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Research papers

Water accounting under climate change in the transboundary Volta River Basin with a spatially calibrated hydrological model

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ABSTRACT

Sustainable water management requires evidence-based information on the current and future states of water resources. This study presents a comprehensive modelling framework that integrates the fully distributed mesoscale Hydrologic Model (mHM) and climate change scenarios with the Water Accounting Plus (WA+) tool to anticipate future water resource challenges and provide mitigation measures in the transboundary Volta River basin (VRB) in West Africa. The mHM model is forced with a large ensemble of climate change projection data from CORDEX-Africa. Outputs from mHM are used as inputs to the WA+ framework to report on water flows and consumption over the historical baseline period 1991–2020 and the near-term future 2021–2050 at the basin scale, and also across spatial domains including four climatic zones, four sub-basins and six riparian countries.

The long-term multi-model ensemble mean of the net inflow to the basin is found to be 419 km^3/year with an inter-annual variability of 11% and is projected to slightly increase in the near-term future (2021–2050). However, evaporation consumes most of the net inflow, with only 8% remaining as runoff. About 4 km^3/year of water is currently used for man-made activities. Only 45% of the available water is beneficially consumed, with the agricultural sector representing 34% of the beneficial water consumption. Water availability is projected to increase in the future due to the increase in rainfall, along with higher inter-model and inter-annual variabilities, thereby highlighting the need for adaptation strategies. These findings and the proposed climate-resilient land and water management strategies can help optimize the water-energy-food-ecosystem nexus and support evidence-based decisions and policy-making for sustainable water management in the VRB.

1. Introduction

Climate change and socioeconomic development are projected to exacerbate water scarcity, contributing to food insecurity and conflicts between those who share resources (Damania, 2020; Leal Filho et al., 2022; Mekonnen and Hoekstra, 2016). Consequently, there is a pressing need for planners, policymakers, implementers, and basin authorities to have quantified data and evidence-based information on the current and projected states of water resources and their users. This is more urging in transboundary basins, where transparent management and equitable allocation of natural resources are essential for geopolitical stability (De Stefano et al., 2017; Mirzaei-Nodoushan et al., 2022; Zeitoun et al., 2016). Nevertheless, data unavailability and inaccessibility hinder sustainable water management and planning of interventions in many regions (Dinku, 2019; Sultan et al., 2020). Moreover, there are challenges in translating hydrology research into practice because methods usually need more clarity, and outputs are difficult to interpret (Rokaya and Pietroniro, 2022). It has become apparent that water information systems require adequate tools for measuring, planning, reporting and monitoring water resources across scales to optimize water uses and develop responsive, proactive and robust strategies for adaptation and mitigation of water risks (Adekola et al., 2022; Uhlenbrook et al., 2022).

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In this context, decision-making tools like water accounting systems can make a difference.

Water accounting is the systematic assessment and presentation of information on the status and trends in water supply, water demand, accessibility and use in time and space within specified regions and with particular standards and clear definitions accessible to various water professionals (Batchelor et al., 2016; Van Dijk et al., 2014). Water accounting serves as a basis for evidence-informed decision-making and is relevant for policy development and water resource planning (Bassi et al., 2020; Mohammad-Azari et al., 2021; Momblanch et al., 2014; Pedro-Monzonís et al., 2016b). Therefore, water accounting can enhance the water-energy-food-ecosystem nexus thus moving towards the sustainable development goals (SDGs), SDG6 in particular, as it highlights connections, synergies and trade-offs among activity sectors (Elmahdi, 2020; Liu et al., 2018; Nkiaka et al., 2021). Several water accounting systems exist (see Dembélé (2020)) but none have been adopted as a general standard (Chalmers et al., 2012; Dost et al., 2013; Momblanch et al., 2018). Reasons for this failure include the facts that their terminologies are ambiguous and their outputs are usually too complex for decision making (Perry, 2007; 2011), their input data are often not readily available (Bagstad et al., 2013; Perry, 2012), and they do not explicitly link land and water management practices and usually lack spatial details (Karimi, 2014; Muratoglu et al., 2022).

More recently, the Water Accounting Plus (WA+) framework was developed to address the shortcomings of previous water accounting systems (Karimi et al., 2013a). WA+ provides estimates of manageable and unmanageable water flows, stocks, consumption by different users, and explicitly accounts for interactions with land use. The core of the WA+ methodology is based on a water balance calculation using a spatial analysis of water fluxes and stocks obtained via remote sensing. Compared to other water accounting frameworks, WA+ is particularly valuable for water resource reporting in data-scarce regions and ungauged locations because it primarily relies on open-access remotely sensed data. WA+ based on satellite data is rather suitable for the scale of large river basins (larger than a few 1000 km^2) and regional studies due to the usually coarse spatial resolution of satellite data. Moreover, WA+ is convenient for independent assessments of water resources in transboundary basins where data accessibility and data exchange are limited (Dembélé et al., 2019; Mukuyu et al., 2020). However, challenges in closing the water balance were observed when solely deploying satellite data with the WA+ framework (e.g. FAO and IHE Delft, 2020a; b; c; Hirwa et al., 2022).

To address this drawback, this study proposes a comprehensive framework that uses the outputs of a spatially distributed hydrological model as inputs to the WA+ framework. Major advantages include the closure of the water balance via hydrological simulations, identification of the sources of uncertainties in the components of the water cycle as opposed to using various sources of satellite data, and development of scenarios to assess changes in the water cycle as a result of planned interventions, land use change, climate change, etc. In addition, spatially explicit hydrological modelling offers new possibilities to apply WA+ to future periods and provide projections of water accounts (i.e. water balance components) under changing environments (Dembélé, 2020), i.e. it represents an essential step towards the predictive use of water accounting frameworks.

This study aims to propose a comprehensive framework that integrates remotely sensed data, a spatially calibrated hydrological model, climate change scenarios and the WA+ tool for water accounting of past trends as well as future predictions. The developed framework is implemented at a large scale in the transboundary Volta River Basin and water accounts are summarized at three spatial scales including sub-basins, riparian countries and climatic zones. Consequently, the proposed novel WA+ modelling framework brings advances as compared to previous studies. These advances all combined in this study include (i) the use of a spatially-calibrated fully distributed (i.e. grid-based) hydrological model as opposed to lumped or semi-distributed models (e.g. Delavar et al., 2020; Delavar et al., 2022; Esen and Hein, 2020; Gao et al., 2020), (ii) the use of a large ensemble of climate change projection data to assess future conditions as opposed to only historical period analyses (e.g. Kivi et al., 2022; Kumar et al., 2023; Patle et al., 2023; Singh et al., 2022a; Singh et al., 2022c), (iii) a case study in a large transboundary basin with a multi-scale analysis across sub-basins, climatic zones and riparian countries to provide detailed insight that support transboundary water management as opposed to small or in-country basins (e.g. Hunink et al., 2019; Momblanch et al., 2014; Singh et al., 2022c), and (iv) the use of the novel WA+ framework instead of previous frameworks (e.g. Pedro-Monzonís et al., 2016a; Vicente et al., 2016; Vicente et al., 2018).

2. Study area

The Volta River Basin (VRB) is a transboundary basin covering about 415605 km^2 spread across six countries in West Africa, i.e. Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali and Togo (Fig. 1). Burkina Faso and Ghana alone share about 82.5% of the basin's total area (Dembélé, 2020). The VRB extends over four eco-climatic zones characterized by increasing vegetation density and precipitation from north to south, namely the Sahelian, Sudano-Sahelian, Sudanian, and Guinean zones. The drainage system comprises four sub-basins known as the Black Volta, White Volta, Oti and Lower Volta. The Volta River flows north–south over 1850 km and drains into the Atlantic Ocean at the Gulf of Guinea after transiting into the Lake Volta formed by the Akosombo dam (Fig. 1). The population of the VRB is essentially rural (70% of the basin's total population), and its annual growth rate is 2.5%, which means the population will double every 28 years (Rodgers et al., 2006). In 2010, 23.8 million people lived in the VRB and the population is projected to reach 56.1 million in 2050 (Williams et al., 2016). Water resources in the VRB play an essential role in socio-economic development, especially for agriculture, hydropower production, aquaculture, livestock and domestic water supply (McCartney et al., 2012). They provide livelihood for the rural populations primarily active in the agricultural sector (Amisigo et al., 2015; van de Giesen et al., 2001).

Water demand in the VRB is projected to increase considerably by 2050 (Kotir et al., 2016; Mensah et al., 2022; Mul et al., 2015), thereby posing challenges for transboundary water resource management. First, VRB rainfall is erratic and has high spatiotemporal and inter-annual variabilities, which is expected to be exacerbated under climate change (Nicholson et al., 2018). Secondly, countries in the VRB have different national priorities in terms of water use. The upstream consumptive use of water in Burkina Faso is essentially dominated by agriculture. As Burkina Faso occupies the driest part of the VRB, its priority is the construction of small and medium reservoirs to develop irrigated agriculture (De Fraiture et al., 2014; Owusu et al., 2022). Meanwhile, the downstream priority in Ghana is the production of hydroelectricity from large dams (Darko et al., 2019; Han and Webber, 2020). Despite progress in water governance, the divergent priorities regarding water consumption and management remain sources of tension between both states (Biney, 2010; Owusu, 2012; Yankey, 2019). However, no major explicit conflict has occurred between the two countries, suggesting a certain degree of cooperation demonstrated by the establishment of the Volta Basin Authority and the 2007 riparian state convention (Matthews, 2013). In this context, an independent and unbiased assessment of the spatiotemporal availability of water and various uses could provide a basis for decision-making and potentially alleviate future tensions, in addition to game-theory-developed strategies with issue linkage to support sustainable transboundary water sharing in the VRB (Bhaduri et al., 2011; Bhaduri and Liebe, 2013).

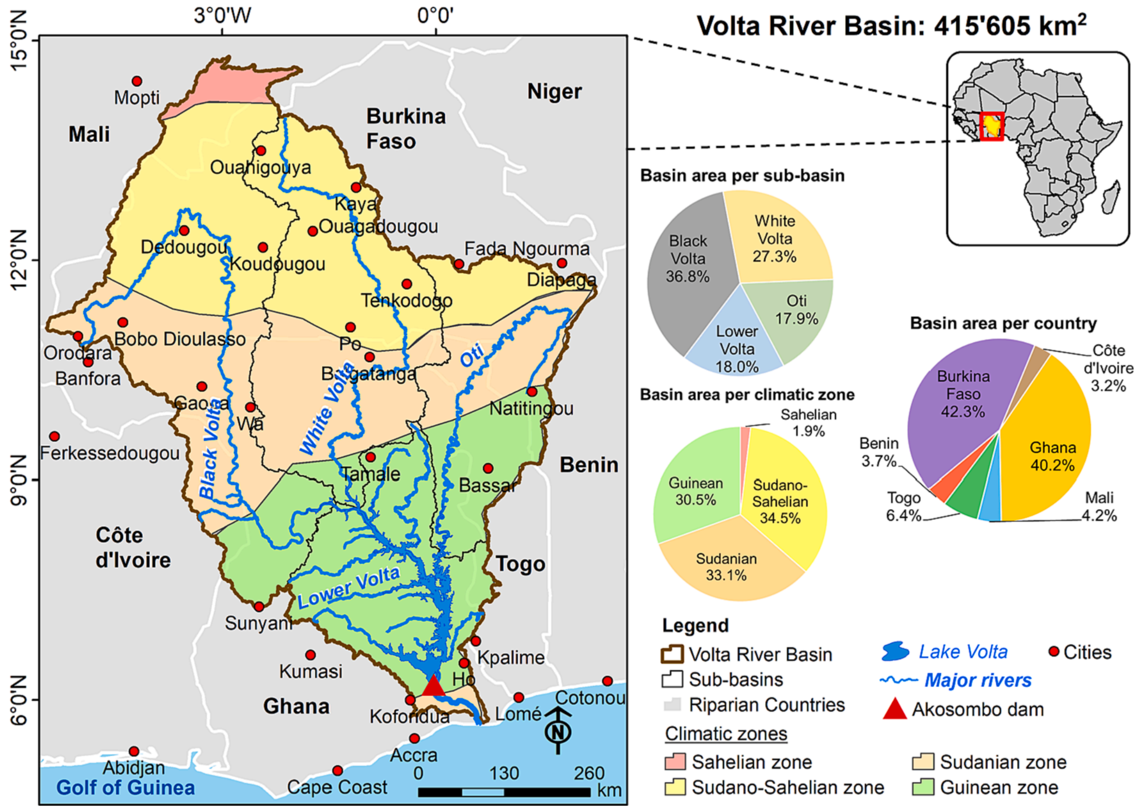

Fig. 1. Volta River Basin in West Africa.

