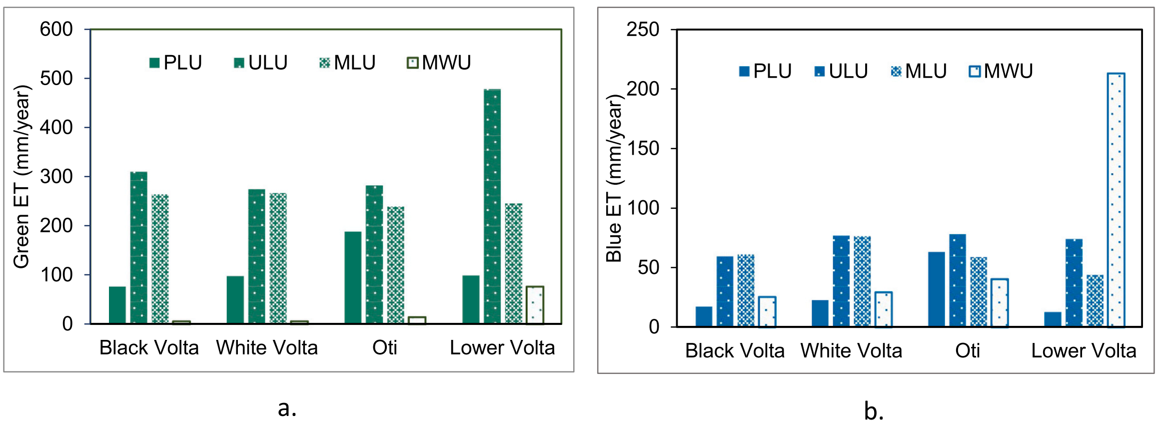



**Fig. 12.** Average green (a) and blue (b) ET across the four main landcover classes in each subbasin (2003 – 2021).

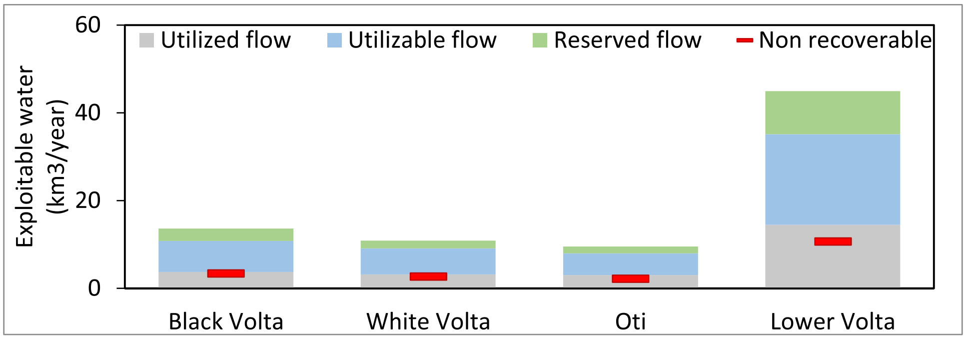