3. Data and methods

3.1. Overview of the modelling framework

The proposed methodological framework for water account projections is summarized in Fig. 2. Climate projection data from global and regional models forces a fully distributed and spatially calibrated hydrological model after a multivariate bias correction of the climatic inputs (rainfall and temperature). The entire climate change impact modelling chain is described by Dembélé et al. (2022). To ensure a reliable spatial and temporal representation of hydrological processes, the hydrological model is calibrated with multiple variables including in-situ streamflow and satellite remotely sensed soil moisture, actual evaporation, and water storage anomaly, as presented by Dembélé et al.

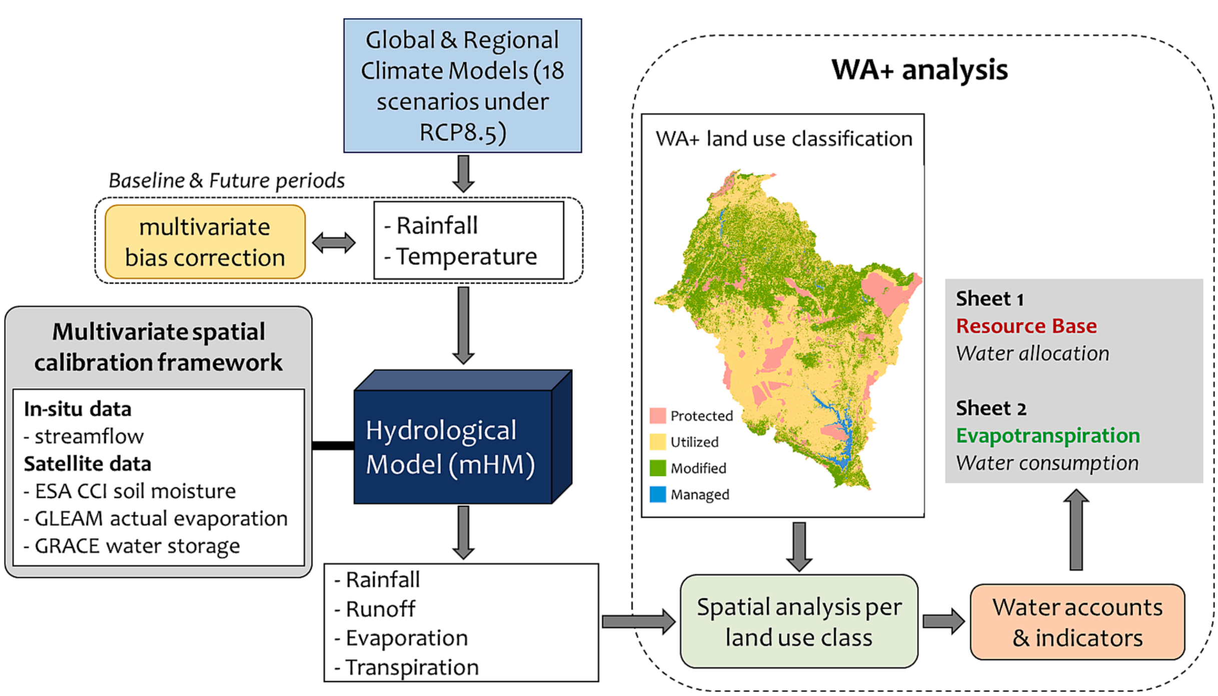

Fig. 2. Methodological framework for water accounts assessment under climate change.

(2020b). The outputs of the hydrological model simulated over past (1991–2020) and one future period (2021–2050) are fed into the WA+ framework for spatial analysis based on land use and land cover types. The near future was selected because it is deemed more realistic and useful for water management compared with a time further in the future when assumptions underlying the WA+ framework will have evolved. Future land use and land cover scenarios are not integrated in this study because they lie outside the scope of the impacts of climate change on water resources. Results of this study can however help identify future land use practices which would be adaptations to water scarcity and improve water security (Cook and Bakker, 2012; Steduto et al., 2012).

Variations in the hydrological model inputs and outputs are assessed with the second-order coefficient of variation (V_2) (Kvålseth, 2017), defined as follows:

$$V_2 = \left(\frac{s^2}{s^2 + \overline{x}^2}\right)^{1/2} \quad (1)$$

where s is the standard deviation and $\overline{x}$ is the mean of x. V_2 varies between 0% and 100%.

3.2. Climate projection data

An ensemble of eleven general circulation models (GCMs) and four regional climate models (RCMs) are selected from the Coordinated Regional Climate Downscaling Experiment (CORDEX) for Africa (Giorgi et al., 2009). This gives 18 possible RCM-GCM combinations under the representative concentration pathway RCP8.5 (Table 1), which corresponds to a high greenhouse gas emission scenario with rising radiative forcing pathway leading to 8.5 W m^{-2} (~1370 ppm CO_2 equivalent) by 2100 (Van Vuuren et al., 2011). Only RCP8.5 is used because it was found to align more with historical and anticipated total cumulative greenhouse gas emissions to 2050 than other RCPs, so it is the most useful RCP for informing societal decisions over short time horizons including mid-century and sooner (Schwalm et al., 2020a,b). In addition, significant changes to hydrological variables were mainly observed under RCP8.5 over the period 2021–2050 in the VRB (Dembélé et al., 2022).

The Rank Resampling for Distributions and Dependences (R2D2) method (Vrac and Thao, 2020) is used for a multivariate bias correction of the climate projection datasets, which are subsequently evaluated with the best-performing satellite and reanalysis rainfall and temperature products in the VRB (Dembélé et al., 2020c).

3.3. Spatially explicit hydrological model

The fully distributed mesoscale Hydrologic Model (mHM) (Samaniego et al., 2010) is used to simulate the hydrological variables required for WA+. The model configuration is adopted from Dembélé et al. (2020b). In this study, the term evaporation represents all forms of evaporation (from canopy, soil and water bodies) including transpiration (Coenders-Gerrits et al., 2020; Shuttleworth, 1993). The full description of mHM and the calculation of the hydrological processes are given by (Kumar, 2010) and Telteu et al. (2021).

Despite their limitations, earth observation data are still valuable for water resource monitoring and can improve hydrological model simulations if appropriately used (Dembélé et al., 2020a; Gleason and Durand, 2020; Papa et al., 2022). For this study, a multivariate spatial calibration scheme is used to provide a reliable representation of the water balance and the spatial patterns of hydrological fluxes and state variables in mHM. Satellite remote sensing datasets of actual evaporation from the Global Land Evaporation Amsterdam Model (GLEAM), soil moisture from the European Space Agency Climate Change Initiative (ESA CCI), terrestrial water storage anomaly from the Gravity Recovery and Climate Experiment (GRACE), and in-situ streamflow data are simultaneously used to calibrate mHM. The mHM model is chosen because it is an open source and grid-based model, which make it suitable for the WA+ analysis, and it showed good performance in the VRB, with Kling Gupta Efficiency (KGE) scores varying between 0.35 and 0.80 (average KGE = 0.59) for eleven streamflow stations. Details on the multivariate spatial calibration and the good model performance across scales are available from Dembélé et al. (2020b), see Fig. 2 and Fig. 8 therein.

Although land use and land cover (LULC) scenarios are not used in this study, the temporal dynamic of LULC is considered by using different land cover maps over the study period. Based on the availability of high resolution LULC data from the European Space Agency Climate Change Initiative (ESA CCI, 2017), LULC data of 2005 and 2015 are used for the historical period (1991–2020) and for the future period (2021–2050), respectively. The ESACCI-LC-L4-LCCS v2.0.7 data of LULC with a high spatial resolution of 300 m is resampled to 1/512° using the nearest neighbour method, thereby resulting in 8,834,858 grid cells in the VRB. This resampling is necessary for mHM, as the spatial resolution of the morphological data should be a submultiple of the hydrological simulation resolution. The mHM model is run at a daily time step with a spatial discretization of 0.03125° (~3.5 km), which corresponds to 34,547 active grid cells in the VRB and was chosen because of restrictions in computational resources. However, it can be considered as a high-resolution modelling in view of the large basin size. The sub-grid variability of the basin physical characteristics (topography, soil texture, geology and land cover properties) is accounted for with a multiscale parameter regionalization technique (Samaniego et al., 2017), which is a critical strength in spatial accounting of ecosystem services (Nedkov et al., 2022). The bias-adjusted climate variables (rainfall and temperature) are used to force the mHM model and the outputs (runoff, potential evaporation, actual evaporation, transpiration, interception, soil evaporation, water evaporation) generated over the historical period (1991–2020) and the near-term future (2021–2050) are subsequently used for the WA+ analyses.

3.4. Water accounting plus (WA+)

WA+ is a standardized reporting framework that summarizes and presents water conditions and management practices in river basins (Karimi et al., 2013a). It was developed based on the water accounting framework of the International Water Management Institute (Molden, 1997; Molden and Sakthivadivel, 1999). Beyond the quantification of water volumes, WA+ explicitly considers land use interactions with the water cycle, and assesses depletions rather than withdrawals. In the following, the term total evaporation is used in replacement of the debated "evapotranspiration" term (Miralles et al., 2020; Savenije, 2004), which is however used in the terminology of WA +. To avoid changing the WA+ terminology, the abbreviation "ET" is conserved but is defined as total evaporation in this study. WA+ results are presented in volume of water and the water accounts are reported on an annual basis as WA+ is meant for long-term planning (Bastiaanssen et al., 2015; FAO and IHE Delft, 2020b). Therefore, daily outputs of mHM are aggregated into annual values for WA+ analyses. More information and updates on WA+ can be accessed at https://wateraccounting.un-ihe.org (last accessed on 17 October 2022).

Table 1
Selected GCMs and RCMs from CORDEX-Africa under RCP8.5.

RCMs	GCMs
CCLM4-8-17	CNRM-CM5, HadGEM2-ES, MPI-ESM-LR
RACMO22T	EC-EARTH
RCA4	CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, EC-EARTH, IPSL-CM5A-MR, MIROC5, HadGEM2-ES, MPI-ESM-LR, NorESM1-M, GFDL-ESM2M
REMO2009	IPSL-CM5A-LR, MIROC5, HadGEM2-ES, MPI-ESM-LR

3.5. Land use and land cover in WA+

Land use and land cover (LULC) is an essential input in WA+ because it determines whether the water is manageable or non-manageable. Four categories are used to group land use and land cover classes and they differ in terms of water management (Karimi et al., 2013a), see a description in Table S1 (supplementary material) and a summary in Table 2.

For conciseness, the ESA CCI maps are first reclassified from the original 22 LULC classes into the 10 major LULC classes in the VRB, namely, water bodies, bare areas, urban areas, rainfed croplands, irrigated croplands, grassland, shrubland, evergreen forest, deciduous forest and wetlands (Table S2). Based on ESA CCI data availability, the LULC map of 2005 is used for analysis over the historical period (1991–2020) and the map of 2015 is used for the future period (2021–2050), which helps add dynamics in LULC over the modelling periods. Table 2 provides the proportions of LULC classes in the VRB. The final LULC maps for WA+ are obtained by overlapping and intersecting the basic LULC maps from ESA CCI with other spatial data on various land status and uses. The maps of the World Database on Protected Areas (WDPA, 2016) and the Global Reservoir and Dam Database (GRanD; Lehner et al., 2011; Mulligan et al., 2020) are used to reclassify the primary LULC data and distinguish between protected versus non-protected lands and identify managed water bodies. The final LULC maps for WA+ (Fig. 3), with a spatial resolution of 1/512°, have additional information about the protection, utilization and management status of each LULC types.

3.6. WA+ sheets and performance indicators

3.6.1. Overview

WA+ differentiates between exploitable, utilized, managed and consumed water flows and stocks among many other components of the water cycle. Table 3 gives a definition of key WA+ terms and the estimation of water accounts (i.e. water balance components). WA+ is still under development with currently eight standardized accounting forms that are called "sheets" to describe water conditions (Bastiaanssen et al., 2015). Each sheet has a set of indicators that are used to summarize the overall water resources situation. However, this study focuses on the two most important sheets (i.e. sheet 1: the resource base sheet and sheet 2: the consumption or ET sheet) because the other sheets require information that are not available for future predictions (e.g. biomass production, agriculture, etc.). Examples of analyses with other sheets can be found in the literature (e.g. FAO and IHE Delft, 2019; Kivi et al., 2022; Salvadore et al., 2020).

3.6.2. Evaporation partitioning from green and blue water sources

A specific feature of WA+ is the explicit consideration of green water sources (precipitation, unsaturated soil water available to plants) and blue water sources (runoff and deep drainage recharging aquifers and supplying reservoirs, lakes and streams) (Falkenmark and Rockström, 2006; Velpuri and Senay, 2017). Thus, WA+ separates total actual evaporation (E_{act}) into green ET (E_{green}) or rainfall ET and blue ET (E_{blue}) or incremental ET, which helps identify managed water flows and is achieved here using the Budyko approach (Msigwa et al., 2021; Singh et al., 2022a).

Mikhail Budyko developed a supply–demand framework to describe the hydrology of a catchment assuming steady state conditions over large spatial and temporal scales considering long-term water balance and energy balance (Donohue et al., 2011; Sposito, 2017). The long-term annual water balance can be defined as:

$$\frac{\Delta S}{\Delta t} = P - E_{act} - Q \tag{2}$$

where P, E_{act} and Q are long-term annual averages of precipitation, actual evaporation and runoff, respectively. $\Delta S/\Delta t$ is the change in water stored in the soil and groundwater and is considered negligible under a steady state.

The Budyko framework (Budyko, 1974) relates the ratio of long-term mean annual potential evaporation (E_{pot}) to precipitation (climatic dryness or aridity index) and the ratio of long-term mean actual evaporation to precipitation (evaporative index), resulting in a curvilinear function known as the Budyko curve described by the following equation (Donohue et al., 2010; McVicar et al., 2012; Simons et al., 2020):

$$\varepsilon = \left[\phi \tanh\left(\phi^{-1}\right)\left(1 - \exp(-\phi)\right)\right]^{1/2}, \ with \tag{3}$$

$$\varepsilon = \frac{E_{green}}{P} \tag{4}$$

and

Table 2
Proportions of land use and land cover classes in the Volta River Basin per WA+ LULC classes.

WA+ classes	LULC	1991–2020 Area (km^2)	Area (%)		2021–2050 Area (km^2)	Area (%)	
Protected Land Use (PLU)	Water Bodies	16.3	0.004	10.73	27.8	0.007	10.68
	Bare areas	0.8	0.0002		1.7	0.0004	
	Grasslands	6720.2	1.62		6884.6	1.66	
	Shrublands	17932.8	4.31		17431.9	4.19	
	Evergreen forest	488.1	0.12		487.4	0.12	
	Deciduous forest	19313.3	4.65		19460.3	4.68	
	Wetlands	141.5	0.03		82.6	0.02	
Utilized Land Use (ULU)	Water Bodies	1004.1	0.24	53.76	1017.1	0.24	53.36
	Bare areas	56.5	0.01		59.4	0.01	
	Grasslands	89142.4	21.45		90762.0	21.84	
	Shrublands	57705.3	13.88		52919.5	12.73	
	Evergreen forest	951.8	0.23		1009.2	0.24	
	Deciduous forest	74366.5	17.89		75802.0	18.24	
	Wetlands	196.4	0.05		194.2	0.05	
Modified Land Use (MLU)	Rainfed croplands	139283.0	33.51	33.51	140582.3	33.83	33.83
Managed Water Use (MWU)	Water Bodies	6185.3	1.49	1.99	6465.3	1.56	2.14
	Urban areas	407.5	0.10		720.9	0.17	
	Irrigated croplands	1693.5	0.41		1696.9	0.41	

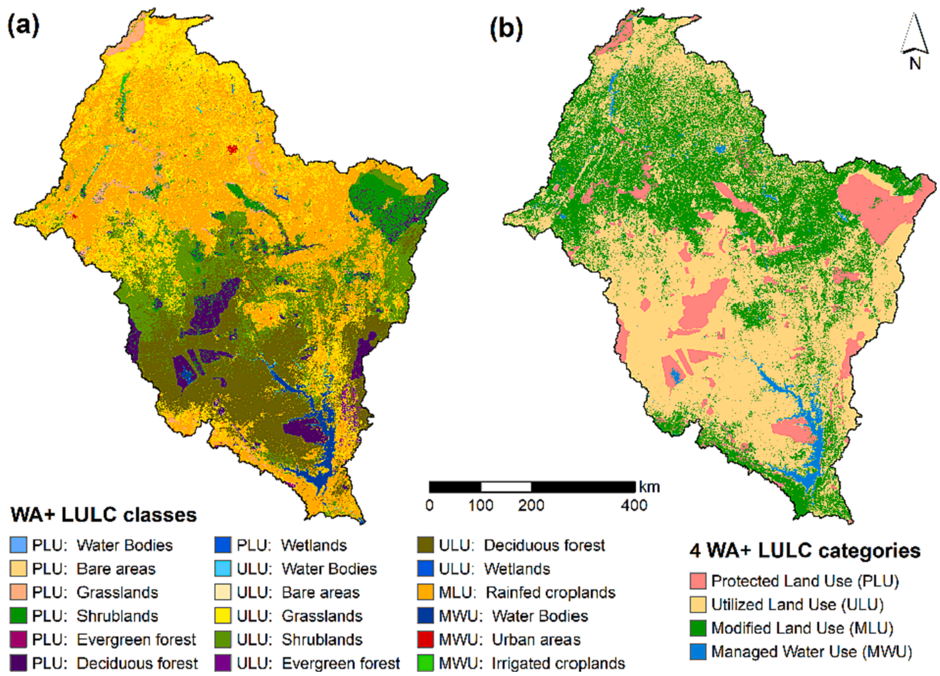

Fig. 3. WA+ land use classes of the Volta River basin based on ESA CCI data of 2015 (a), and grouped into the four WA+ classes (b).

$$\phi = \frac{E_{pot}}{P} \quad (5)$$

where ε is the long-term mean annual evaporative index and ϕ is the long-term mean annual dryness index.

Finally, E_{green} and E_{blue} are calculated as follows (Simons et al., 2020; Singh et al., 2022b):

$$E_{green} = \min((\varepsilon \times P), E_{act}) \quad (6)$$

$$E_{\text{blue}} = E_{\text{act}} - E_{\text{green}} \quad (7)$$

3.6.3. Resource base sheet

The WA+ resource base sheet provides an overview on over-exploitation and quantifies exploitable, utilized, consumed and non-consumed water at river basin scale. It is important to note that in the WA+ terminology, all water input to a basin (from precipitation or upstream basins) is called "inflow", all water output from the basin is called "outflow". The resource base sheet gives information on all inflows and outflows of water volumes in a river basin and relates them to various hydrological and water management processes (Fig. 6).

The net inflow to the basin is obtained by adding the change in storage to the gross inflow. A fraction of the net inflow is consumed as landscape ET, representing the part of total evaporation that occurs naturally and includes green water consumption (i.e. rainfall ET) and natural blue water evaporation without human influence (FAO and IHE Delft, 2020b). The remaining fraction of the net inflow after subtracting the landscape ET is the exploitable water, i.e. the non-evaporated water, which is available as blue water (Falkenmark and Rockström, 2006). The exploitable water comprises the utilized flow and the non-consumed water. The utilized flow corresponds to the manmade component of the incremental ET (i.e. E_{blue}) resulting from anthropogenic activities (e.g. irrigation, aquaculture, hydroelectricity, urban and domestic uses, and industries). The non-consumed water or total outflow represents the amount of water that physically leaves the basin through surface and subsurface outlets. It is composed of the water that could be additionally used (i.e. utilizable outflow) and the reserved flow for downstream commitments, navigational flows and environmental flow (Smakhtin et al., 2004). The landscape ET and the utilized flow form the consumed water (i.e. E_{act}). Table 3 provides a description of the data used and the calculation of the water accounts. A set of WA+ indicators are defined in Table 4 to support the analysis of water accounts (FAO and IHE Delft, 2020b; Karimi et al., 2013a).

3.6.4. Consumption sheet

The WA+ consumption sheet or ET sheet quantifies managed, manageable, and non-manageable water consumptions and defines their beneficial and non-beneficial proportions by activity sector including agriculture, environment, economy, energy, and leisure. It gives a summary of outflows related to total evaporation from different land use types (Fig. 8). Table 4 provides a set of WA+ indicators used for the consumption sheet.

The breakdown of total evaporation into evaporation from soil, water, interception, and vegetation transpiration allows differentiating between beneficial and non-beneficial ET. The proportions of beneficial and non-beneficial ET, as well as the share of the beneficial water consumption per activity sector, depend on case studies and they are determined by value judgment of experts (Bastiaanssen et al., 2015; FAO and IHE Delft, 2019; Karimi et al., 2013b). Nevertheless, there is a list of default values developed by WA+ experts that can be used in first instance and adapted as per case study specifications (see dictionary by IHE Delft, 2016). The following assumptions are made:

- Transpiration from vegetative cover is considered to be beneficial as it reflects the amount of water consumed for biomass production (e.g. crops), except for undesirable vegetation such as weed infestation in croplands, alien invasive species and floating vegetation in water bodies that can prevent evaporation (Bastiaanssen et al., 2015).
- Interception evaporation from wet leaves and canopies is assumed non-beneficial as it reduces the productive amount of rainfall that effectively reach the ground (i.e. throughfall and stemflow) (Li et al., 2012; Zheng and Jia, 2020). However, interception can have some benefits for micro-meteorological conditions for crops and plant temperature regulation, and contribute to continental rainfall through moisture recycling (Karimi et al., 2013a; Savenije, 2004).
- Evaporation from soil and open water bodies as well as from wet surfaces such as roads and buildings, is considered non-beneficial, except for natural lakes, wetlands, water bodies exploited for

Table 3
Key WA+ terminology adapted from FAO and IHE Delft (2020b).

Water accounts	Description	Calculation approach/Data used
$P_{advection}$	Precipitation	From climate models (RCM/GCM)
Q_{desal}	The inflow from desalinated water	not applicable
Q_{SW}^{in}	Inter-basin surface water inflow.	not applicable
Q_{GW}^{in}	Interbasin groundwater inflow.	not applicable
Gross Inflow	Total inflow to the basin from all sources.	$P_{advection} + Q_{desal} + Q_{SW}^{in} + Q_{GW}^{in}$
Consumed water (E_{act})	Water removed from the basin in the form of evaporation. This is total actual evaporation from all sources.	E_{act} from mHM
Q_{SW}^{outlet}	The river outflow at the outlet of the basin.	Q from mHM
Q_{SW}^{out}	Interbasin surface water outflow.	not applicable
Q_{GW}^{out}	Interbasin groundwater outflow.	not applicable
Non-consumed water (Outflow)	Total outflow from the basin.	$Q_{SW}^{outlet} + Q_{SW}^{out} + Q_{GW}^{out}$
Net Inflow	The gross inflow and the storage change. It represents water available for landscape ET and exploitable water.	Consumed water + Outflow
ΔS	Change in total water storage	Net Inflow - Gross Inflow
Rainfall ET (E_{green})	Total evaporation from green water sources (e.g. precipitation, unsatured soil).	Partitioning E_{act} with Budyko method
Incremental ET (E_{blue})	Total evaporation from blue water sources (e.g. lakes, streams, reservoirs, deep-root water uptake from groundwater, irrigation water).	E_{act} - E_{green}
Utilized flow (E_{blue_MWU})	Incremental ET from Managed Water Use (MWU) classes (i.e. irrigated crops, managed reservoirs).	E_{blue} extracted from MWU land type.
Landscape ET	Total evaporation that occurs naturally without water management.	E_{act} - E_{blue_MWU}
Exploitable water	The Net Inflow minus Landscape ET. It represents the non-evaporated water that forms blue water resources.	Utilized flow + Outflow
Non-manageable ET	Total evaporation from Protected Land Use (PLU) classes where land and water management are restricted.	E_{act} extracted from PLU land type.
Manageable ET	Total evaporation from Utilized Land Use (ULU) classes where land and water are not actively managed but they are used.	E_{act} extracted from ULU land type.
Managed ET	Total evaporation from Modified Land Use (MLU) and Managed Water Use (MWU) classes where land or water is actively managed.	E_{act} extracted from MLU and MWU land types.
Beneficial consumption	Water consumed for the intended purpose.	Based on value judgment and site-specific assessment.
Non–beneficial consumption	Water consumed for purposes other than the use.	Based on value judgment and site-specific assessment.

fishing, hydropower production, aquatic birds, water sports and leisure (Karimi et al., 2013b).