**Fig. 13.** Average exploitable water in the Volta subbasins (2003–2021).

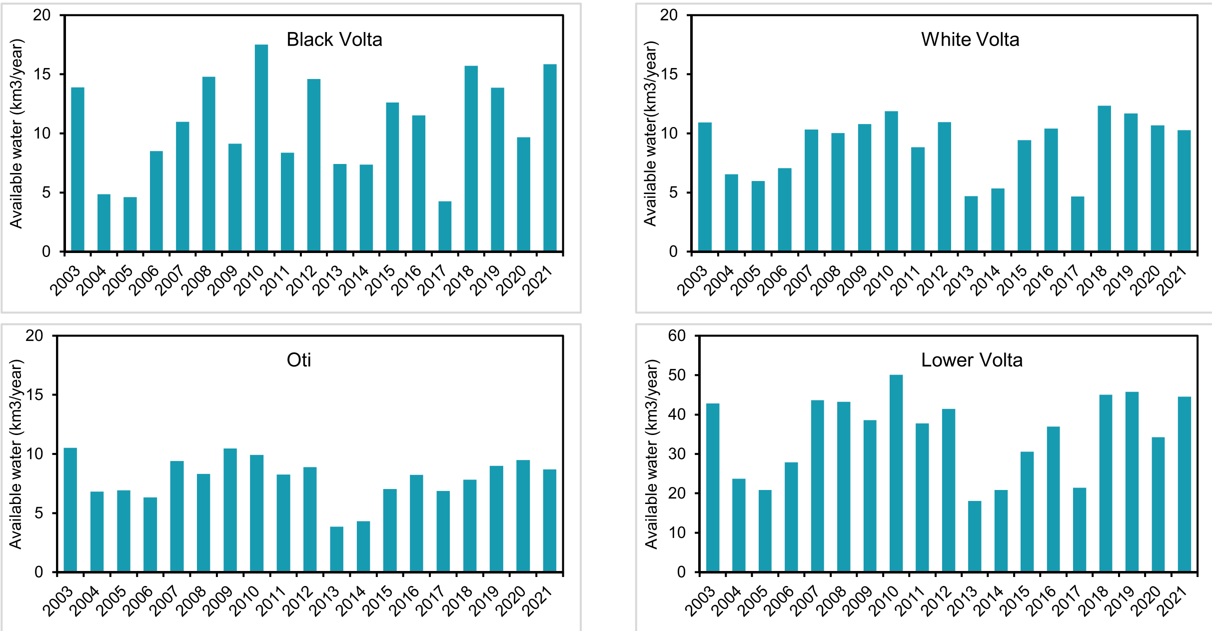
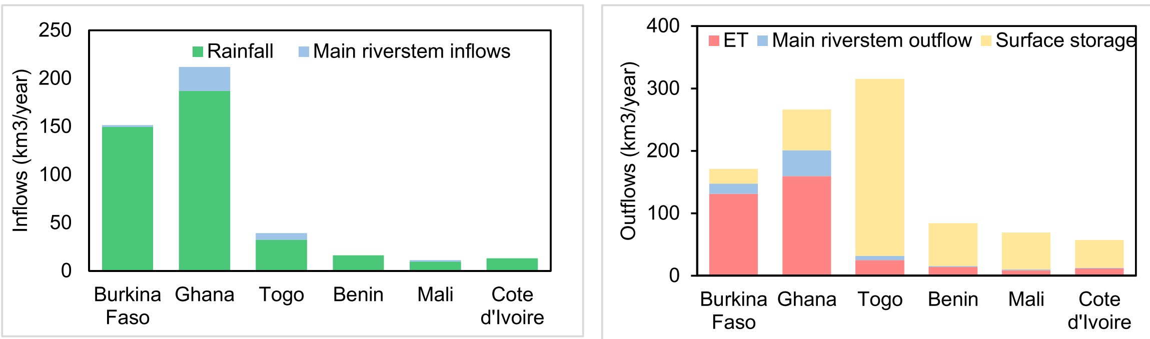



**Fig. 14.** Annual available water in the Volta subbasins from 2003 to 2021.




a. b.

**Fig. 15.** Average inflows (a) and outflows (b) from 2003 f to 2021 for the riparian countries (2003 – 2021).

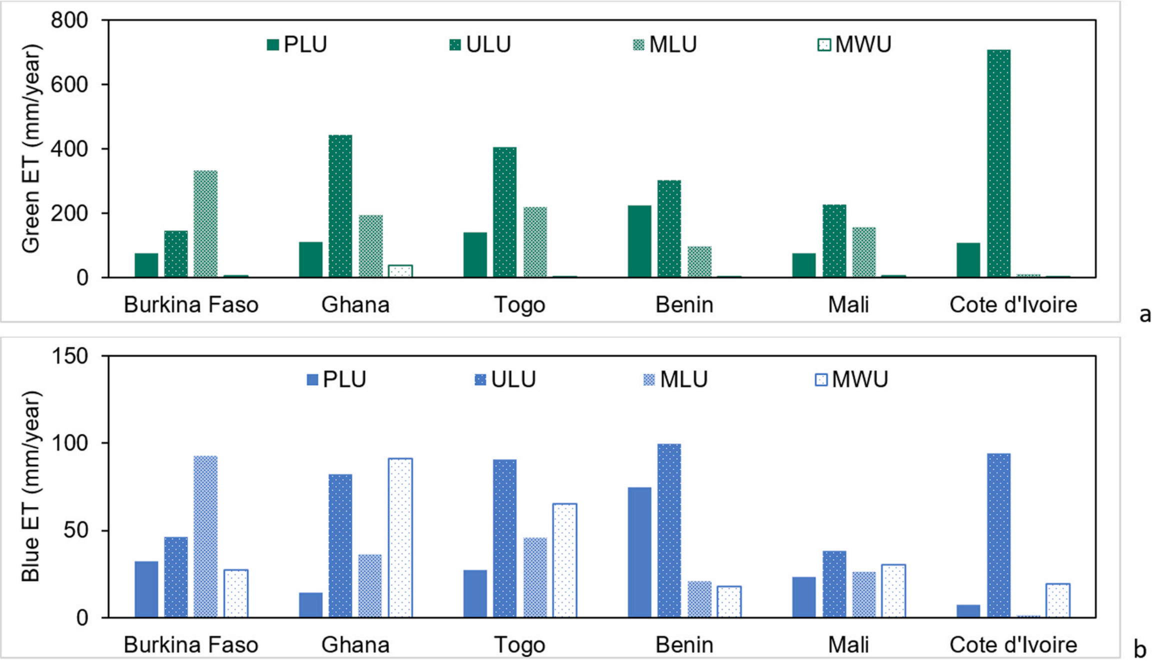



**Fig. 16.** Average green (a) and blue (b) ET across the four main landcover classes in each riparian country (2003 – 2021).

**Table 3**
Internally generated flows for each riparian country.

| Riparian countries | Area in Volta Basin (km$^2$) | Area of Volta (%) | Flows generated internally (km$^3$/year) | Inflows from other countries (km$^3$/year) | Outflows (km$^3$/ year) | Inflows/ Exploitable water (%) |
|---|---|---|---|---|---|---|
| Burkina Faso | 178,000 | 42 | 13.9 | 2.1 | 16.0 | 13 |
| Ghana | 167,692 | 41 | 16.6 | 24.7 | 41.3 | 54 |
| Togo | 26,700 | 6 | 0.2 | 6.6 | 6.8 | 98 |
| Benin | 17,098 | 4 | 1.2 | 0 | 1.2 | 0 |
| Mali | 15,392 | 4 | 0.2 | 1.4 | 1.6 | 81 |
| Côte d'Ivoire | 12,500 | 3 | 1.0 | 0 | 1.0 | 0 |

benefit from the fact that it is the most downstream nation receiving inflows from upstream countries and given its location in the wetter south (Fig. 17). As such, Ghana has the highest exploitable water fraction and total net inflows (24.7 km$^3$/year) with Burkina Faso directly contributing 45 %; Togo, 32 % and Côte d'Ivoire, 23 % (Fig. 17 and Fig. 18). Togo as well, benefits from high inflows (6.6 km$^3$/year) directly from Benin (73 %) and Burkina Faso (27 %) as well as high precipitation in the Oti subbasin and this results in high exploitable water per unit area (252 mm/year) (Fig. 17 and Fig. 18).