- Beneficial evaporation occurring over protected areas (PLU class) and utilized areas without regular land and water management (ULU) is mainly considered beneficial for the environment (e.g. biota sustainability), moderately to barely beneficial for leisure (e.g. ecotourism and wildlife viewing), and barely to insignificantly beneficial for other sectors. Over areas with land management and natural water supply (MLU) and areas with active water management (MWU), beneficial ET is largely to moderately beneficial for agriculture (e.g. cereals, vegetables and fruits), moderately to barely beneficial for economy (e.g. fishery, breeding and cash crops), energy (e.g. hydropower) and leisure (e.g. urban parks and reservoirs), and barely to insignificantly beneficial for environment.

Table 4
WA+ indicators.

WA+ Sheets	Definitions/Indicators	Calculation
Sheet 1: Resource base sheet	Exploitable Water Fraction (*EWF*) represents the part of the net inflow that is not depleted through landscape ET.	$\text{EWF:} = \frac{\text{Exploitable Water}}{\text{Net Inflow}}$
	Stationarity Index (*SI*) indicates the depletion of water storage (negative values) or increase (positive values).	$\text{SI:} = \frac{\text{Storage Change}}{\text{Total Evaporation}}$
	Basin Closure Fraction (*BCF*) defines the fraction of consumed and/or stored available water within the basin. A value of 100% indicates that all available water is consumed and/or stored.	$\text{BCF:} = 1\text{-}\frac{\text{Outflow}}{\text{Gross Inflow}}$
	ET Fraction (*ETF*) indicates which fraction of the total inflow of water is consumed and which part is converted into renewable resources. A value higher than 100% suggests over- exploitation or a dependency on external resources.	$\text{ETF:} = \frac{\text{Total Evaporation}}{\text{Gross Inflow}}$
Sheet 2: Consumption sheet	Transpiration Fraction (*TF*) describes the part of total evaporation (*ET*) that is produced by plants.	$\text{TF :} = \frac{\text{Transpiration}}{\text{Total Evaporation}}$
	Managed Fraction (*MF*) indicates the proportion of total evaporation that occurred by manipulation of land use and water management.	$\text{MF:} = \frac{\text{Managed ET}}{\text{Total Evaporation}}$
	Agriculture ET Fraction (*AEF*) corresponds to the part of total evaporation related to agricultural production.	$\text{AEF:} = \frac{\text{Agricultural ET}}{\text{Total Evaporation}}$
	Irrigation ET Fraction (*IEF*) describes the fraction of agricultural *ET* that is attributable to irrigation.	$\text{IEF:} = \frac{\text{Irrigation ET}}{\text{Agriculture ET}}$

Based on these assumptions, the proportions of beneficial ET per evaporation source (i.e. interception, soil, water and transpiration) and its distribution per activity sector (i.e. agriculture, environment, economy, energy and leisure) are estimated for the VRB (Table S4). The beneficial ET fraction per source varies between 0% and 100% for each evaporation source, while the sum of the share of the beneficial ET per activity sector is 100% for each LULC class as presented in Table S4.

4. Results

The results are organized in three parts. The first part gives an overview of the consistency of the WA+ estimates in the Budyko framework. The second part focuses on the basin scale analysis and includes sub-sections on the resource base sheet, the consumption or ET sheet and the WA+ indicators. The third part provides multi-scale summaries of key water budget components across spatial domains (i.e. countries, sub-basins and climatic zones). All results are provided as long-term averages over 30 years along with the inter-annual variability for the historical (1991–2020) and future (2021–2050) periods.

4.1. Hydrological plausibility of the WA+ LULC classes

A first important check is made here to examine the plausibility of water fluxes simulated with mHM per LULC in the Budyko space (Fig. 4). The simulated long-term values for the different LULC classes (period 1991–2020 and 2021–2050) plot well in the physically possible space below the energy and water limits (Donohue et al., 2011; McVicar et al., 2012), and close to the theoretical curve postulated by Budyko. The evaporative index is between 0.76 and 0.98, and the aridity index is between 1.4 and 5.6, which are expected values for sub-humid to semi-arid environments such as the VRB (Gunkel and Lange, 2017). It is noteworthy that LULC classes, particularly bare areas, show leftward and downward shifts in the Budyko space under future conditions, which denotes an increase in precipitation. The consistency of the simulated water fluxes for the retained LULC classes, thus underlying a suitable model parametrisation of mHM, is further demonstrated by the fact that the irrigated croplands have a slightly higher evaporative index than the rainfed croplands, and forests, water bodies and wetlands have a lower aridity index than the other LULC classes. However, E_{act} seems to be underestimated for water bodies. Variations are also observed depending on the RCM-GCM simulations as shown by the spread of forest and bare areas classes across different ranges of evaporative index and aridity index.

4.2. Basin scale WA+ reporting

4.2.1. WA+ resource base sheet

Long-term annual averages of water accounts over the historical and future periods are provided in Fig. 5. The WA+ resource base sheet gives an overview of the water repartition into flows, stocks and fluxes as depicted in Fig. 6.

For the baseline period 1991–2020, the long-term multi-model ensemble mean of annual total precipitation in the VRB is 419.6 km^3/year with 4% inter-model variability (V_2) across RCM-GCM combinations. The average storage change is −0.55 km^3/year (V_2 = 71%), thereby resulting in a net inflow to the basin of 419.1 km^3/year (V_2 = 3.9%). The landscape ET from green and blue water sources accounts for 92% of the net inflow and occurs at 56% in the ULU class (for abbreviations see Table 2) and at 32% in the MLU class. In the MLU, rainfed croplands represent about 33.51% of the basin area, which justifies the high proportion of the landscape ET. The ULU is dominated by grasslands (21.5%), shrublands (13.9%) and deciduous forest (17.9%), which represent more than half of the basin area (Table 2). The total consumed water in the basin is 388.8 km^3/year (V_2 = 2.7%), with 95% ascribed to rainfall ET (368.7 km^3/year and V_2 = 2.8%) from green water sources and the remainder to incremental ET (20.1 km^3/year and V_2 = 5.1%) from blue water sources, of which 20% is due to manmade activities.

Only 34.3 km^3/year (V_2 = 19.4%) of water in the VRB are exploitable and correspond to 8.2% of the net inflow. The exploitable water refers to the blue water storage available in the basin, of which 11% is utilized (4 km^3/year and V_2 = 2.4%), while the remainder 88% are not consumed and leave the basin as total outflow (30.3 km^3/year and V_2 = 21.7%). The total outflow has the highest inter-model variability varying between 40% and 57% (Fig. 5) and represents 7.2% of the net inflow. The estimated outflow of the VRB is in the range of previous findings, which is 30–40 km^3/year (Amisigo et al., 2015; Barry et al., 2005; McCartney et al., 2012; Sood et al., 2013; Williams et al., 2016). The basin rainfall was also found to be around 400 km^3/year (Andreini et al., 2000). The utilized flow occurs over the MWU that occupies about 2% of the basin area (Table 2) and is essentially composed of managed water bodies (1.49%), irrigated croplands (0.41%) and urban areas (0.1%).

The evolution of the water resources over the future period 2021–2050 in the VRB shows an increase in most of the indicators presented in WA+ sheet 1 (Fig. 5 and Fig. 6). A slight increase in net inflow of +1.6% (6.5 km^3/year and V_2 = 3.2%) relative to the historical period is expected, which results from an increase in precipitation by +1.4% (5.8 km^3/year and V_2 = 3.2%) and an increase in storage change by +131% (0.7 km^3/year and V_2 = 24%). As a consequence of the rise in net inflow, most of the water accounts are projected to increase, including landscape ET by +0.4% (1.5 km^3/year and V_2 = 2.7%), rainfall ET by +0.5% (1.7 km^3/year and V_2 = 2.6%), exploitable water by +15% (5.1 km^3/year and V_2 = 9.5%) and total outflow by +16% (4.9 km^3/year and V_2 = 10.1%). However, a slight decrease is projected for the incremental ET by −0.3% (−0.1 km^3/year and V_2 = 4.1%). These results align with previous studies in the West African region where projections show an increase in E_{green} and a decrease in E_{blue} under climate change over 2021–2050 (Badou et al., 2018). In general, higher inter-model variabilities are projected in the future as compared to the baseline historical period (Fig. 5).

Inter-annual variabilities of water accounts are given in Fig. 7. Over

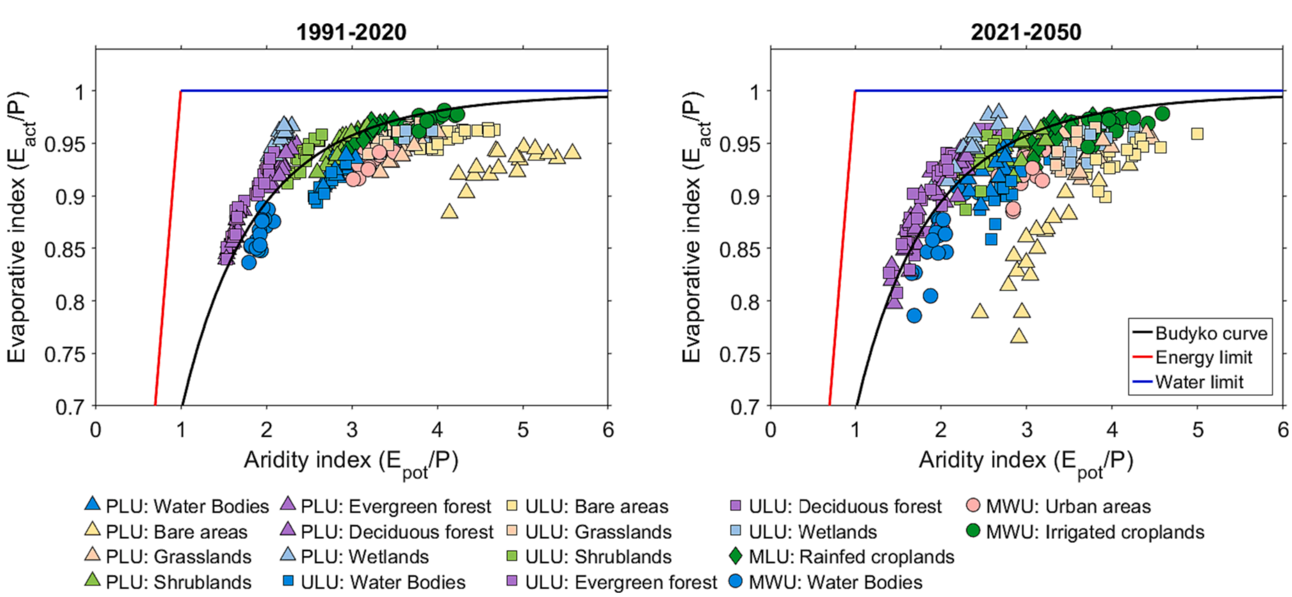

Fig. 4. WA+ LULC classes repartition in the Budyko framework over historical (1991–2020) and future periods (2021–2050). The y-axis is truncated and starts at 0.7 for a better display.

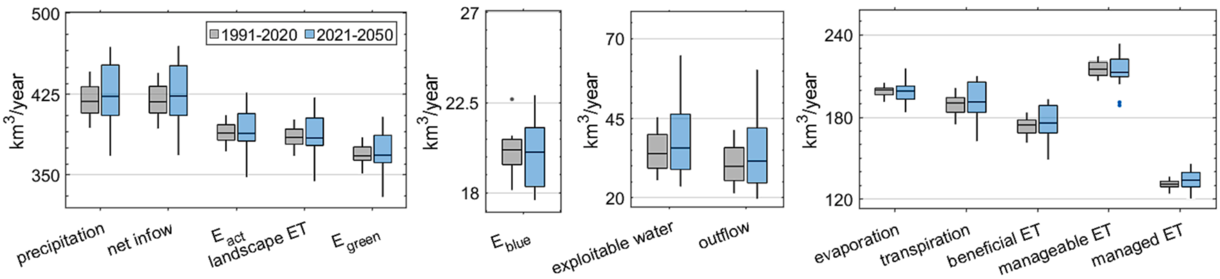

Fig. 5. Long-term (30-year average) annual water accounts in the VRB over historical (1991–2020) and future periods (2021–2050). Each boxplot represents the variation across 18 RCM-GCM combinations.

the historical period, the average inter-annual variability across RCM-GCM combinations for precipitation is 13%. While the inter-annual variability of the net inflow is 11%, landscape ET and exploitable water show 14% and 8.7%, respectively. The highest average inter-annual variability of 99.9% is shown by the storage change, followed by the 48% for total outflow and 43% for incremental ET or E_{blue}, while the lowest values are 4.7% for the utilized flow and 8.7% for rainfall ET or E_{green}. The inter-annual variabilities of water accounts are projected to increase with various magnitude in the future but the ranking of variabilities are conserved (i.e. the storage change and the utilized flow still have the highest and lowest inter-annual variabilities, respectively). The exploitable water gives the maximum increase in the inter-annual variability, which is +11%, while the inter-annual variability of outflow remains almost unchanged.