## 5. Discussion

This study expands on the hydrological dynamics of the Volta Basin over nearly two decades. It reveals a dynamic interplay between rainfall, evapotranspiration (ET), and outflow, with a notable portion (90 %) of the inflow to the basin consumed as ET. One recurring theme in past research, also highlighted in this study, is the significant role of seasonal rainfall variability in shaping the basin's hydrological regime and consequently water availability (Kabo-Bah et al., 2016; McCartney et al., 2012; Oguntunde et al., 2006). Studies have noted the pronounced wet and dry seasons experienced in the region, whereby about 75 % of annual rainfall falls in four months, between May and August, when the entire basin falls southwards of the ITCZ (McCartney et al., 2012). This seasonality is highlighted in the seasonal water yield of the basin (Fig. 6). However, while flooding is a frequent occurrence in the basin, unless this occurs close to the outlet of the basin, the water is not considered as lost from the basin in WA+ -hence non-utilizable flows, flood waters *lost* from the basin are < 1 %. This is due to the fact that this water can be utilized once it recedes and even in some cases, in the inundated area. For instance, flooding of adjacent riparian land provides important environmental benefits including the replenishment of soil water and deposition of nutrients (Bunn and Arthington, 2002). In northern Ghana, flood recession agriculture thrives off seasonal inundation of land adjacent the rivers (Balana et al., 2019). Nonetheless, improved flood management is needed in the basin to reduce the negative impact of flooding, for instance through improved land management practices and improved drainage infrastructure.

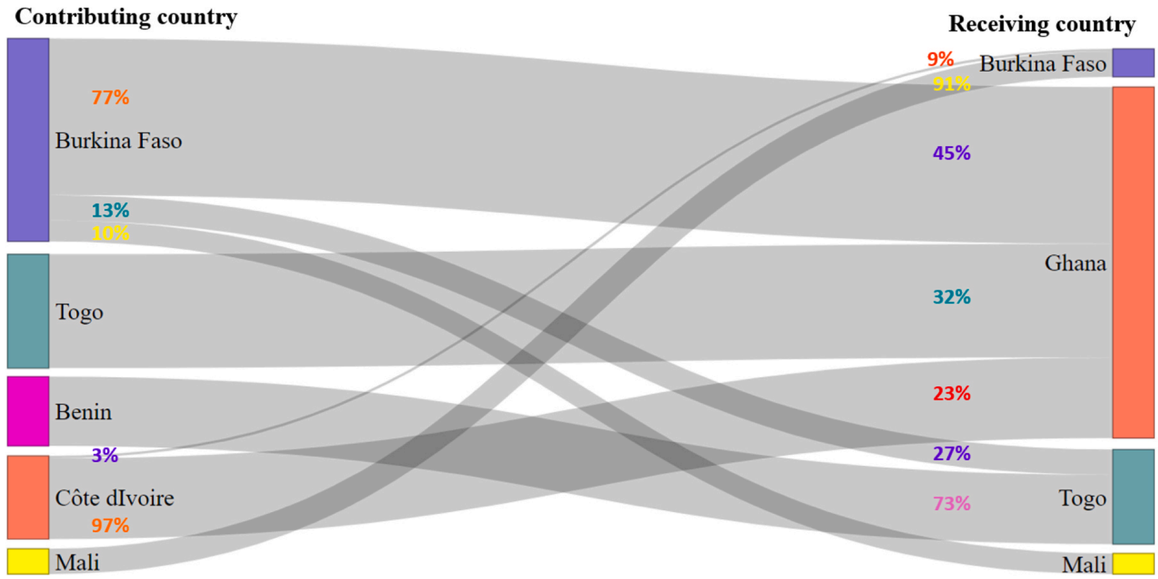



**Fig. 17.** Proportion of inflows and outflows between riparian countries of the Volta Basin. The percentage values next to the names of the Contributing country show the proportion of its outflows going to a given Receiving country. On the other hand, the percentage values next to the names of the Receiving countries show the proportion of its inflows coming from a given Contributing country. Where all inflows or outflows go to one country, the 100 % proportion is not written. On the Contributing country edge, the percentage values are denoted in the colours of the bars representing the Receiving country and vice versa.

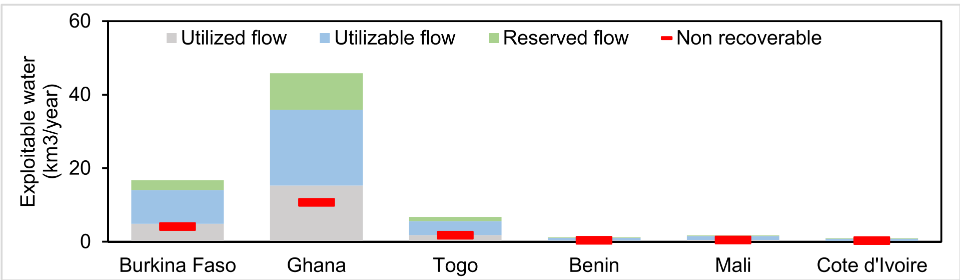



**Fig. 18.** Average exploitable water in the riparian countries of the Volta Basin (2003–2021).

Given that approximately two-thirds of the year is the dry season with only about 25 % of annual rainfall occurring, droughts are a frequent occurrence in the Volta basin. The interannual variability of available water across the subbasins highlights dry hydrological years such as 2017 in the Black Volta and White Volta, and then 2013 in the Oti and Lower Volta (Fig. 14). Gebrechorkos et al. (2022) found that there is a clear propagation signal of about two weeks from meteorological to hydrological drought in the Volta Basin. They also observed divergent trends in the severity and duration of droughts between 1979 and 2013, with a general decreasing trend in the north-eastern part of the basin and vice versa in the southern part of the basin (Gebrechorkos et al., 2022). With respect to future trends, there is uncertainty as predictions vary with the climate model adopted, but studies show that under all Representative Concentration Pathways (RCPs), temperature and potential evaporation rise (Dembélé et al., 2022; Yeboah et al., 2022) Unlike the 1970s and 80 s when the basin experienced prolonged, severe droughts, the period under study, 2003–2021, had relatively shorter dry periods (Eshun and Amoako-Tuffour, 2016). However, even short droughts in the Volta Basin result in diminished water availability, affecting agriculture, hydropower generation, and livelihoods, thereby exacerbating food insecurity and economic hardships in the region (Obahoundje et al., 2017). For instance, in the White Volta sub-basin, rain-fed agriculture is increasingly precarious and less dependable, and it is predicted that mixed cropping patterns will give way to livestock rearing due to droughts (Mohammed et al., 2013; Ngcamu and Chari, 2020). Beyond food security, in 2004–2006 and also 2014–2015 (see Fig. 7 and Fig. 8), drought conditions in the basin led to reduced inflows to the Akosombo Dam resulting in power rationing in Ghana and curtailing exportation of power to Togo and Benin (Eshun and Amoako-Tuffour, 2016).