4.2.2. WA+ consumption or ET sheet

The WA+ consumption or ET sheet summarizes water consumption and provides the breakdown of total evaporation (ET) into transpiration and evaporation from soil, water bodies and interception (Fig. 8). Over the historical baseline period (1991–2020), the long-term multi-model ensemble mean of total annual ET (E_{act}) is 388.8 km^3/year with 3.9% of inter-model variability (V_2) across RCM-GCM combinations (Fig. 5). The total ET represents the consumed water, of which 11% are non-manageable because occurring in protected lands (PLU), 55% are manageable on the utilized lands (ULU) and 34% are managed on modified lands (MLU) and water-managed lands (MWU). Transpiration is 189.5 km^3/year ($V_2 = 4.2\%$) and alone accounts for 49% of total ET, followed by soil evaporation (26% or 102 km^3/year), interception evaporation (23% or 88.3 km^3/year), while water evaporation was the lowest (2% or 9 km^3/year).

From the total water consumed in the VRB during the period 1991–2020, only 45% was beneficial. The total beneficial consumption was 173.5 km^3/year ($V_2 = 3.9\%$), with 55% attributable to the environment, 34% to agriculture, 5% to the economy, 4% to leisure and 2% to energy production. The non-beneficial water consumption represents 55% of the total consumed water. Most of the non-beneficial water consumption is ascribed to interception and soil evaporation that occurred at 62% in the ULU and 30% in the MLU.

The projected water accounts over the period 2021–2050 (Fig. 5 and Fig. 8) show that the overall water consumption in the VRB remains almost unchanged with a minimal increase of +0.4% (1.7 km^3/year and $V_2 = 2.7\%$), which could be expected because of the low increase of the net inflow over the same period (Fig. 5). By maintaining the current land and water management practices, the beneficial water consumption could increase by +1.6% as a result of the +1.4% increase in transpiration. Moreover, the managed, manageable and non-manageable proportions of water consumption are conserved. The consumed water has an inter-annual variability of 7.6% (Fig. 7), which is projected to increase by +5% on average in the future, while its managed portion (i.e. managed water consumption) has an inter-annual variability of 36%, with +1.2% increase over the future period.

The contribution of each WA+ land categories to total ET and its components as well as to the beneficial fraction and the water consumption in different activity sectors is shown in Fig. 9. For the historical period, most of the consumed water occurs in the ULU (55%), followed by the MLU (32%), the PLU (11%), and the MWU (2%). The MLU accounts for 88% of the water consumed for agriculture and 73% for the economy. The ULU is accountable for 77% of the water consumed by the environment, 60% for energy production and 34% for leisure. The PLU contributes at 55% of the water consumed for leisure and at 22% for the environment. The beneficial water consumption mainly occurs in the ULU (48%) due to the forests, followed by the MLU (34%) because of rainfed croplands, and the PLU (14%) because of protected vegetation species, forests and wetlands. Only 4% of the beneficial water consumption occurs in the MWU, which encompasses the irrigated croplands and the managed water bodies. Over the future period, the proportions of total ET per evaporation sources and beneficial ET per activity sectors based on the WA+ land categories are projected to decrease slightly for the PLU and ULU, and increase for MLU and MWU (Fig. 9), because of the future changes in land category areas (Table 2).

4.2.3. WA+ key indicators

A set of performance indicators (Table 4) are used to understand better the present and future water resource conditions summarized in the WA+ sheets (Fig. 10). The indicators of the resource base sheet show that the long-term multi-model ensemble mean of the exploitable water fraction (*EWF*) is 0.08 (inter-model variability $V_2 = 16\%$) over the baseline period 1991–2020 with an expected increase of +12% in the near future (2021–2050). The low *EWF* indicates that a small fraction of the net inflow can be exploited in the VRB, because of the large fraction of water consumed through landscape ET (Fig. 6). The stationarity index (*SI*) is −0.0014 ($V_2 = 71\%$), indicating a decrease in storage, with a projected increase by +132% in the future. The basin closure (*BC*) of 0.93 ($V_2 = 1.4\%$) indicates that a large fraction of the available water is consumed and/or stored in the basin and is projected to decrease slightly by −1%. The ET fraction (*ETF*) is 0.93 ($V_2 = 1.4\%$), confirming that a substantial fraction of the total inflow to the basin is consumed through evaporation, while a small fraction is converted into renewable resources that increase storage or generate outflow from the basin.

The indicators of the consumption sheet only show minimal changes for future projections of water accounts (Fig. 10). All the performance indicators are projected to slightly increase between +1% and +3%, except the irrigated ET fraction (*IEF*) that could decrease by −2%. The average transpiration fraction (*TF*) is 0.49 (inter-model variability $V_2 =$ 1.8%) and indicates that transpiration is a major process in water depletion in the VRB, which can be explained by the large presence of vegetated lands (rainfed croplands, irrigated croplands, grasslands, shrublands and forests) covering about 98% of the basin area. However, only 45% of the water consumption is beneficial, which can be justified by the low land and water management practices as the managed fraction (*MF*) is 0.34 ($V_2 = 0.5\%$). Although agriculture occupies 34% of the basin area, the agricultural ET fraction (*AEF*) is only 0.15 ($V_2 = 2.2\%$), while the contribution of irrigated agriculture is very low with an irrigated ET fraction (*IEF*) of 0.02 ($V_2 = 2.2\%$). These results suggest that

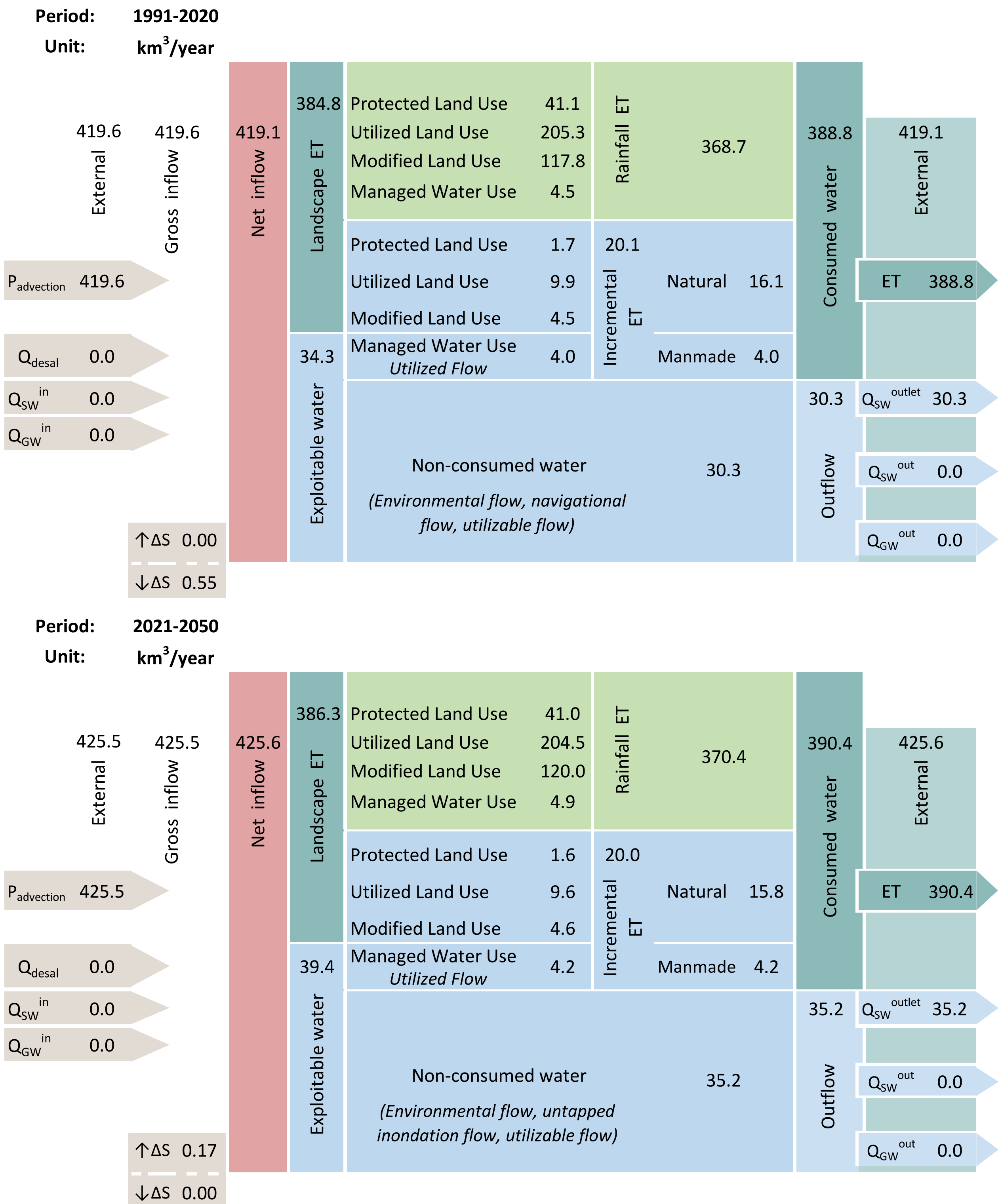

Fig. 6. WA+ resource base sheets with multi-model ensemble mean of long-term annual water accounts for the historical (1991–2020) and future (2021–2050) periods.

there are possibilities for improving land and water management to increase the benefits of water consumption in the VRB.

4.3. Water accounts across spatial domains

The spatial distributions of key water accounts across spatial domains, including the four climatic zones, the four sub-basins and the six riparian countries of the VRB are presented in this section.

4.3.1. Spatial patterns of water accounts

The spatial patterns of long-term multi-model ensemble mean of annual key water accounts over the historical baseline period (1991–2020) are displayed in Fig. 11 along with the projected changes over the future period (2021–2050), and the associated inter-model

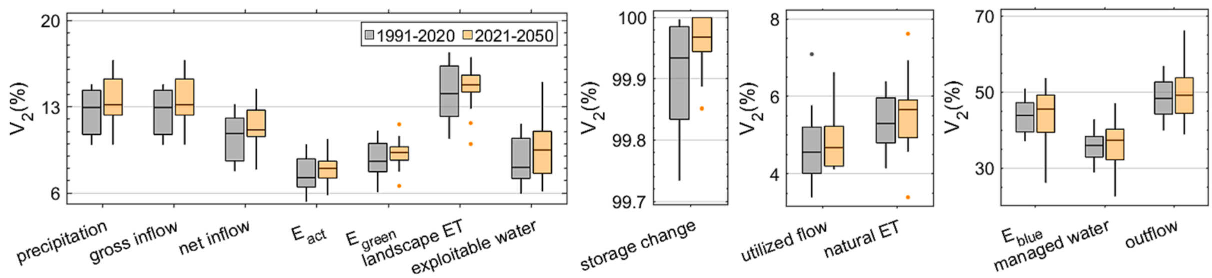

Fig. 7. Inter-annual variability of water accounts over 30 years in the VRB for historical (1991–2020) and future periods (2021–2050). Each boxplot represents the variation across 18 RCM-GCM combinations.

(RCM-GCMs) variabilities, while the inter-annual variabilities are shown in Fig. 12. Total annual precipitation depicts a north–south increasing amount, varying between 450 mm/year in the north to about 1430 mm/year in the south, with the highest values in the south-eastern zones of the basin. Similar patterns to precipitation are shown by actual evaporation (415–1250 mm/year) and runoff (3–400 mm/year), implying that precipitation is the primary driver of the water cycle in the VRB. Green ET (0–1180 mm/year) and blue ET (0–1220 mm/year) patterns are generally inversed as expected, i.e. places with lower green ET have higher blue ET and vice versa. This is clear from water bodies, especially from the Lake Volta in the south.

Future projections generally show an increase for most of the water accounts and in most parts of the basin, with some exceptions. Runoff is projected to increase with the highest rates of change among the water accounts and exceeding +100% in some parts of the basin. The patterns of future changes for actual evaporation are very similar to green ET, both vary between −5% to +5%, and their patterns show the imprints of the precipitation pattern, which changes between −6% to +7%. Blue ET shows contrasting spatial changes dominated by a decrease in the southwestern and central-eastern regions of the basin, up to −100%, and an increase in the southeastern side, exceeding +100% in some regions. However, the highest inter-model variabilities and inter-annual variabilities are found for runoff and blue ET, with higher variabilities for all water accounts projected in the future (Fig. 11 and Fig. 12).

4.3.2. Multi-scale summary across spatial domains

For conciseness, this section focuses more on the country-scale results, particularly for Burkina Faso and Ghana, as they share most of the basin area (Fig. 1), and briefly on the climatic zones and sub-basins. However, additional information and illustrations of the results for the climatic zones and sub-basins are provided in the supplementary material (Tables S5-S8, Figs. S3-S9).

Regarding the proportions of WA+ land categories per country (Fig. 13), Ghana hosts the largest fraction of PLU (41.3%), ULU (49%) and MWU (73.1%) of the basin, while Burkina Faso has the largest fraction of MLU (66%) and ranks second for the other land categories. The detailed proportions of WA+ land categories for all countries, sub-basins and climatic zones are given in Table S3.

A summary of key water accounts (precipitation, actual evaporation, green ET, blue ET and runoff) across the four climatic zones, four sub-basins and six riparian countries of the VRB is given in Table 5. The associated inter-model and inter-annual variabilities across RCM-GCM combinations are provided in Tables S5-S6 in the supplementary material. It appears that the highest rates of water accounts are found in the Guinean zone for the climatic zones and in the Lower Volta for the sub-basins, while the lowest rates are in the Sahelian zone and Black Volta (except for blue ET), respectively.

The long-term multi-model ensemble mean of key annual water accounts per country generally shows higher magnitudes in Ghana than in Burkina Faso (Fig. 14). However, the highest precipitation, evaporation and runoff rates are observed in Togo, while the lowest are observed in Mali, because of the climatic zones they are located in (Fig. 1). An inter-comparison reveals similar differences among the countries under future climate change as for the historical baseline period.

In general, the inter-model and inter-annual variabilities for all countries are more critical for blue ET and runoff, and lesser for actual evaporation and green ET (Fig. 14). All variabilities are projected to increase in the future. It is noteworthy that, for all water accounts, inter-annual variabilities are larger than inter-model variabilities, and runoff has a larger inter-model variability than blue ET, while the opposite is observed for inter-annual variability. Burkina Faso has higher inter-model and inter-annual variabilities of water accounts as compared to Ghana. Mali usually has the highest inter-model and inter-annual variabilities. Details on inter-model and inter-annual variabilities are provided in the supplementary material (Table S5-S6).

The evaporative index varies between 87% and 96% among countries, while the runoff coefficient varies between 4% and 13%, with the basin average estimated at 92% and 8%, respectively (Fig. 15). These results corroborate with previous findings, which estimated the evaporative index between 86% and 95% and the runoff coefficient between 5% and 14% in the VRB (Barry et al., 2005; McCartney et al., 2012; Sood et al., 2013; Van de Giesen et al., 2010; Williams et al., 2016). Burkina Faso and Côte d'Ivoire have the lowest runoff coefficient, while Benin and Togo have the highest. A slight decrease of about −1% on average is projected for the evaporative index under future climatic conditions, while an increase of +1% is projected for the runoff coefficient for all countries. Burkina Faso has 5% more evaporation than Ghana, while the opposite is observed for the runoff. The runoff coefficient varies between 4% and 5% in Burkina Faso, whereas it is between 9% and 10% in Ghana.

The share of the basin water volumes per spatial domain is appreciable from Table 6. Ghana is the largest contributor to the basin fluxes and flows with about 46% for precipitation, 46% for actual evaporation, 45% for green ET, 64% for blue ET and 56% for runoff (Table 6). It is followed by Burkina Faso with 36% for precipitation, 37% for actual evaporation, 38% for green ET, 24% for blue ET and 22% for runoff over the baseline period. The third largest contributor is Togo, followed by Benin, Côte d'Ivoire and Mali. It is noteworthy that the contribution of each country to the basin volumes of water accounts depends on the rates or intensities of the water fluxes and flows received or generated over the country area within the VRB. For instance, a country can have high precipitation intensities but a small surface area in the basin, which can result in a relatively smaller contribution to the basin water volumes, like in the case of Togo (Table 5 and Table 6). The contributions of each country, each sub-basin and each climatic zones to the basin water accounts are summarized in Table S8.

The pattern of the country's contributions to the water accounts hardly changes under climate change in the future. However, it is noteworthy that the contribution of Burkina Faso to the basin is projected to increase on average by +2% for runoff in the future, and compensated by a decrease in Ghana, when considering the multi-model ensemble mean.

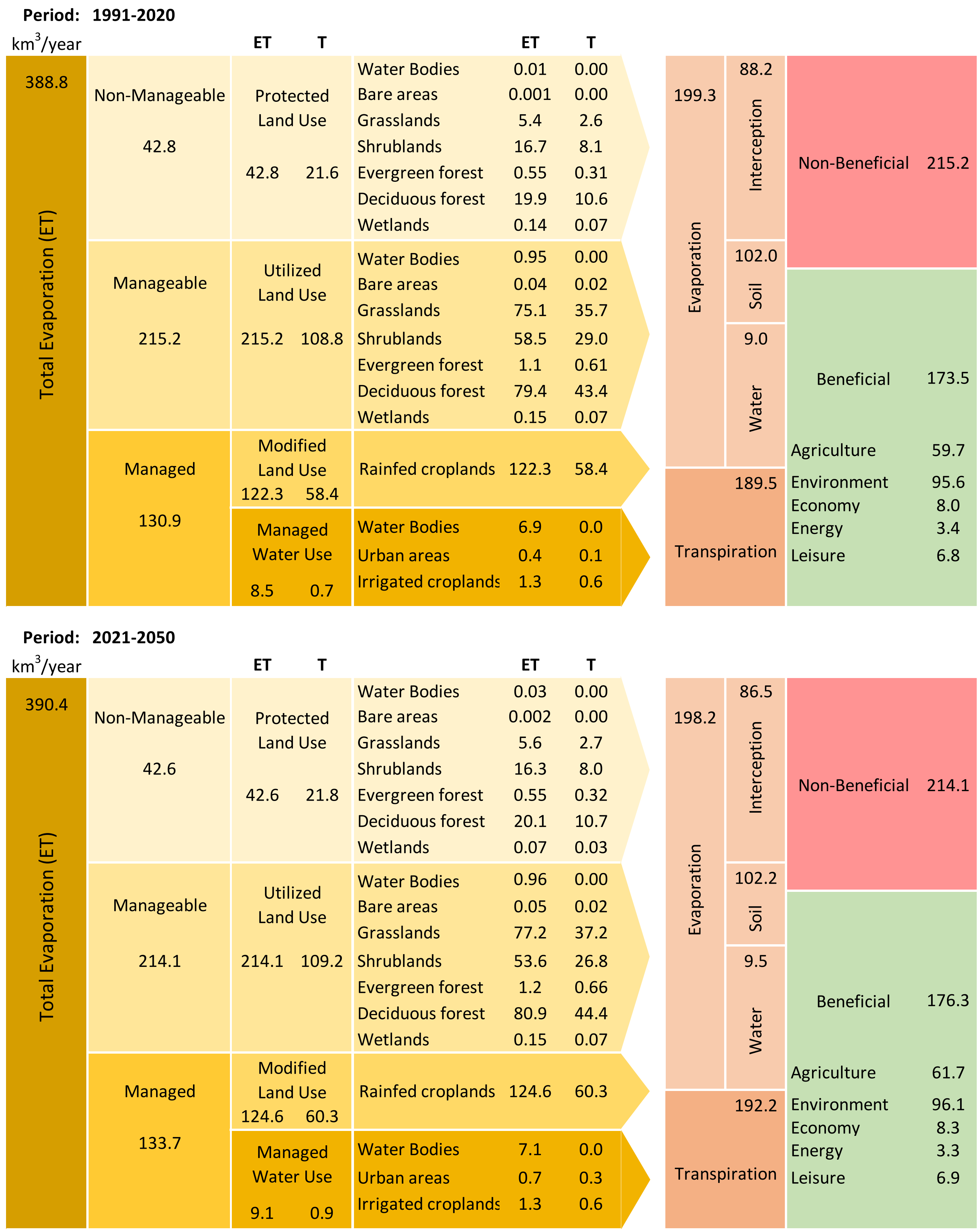

Fig. 8. WA+ consumption or ET sheets with multi-model ensemble mean of long-term annual water accounts for the historical (1991–2020) and future (2021–2050) periods.

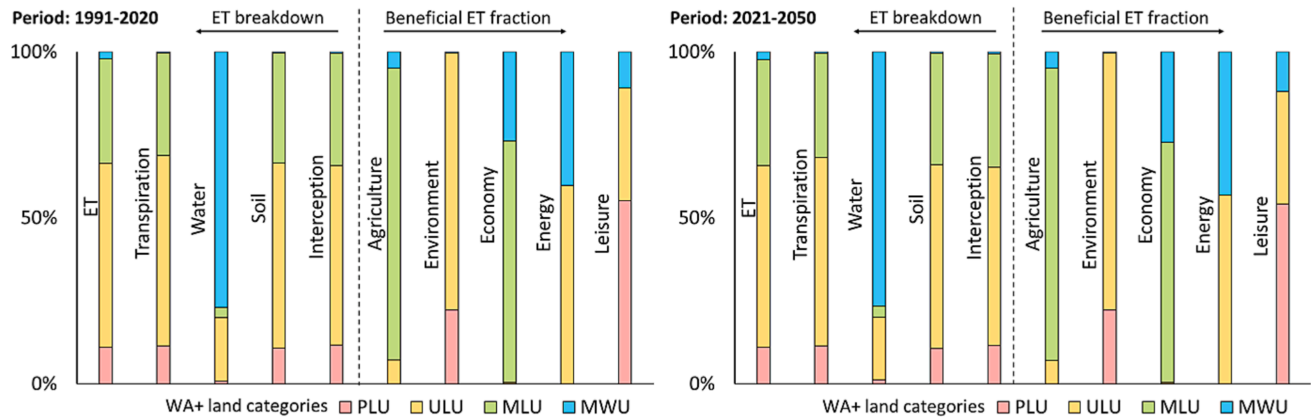

Fig. 9. Total evaporation (ET) breakdown and beneficial ET fraction for each activity sector per WA+ land categories.

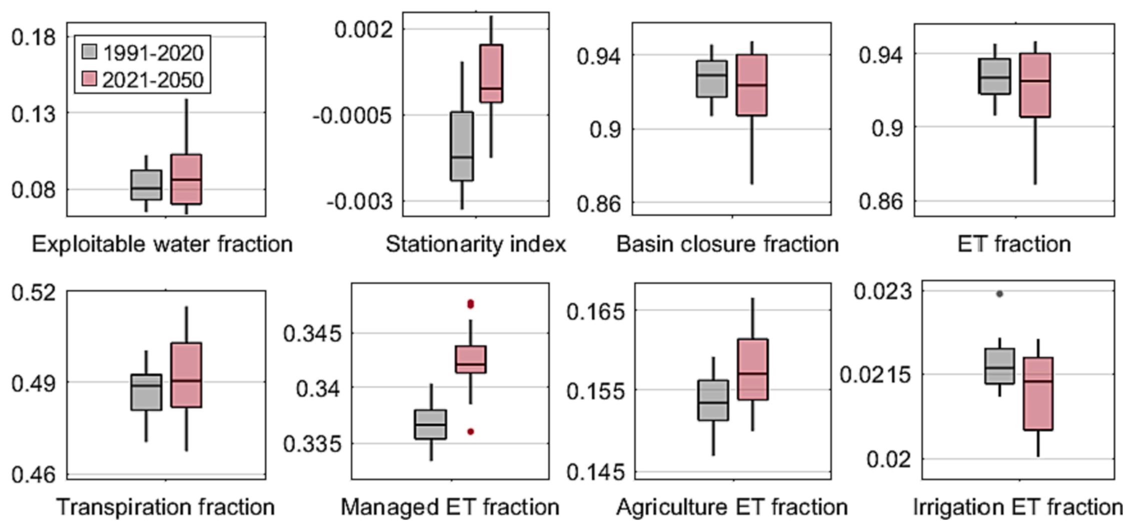

Fig. 10. WA+ indicators in the VRB over historical (1991–2020) and future (2021–2050) periods. Each boxplot represents the variation across 18 RCM-GCM combinations.