For riparian countries, the implications of this study on the management of the Volta Basin are significant and multifaceted. It provides several new and valuable insights into the shared water resources of the basin, highlighting the interconnectedness of hydrological processes across national boundaries. In terms of exploitable water resources, the area of Ghana and Togo in the Volta Basin are currently benefiting from their locations in the wetter south of the basin and from inflows from upstream countries. Yet, these inflows are influenced by how much the upstream countries tap into their exploitable and utilizable flows, especially given the relatively high average basin closure rates of 55 % in Ghana and 42 % in Togo compared to other riparian countries (Buskop, 2022). For instance, inflows from upstream countries are equivalent to 54 % and 98 % of exploitable water of Ghana and Togo in the Volta, respectively. Notably, further exploitation of water for consumptive uses in the northern part of the basin would be in line with findings from this study, whereby MLU (such as rainfed agriculture which consume water resources) dominate green and blue water use (Fig. 16). The above underscores the importance of joint research initiatives, and collaborative decision-making frameworks to ensure equitable and efficient water resource allocation (Buskop, 2022; Owusu, 2011). These should explore opportunities for mutual benefit sharing, for instance, by encouraging upstream states to maintain or modify water flows to also benefit other riparian states with guarantees from downstream countries to share benefits such as hydropower with upstream countries (Buskop, 2022). Such cooperation may be guided by Integrated Water Resources Management (IWRM) principles which promote coordinated management of water, land, and resources to maximize economic and social welfare without compromising ecosystem sustainability (Clausen, 2004). Additionally, at the regional level, the African Ministers' Council on Water (AMCOW) provides a continental framework for policy alignment, capacity building, and regional cooperation, reinforcing commitments to equitable and sustainable water management (Anghileri et al., 2024). At the basin level, institutions like the VBA play a crucial role in fostering transboundary water governance, facilitating dialogue, and implementing joint management strategies to ensure water security and benefit-sharing among riparian states (Volta Basin Authority, 2018). The VBA developed the Water Charter for the basin in 2018, but this document, which includes articles on 'The obligation for equitable and reasonable utilisation', 'Target flows to be maintained' and 'Admissible amounts of abstractions in the Basin' is yet to be adopted and ratified by the governments of the riparian countries (Volta Basin Authority, 2018). This present study provides insights that can help to achieve this target of the VBA. The advantage of cooperative management of the shared water resources of the Volta Basin is affirmed by Gonzalez et al. (2021) who, using the planned Pwalugu Dam in Ghana as a case study, found that cooperative regulations yield greater overall advantages compared to pursuing benefits solely for individual dams or nations. As such, future expansion should occur within the limits of available water in the entire basin, making sure that the benefits outweigh the negative impacts between the riparian countries.

On future water allocation, it is evident that while there may be some scope for increased utilization (approximately 20 $km^3$/year), seasonal variations and the influence of factors like pollution must be carefully weighed. A key consideration is also the socio-economic impacts of future water allocations and associated land use changes on inhabitants and riparian countries with respect to hydropower production (Buskop, 2022; Owusu et al., 2023), agriculture (Abungba et al., 2022; Awotwi et al., 2015; Ocloo, 2023), fisheries and livelihood (Baah-Boateng et al., 2017; Ntiamoa-Baidu et al., 2017). This is particularly evident in cases like dam building, where the benefits of hydropower production generally cause a shift in benefits from local riparian communities to urban and industrial centres, often exacerbating rural livelihood challenges (Owusu et al., 2022; Tsikata, 2008). Past studies have also examined the impact of land use changes and shown that between 1985 and 2020, there was an increase in croplands, built-up areas, and open forests, whereas shrublands, grasslands, and closed forests experienced a decline (Abungba et al., 2022; Awotwi et al., 2015; Ocloo, 2023). These changes alter soil moisture levels, runoff patterns, and sediment transport, affecting water quality and ecosystem health downstream. The high levels of non-recoverable water in this study (approximately 25 % of exploitable flows) are attributed to agricultural pollution, yet concerns remain regarding industrial pollution, notably from sectors such as illegal mining especially in the Black Volta subbasin in Ghana (Bowan and Tingan, 2021; Tahiru et al., 2020). Implementing wastewater treatment and reuse strategies can reclaim portions of these non-recoverable flows for various applications thereby increasing water availability (Tortajada, 2020).