5. Possible land and water management measures

Based on the results of the spatially explicit WA+ modelling of this study, it appears that the projected future increase in net inflow by 6.5 km^3/year over 2021–2050 can be beneficial for the VRB if the available water resources are used appropriately by activity sectors. In this regard, the adoption of integrated water solutions can help cope with the looming and worsening impacts of climate change in the VRB (IWMI, 2021b). As runoff could increase on average by +27% in Burkina Faso and +13% in Ghana by 2050, adaptation measures should consider efficient drainage systems in urban places to mitigate rapid flow accumulations, flood detention and retention basins with minimum environmental impact to exploit excess runoff, and rainwater harvesting systems to combat drought spells during cropping seasons (Campisano et al., 2017; de Sá Silva et al., 2022; Scholz, 2019).

There is a high potential for expanding agriculture in the VRB as exploitable water is projected to increase on average by 5 km^3/year by 2050, thereby setting conditions to grow more crops while adopting sustainable practices to enhance water productivity and water use efficiency. Climate-smart agriculture solutions, including water and soil conservation techniques developed with the inclusion of local knowledge, could be adopted to improve the adaptive capacities of farmers and support food security under disruptions posed by climate variability and change (Lipper et al., 2014; Ogunyiola et al., 2022; Taylor, 2018). For instance, croplands could be expanded by supporting and promoting small-scale initiatives like farmer-led irrigation (IWMI, 2021a; Lefore et al., 2019; Woodhouse et al., 2017). However, water infrastructure development in the VRB was found more important for providing economic benefits to the riparian countries than cropland expansion only (Baah-Kumi and Ward, 2020; Kotir et al., 2016).

With the predicted increase in exploitable water revealed in this study, the construction of resilient water storage infrastructure (e.g. small reservoirs, dams) becomes crucial in the VRB as they have long been the cornerstone of socio-economic development, particularly in regions with high climatic variability (McCartney et al., 2022; Rodina, 2019; Yu et al., 2021). Storing water in the VRB is essential for developing off-season irrigated agriculture as well as hydropower production, which are the top priorities of the upstream and downstream countries (Burkina Faso and Ghana) (Bhaduri and Liebe, 2013). Such additional infrastructure could help reduce the non-consumed water, which is projected to increase by +16% or 5 km^3/year on average, and increase the man-made consumption from water storage, which currently represents 1% of the total consumed water in the VRB. The development of irrigation could increase the beneficial fraction of water consumption in agriculture, which is currently only 34%, with irrigation representing only 2% of water consumed by agriculture. Another potential strategy to increase the share of beneficial water use is to convert parts of the ULU lands (e.g. bare areas and grasslands) into MLU (e.g. rainfed croplands) or MWU lands (e.g. managed water bodies, irrigation) with adequate land and water management practices. These measures can limit non-

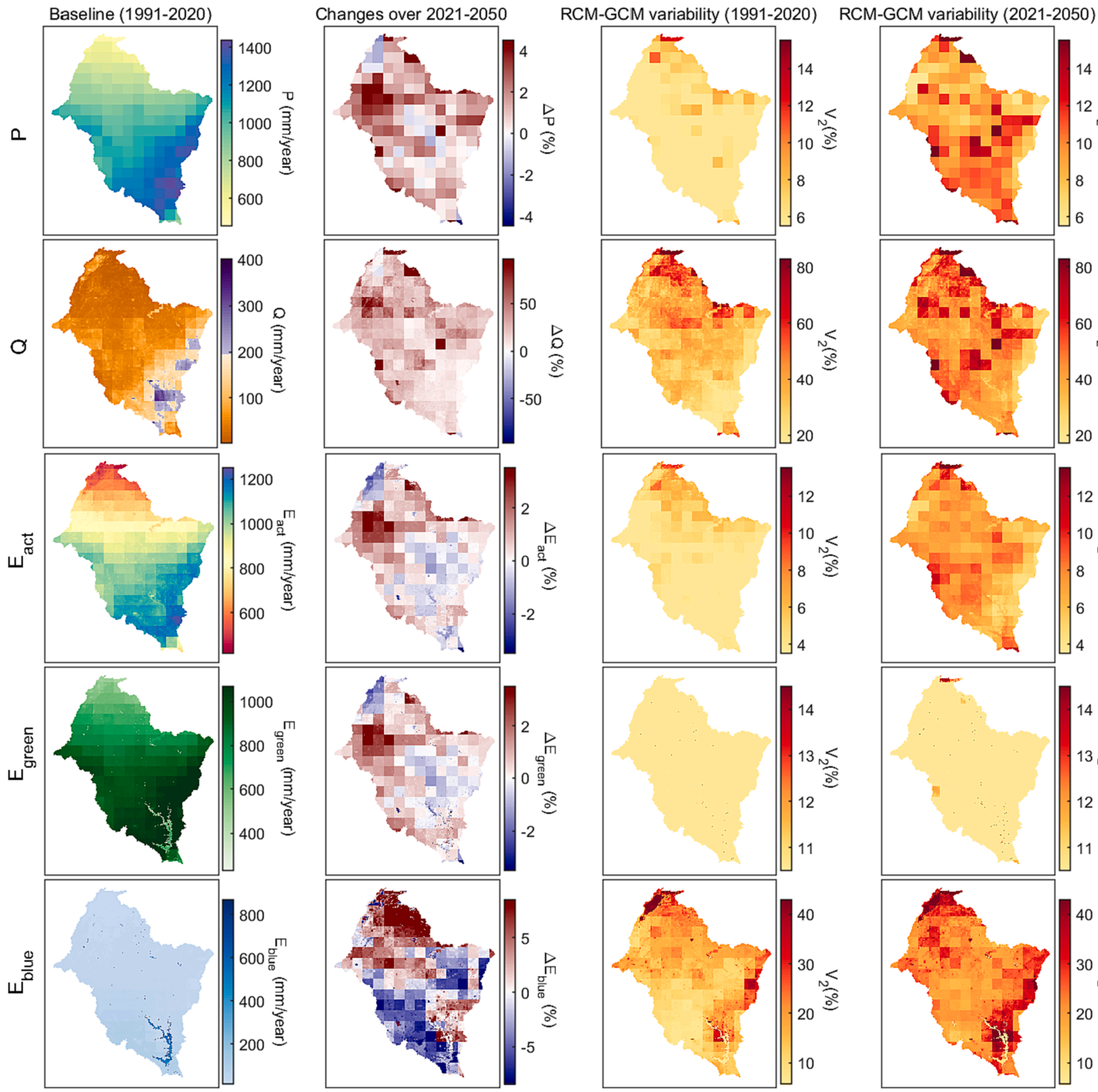

Fig. 11. Long-term multi-model ensemble mean of annual water accounts over the historical baseline period (1991–2020) with the projected changes over the future period (2021–2050) and associated inter-model variability across RCM-GCM combinations in the VRB.

beneficial soil evaporation through increased infiltration and improved irrigation efficiency. Moreover, there is a high potential to unlock further access to green energy with the development of hydropower in the VRB (Gyamfi et al., 2018; Kling et al., 2016), although the high inter-annual variability of runoff between 39% and 66% can be a limiting factor, as previously documented for West Africa (Obahoundje and Diedhiou, 2022; Wasti et al., 2022).

The projected increase in runoff between +9% (Lower Volta) and +27% (Black Volta) across sub-basins implies a potential increase in the likelihood of floods in the VRB (Table S7), as already reported in previous studies (Dembélé et al., 2022; Jin et al., 2018). Possible adaptation strategies consist of green (i.e. vegetation) and blue (i.e. water) nature-based solutions such as forests, urban trees and parks, wetlands, ponds, and grey (i.e. built) infrastructures such as dams and drainage canals, to enhance storm water control, slow down runoff and increase groundwater recharge (Depietri and McPhearson, 2017; Keesstra et al., 2018; Nesshöver et al., 2017). However, hybrid approaches combining green–blue-grey infrastructures, such as rainwater harvesting systems, managed aquifer recharge, bioswales and green roofs, have shown higher effectiveness in flood mitigation (Alves et al., 2019; Sahani et al., 2019).

These solutions, among many others, accompanied by innovative climate-resilient and risk-efficient initiatives, can help balance the water-energy-food-ecosystem nexus in the VRB (Botai et al., 2021; Samberger, 2022), thereby providing a solid foundation for sustainable socio-economic development. Nevertheless, the choice of actual development strategies depends on trade-offs between socio-economic development and nature protection (Dai et al., 2018; Endo et al., 2020), and could be achieved with adequate policy mixes of activity sectors (Schaub et al., 2022). Consequently, care should be taken to avoid environmental degradation and social drawbacks.

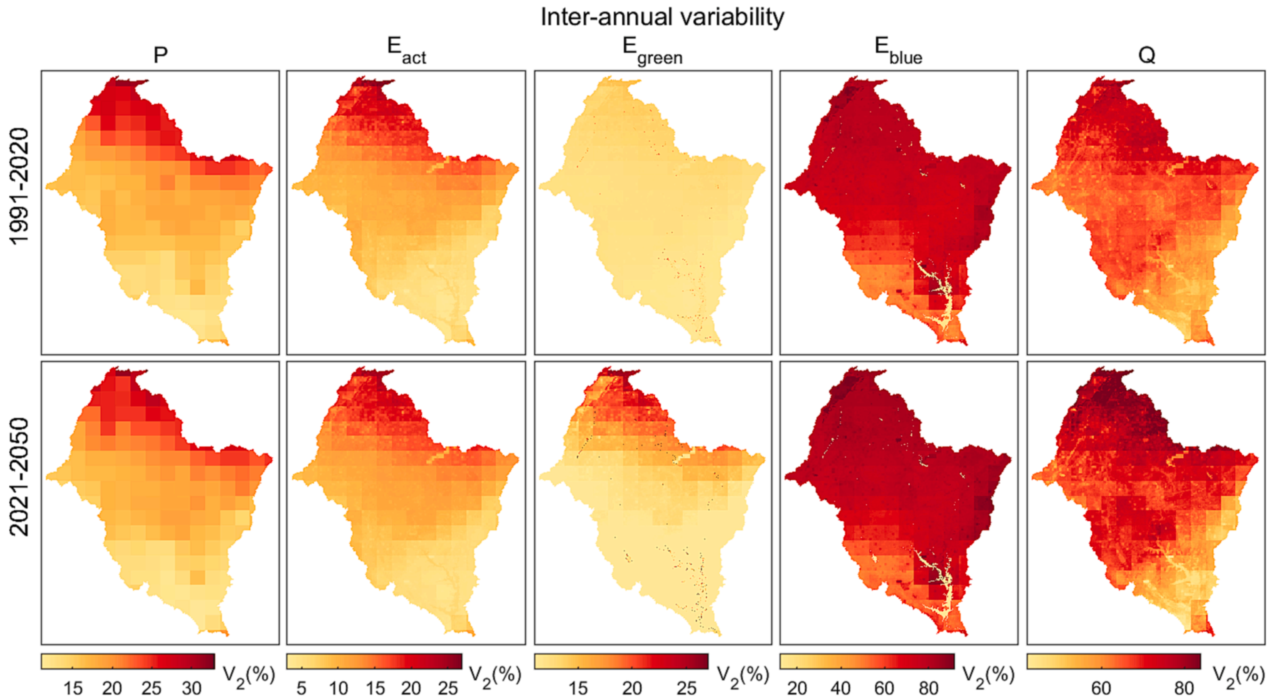

Fig. 12. Inter-annual variability of water accounts over historical (1991–2020) and future periods (2021–2050) in the VRB.

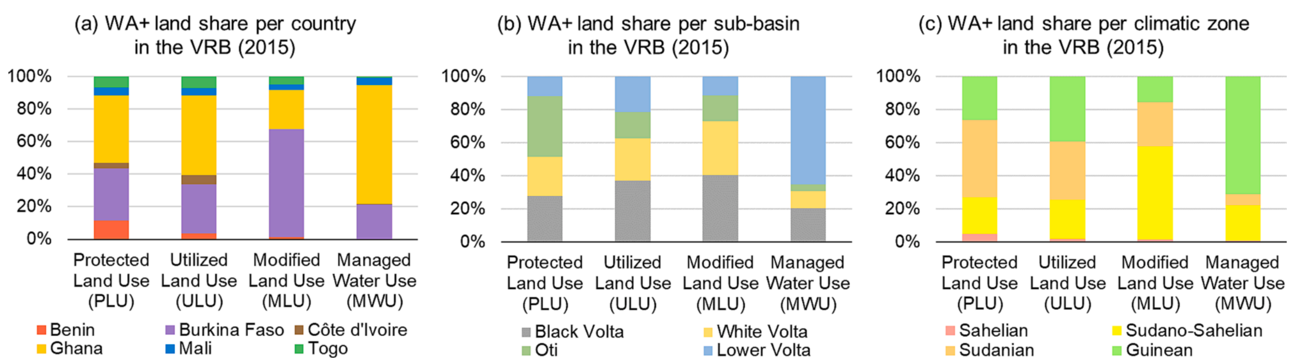

Fig. 13. Share of WA+ land categories per riparian country (a), sub-basins (b) and climatic zones (c) in the Volta River Basin in 2015.