Remote sensing products are essential for monitoring hydrological processes but face limitations in regions with scarce ground-based validation data such as Africa. With only one rain gauge per 26,000 $km^2$ (Awange et al., 2016; Mekonnen et al., 2023) and just six eddy covariance sites across the continent (Weerasinghe et al., 2020), reliable validation remains a challenge. Dembélé and Zwart (2016) highlight that while some studies have assessed remote sensing precipitation in African countries, West Africa remains largely unexamined. Poméon et al. (2017) further emphasize the uncertainty in remote sensing performance in the region due to the decline of rain gauge stations and the reliance on freely available in situ data, which may have already been used in product bias correction. Globally, evapotranspiration (ET) monitoring faces similar challenges, with limited in situ stations unable to provide sufficient spatial and temporal coverage (Nkiaka et al., 2022). While remote sensing ET products effectively capture ET seasonal dynamics in West Africa, significant discrepancies in monthly estimates arise due to differences in model structure, parameters, and input data uncertainties (Adeyeri and Ishola, 2021; Weerasinghe et al., 2020). These variations, consistently observed across studies, suggest that differences between models are unavoidable. Such limitations in ground validation and model consistency pose challenges for studies relying on remote sensing data, potentially affecting the accuracy of hydrological assessments, water accounting, climate modelling, and water resource management in the region.

## 6. Conclusions

The Volta River Basin, shared by six West African countries, faces significant challenges due to variable rainfall, evapotranspiration, and diverse socio-economic pressures. This study presents a comprehensive multi-scale water accounting analysis of the Volta Basin from 2003 to 2021, evaluating water inflows, outflows, and usage across the basin, sub-basins, and individual riparian countries. Approximately 90 % of total inflows are lost to evapotranspiration, with notable seasonal and spatial variations in water yield. Although the basin is 55 % closed, further water allocation is feasible, as the average utilizable outflow is 20 $km^3$ /year. Furthermore, about 25 % of exploitable water is non-recoverable (wastewater) and as such, improved farming practices and wastewater treatment could make this water available. Sub-basin analysis indicates rainfall ranging from 940 to 1250 mm/year and groundwater recharge rates between 18 and 64 mm/year, with southern sub-basins receiving more rainfall and having higher recharge rates.

The WA+ analysis at riparian country level quantifies water distribution and movement between the six riparian countries thereby providing key insights for promoting transparent management practices. Ghana and Togo derive advantages from their positioning in the more humid and downstream southern region of the basin. As it stands, modified land uses like rainfed agriculture consume the most blue and green water in the north of the basin compared to the south where utilised land use and managed water use dominate. Should modified land uses expand, this will reduce inflows and hence the exploitable water downstream.

The findings from this multiscale WA+ assessment point to a growing need for formal cooperation and benefit sharing in basin management in the Volta as well as the ratification of the Volta Basin Authority's Water Charter which was developed in 2018. Changes in water availability have significant socioeconomic implications for water-dependent sectors in the basin such as hydropower, agriculture, industry, and urban water supply. Improved water governance through equitable allocation, improved irrigation efficiency, and wastewater treatment will therefore be key. Strengthening transboundary cooperation primarily through the VBA can support sustainable water management, mitigate conflicts, and enhance climate resilience. By providing a transparent, data-driven assessment of water distribution and usage across the Volta Basin, this study supports conflict resolution and transboundary water governance by fostering a shared understanding of water availability among riparian countries. The WA+ framework offers a neutral basis for negotiations, helping to address disputes over water allocation and promote equitable benefit-sharing agreements. Future research should explore policy pathways for effective water-sharing and adaptation strategies.

## CRediT authorship contribution statement

**Tinonetsana Primrose:** Writing – review & editing. **Tayebi Noosha:** Writing – review & editing, Funding acquisition. **Escalera-Rodriguez Ana Cecilia:** Writing – review & editing, Funding acquisition. **Fofana Rafatou:** Writing – review & editing, Validation. **Velpuri Naga Manohar:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Owusu Afua:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Akpoti Komlavi:** Writing – review & editing, Validation, Investigation, Formal analysis. **Leh Mansoor:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Perera Tharindu:** Formal analysis, Data curation. **Madushanka Lahiru:** Software, Data curation. **Mekonnen Kirubel:** Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102377.

## Data availability

The remote sensing data used in this study is available through the references cited in the manuscript.

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