6. Discussion

As demonstrated in this study, strategic information for water resource management can be obtained from the WA+ framework but it also has limitations. WA+ is not meant for daily monitoring and assessment of water demand and supply and, therefore, cannot be used for day-to-day operation of reservoirs and irrigation systems (Bastiaanssen et al., 2015). It is instead designed for long-term planning of water and land resources in large catchments.

This study uses a large ensemble of global and regional climate models to account for uncertainties associated with the meteorological data. It is noteworthy that the results might differ and even give opposite change signals if different climatic models, different simulation periods or different climate change scenarios (i.e. RCPs) are used, especially for rainfall, which governs the water cycle in West Africa, as highlighted in previous studies (Dembélé et al., 2022; Dosio et al., 2021; Liersch et al., 2020). Furthermore, there are additional uncertainties besides the classical sources of uncertainty associated with climate change impact projections (Eyring et al., 2019; Kundzewicz et al., 2018). The key uncertainties in the presented methodology are associated with i) the identification of WA+ land categories, ii) the Budyko approach for green and blue ET partitioning, and iii) the use of expert knowledge to identify the beneficial fractions of consumed water per activity sectors, which are discussed in the following.

Information on land cover and land use is the backbone of the WA+ framework. Therefore, the reliability of the results highly depends on the accuracy of the LULC data. The used LULC data from ESA has the advantage of being available at a high resolution of 300 m and being subject to thorough quality check (ESA CCI, 2017), and can therefore safely be assumed acceptable for large-scale modelling in the VRB. Additionally, a constant LULC map is used over the 30-year simulation periods because of the primary goal to focus on climate change, which might only partially reflect the inter-annual changes in LULC. Therefore, the use of dynamic LULC maps is recommended for future studies as this can enhance the inter-annual water balance (Yonaba et al., 2021).

Moreover, to bring confidence into the analyses, the Budyko framework was used here to check the plausibility of the LULC classification and the distribution of water and energy fluxes. Although actual evaporation from water bodies seems a little underestimated, the overall distribution of LULC groups in the Budyko space is realistic. Minor inconsistencies in the distribution of LULC groups in the Budyko space might be explained by the difference in spatial resolutions between the LULC maps (~300 m) and the mHM simulations (~3.5 km), as well as the aggregation of hydrological fluxes across contrasting climatic zones.

Table 5
Long-term multi-model ensemble mean of key annual water accounts across spatial domains in the Volta River Basin. The colour scale indicates ranked values from the lowest (red) to the highest (blue).

Long-term average (mm/year)		Historical period (1991-2020)					Future period (2021-2050)				
Spatial scales / Water accounts		P	E_{act}	E_{green}	E_{blue}	Q	P	E_{act}	E_{green}	E_{blue}	Q
Basin	VRB	1010	935	887	48	73	1024	939	891	48	85
Climatic zones	Sahelian	557	523	515	8	34	561	521	512	8	41
	Sudano-Sahelian	796	763	737	25	32	811	771	744	26	41
	Sudanian	1041	979	939	40	60	1057	983	944	39	74
	Guinean	1247	1109	1023	86	135	1257	1110	1024	85	148
Sub-basins	Black Volta	904	862	826	36	41	922	871	833	37	51
	White Volta	911	867	833	35	42	922	870	836	35	52
	Oti	1124	1013	978	35	110	1138	1013	979	34	125
	Lower Volta	1263	1111	1004	107	149	1273	1111	1006	105	163
Countries	Benin	1179	1042	1018	24	136	1203	1043	1021	23	160
	Burkina Faso	855	817	789	28	37	873	826	798	29	47
	Côte d'Ivoire	1048	1006	943	63	40	1065	1010	950	60	55
	Ghana	1161	1059	982	77	101	1172	1059	983	76	114
	Mali	614	576	566	11	38	615	573	561	11	42
	Togo	1221	1084	1048	36	136	1231	1084	1049	35	147

In fact, averaging over spatial heterogeneity affects modelled hydrological processes governed by nonlinear relationships (e.g. evaporation), particularly in places where the spatial variation of precipitation and potential evaporation are inversely correlated like in the VRB (Rouholahnejad Freund et al., 2020).

The Budyko framework is typically recommended for long-term analyses at catchment scale rather than at the grid cell. Therefore, there might be challenges using the Budyko framework for green and blue ET partitioning per grid cell, mainly when only using independent satellite remote sensing data (Msigwa et al., 2021). However, mHM is a grid-based hydrological model that guarantees the closure of the water balance for each grid cell (~12.25 km^2 in this study) in the basin before routing the total grid cell runoff through the river network (Samaniego et al., 2010), which justifies the use of the Budyko framework in this work. Other and new approaches for green and blue ET separation should be further investigated in future studies.

The estimation of the beneficial and non-beneficial fractions of water consumption and its repartition per activity sector (agriculture, environment, economy, energy and leisure) can be biased as it is based on value judgement, which makes it debatable but also flexible because there is room for adjustments according to case studies. The value judgment requires expert knowledge, and the underlying results are initial estimates that can be refined on demand.

A number of improvements and additions can be considered in future studies. For instance, utilizable water (i.e. non-consumed water fraction that could be used), non-recoverable flow (i.e. aquifer recharge and polluted water), non-utilizable outflow (i.e. inundation water) and reserved flows (e.g. downstream commitment for ecosystems and livelihoods) can be estimated, if reliable data and information are available on floods, water pollution, environmental flow, etc. (Mekonnen and Hoekstra, 2015; Pahl-Wostl et al., 2013). Moreover, different approaches to green and blue ET partitioning should be further investigated to better distinguish between natural and anthropogenic water consumption (Msigwa et al., 2021). Scenarios of LULC changes (e.g. deforestation, afforestation, irrigation schemes, reservoirs, etc.) can be used to examine how decisions on land use practices and investments in water infrastructures can affect water accounts. For climate change projections, the use of the new Shared Socioeconomic Pathways (SSPs) is recommended for future studies (Riahi et al., 2017), and multi-model approaches based on different hydrological models are encouraged to account for model structural uncertainties (Dion et al., 2021; Moges et al., 2020). Finally, system dynamics modeling and participatory modelling should be explored to consider the interactions between population, water, land and activity sectors, including industry and domestic uses that can have a higher water demand in the future (Kotir et al., 2017; Zomorodian et al., 2018). The combination of these efforts will help operationalize the WA+ framework (Hundertmark et al., 2020).

7. Conclusion

This study successfully demonstrates the benefits of a modelling framework that integrates a spatially explicit hydrological model and climate change scenarios with the WA+ tool for a better understanding and visualization of the impacts of climate change on a large basin's water resources and the various users, with a case study in the transboundary Volta River Basin in West Africa. The proposed WA+ modelling framework has several advantages compared to the traditional WA+ approach solely based on earth observation data. In fact, the use of a spatially explicit hydrological model allows future predictions with climate change scenarios and at a higher spatial resolution with a proper closing of the water balance, which would have been impossible if only using satellite remote sensing data. The proposed standardized reporting method allows managers and policy developers, and implementers to interpret complex modelling outputs and develop evidence-informed climate change mitigation measures across multiple spatial scales, including countries, sub-basins and climatic zones, which is very useful for transboundary applications in large basins.

The case study in the Volta River Basin revealed a slight increase in the net inflow under climate change over 2021–2050, driven by an increase in rainfall, and resulting in an increase in the future exploitable water and the total outflow of the basin. The projected increase in net inflow could benefit the Volta River Basin if appropriate measures are implemented for efficient water allocation and management per activity sector. The water storage capacity of the Volta River Basin could be increased to better satisfy the water requirements for agriculture and hydropower generation, which are the priorities of Burkina Faso and Ghana, besides the basic water needs for domestic uses. However, the high inter-annual variability of runoff could be a constraint. Nature-based solutions would be valuable for mitigating the impacts of floods and droughts. The adopted solutions and strategies should consider trade-offs among activity sectors to optimize the water-energy-food-ecosystem nexus.

In this era of big data sustained by satellite imagery, artificial

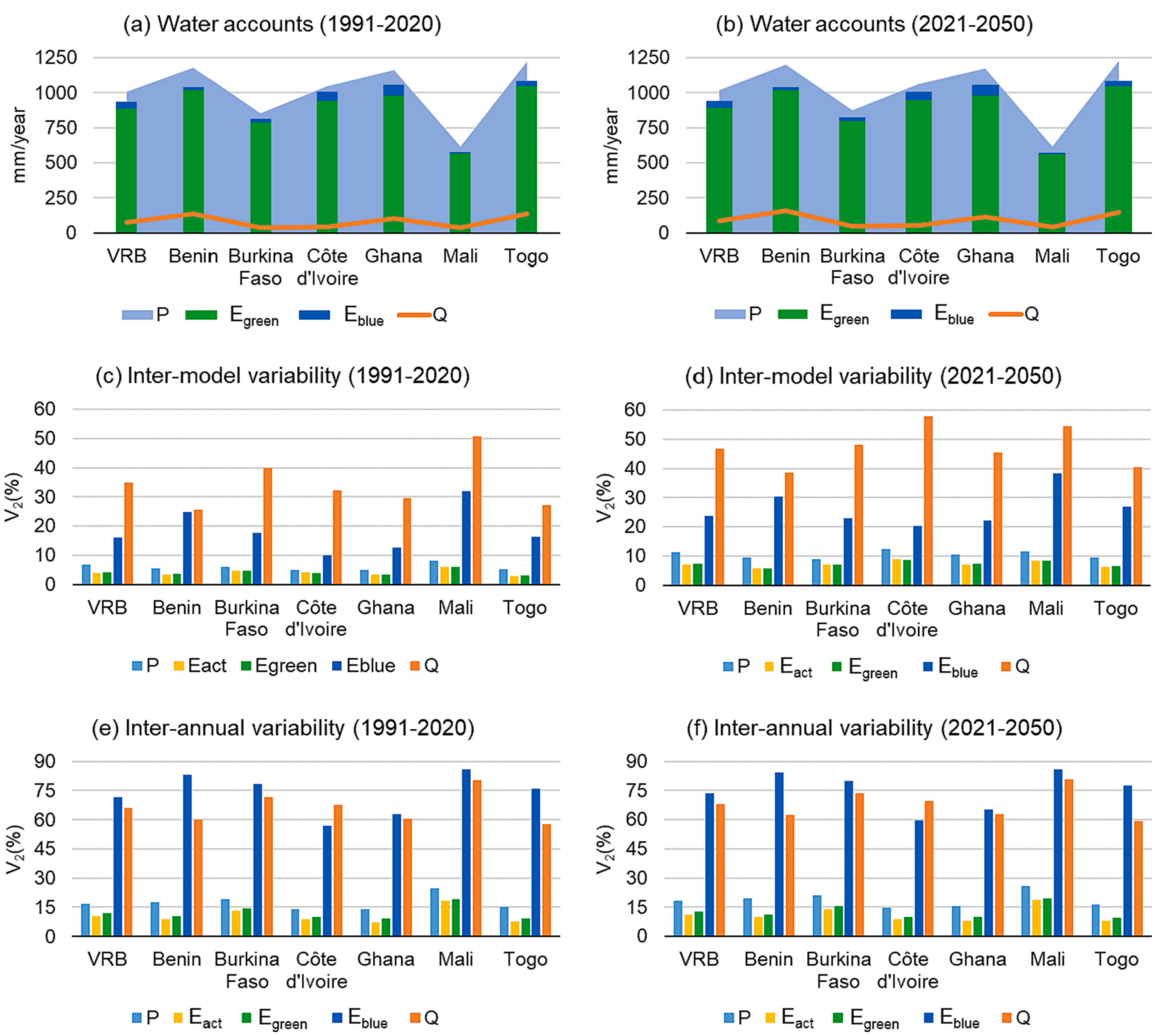

Fig. 14. Long-term average of annual water accounts (a, b) with the associated inter-model variability across RCM-GCM combinations (c, d) and inter-annual variability (e, f) for the VRB and its riparian countries over the historical (1991–2020) and future (2021–2050) periods.

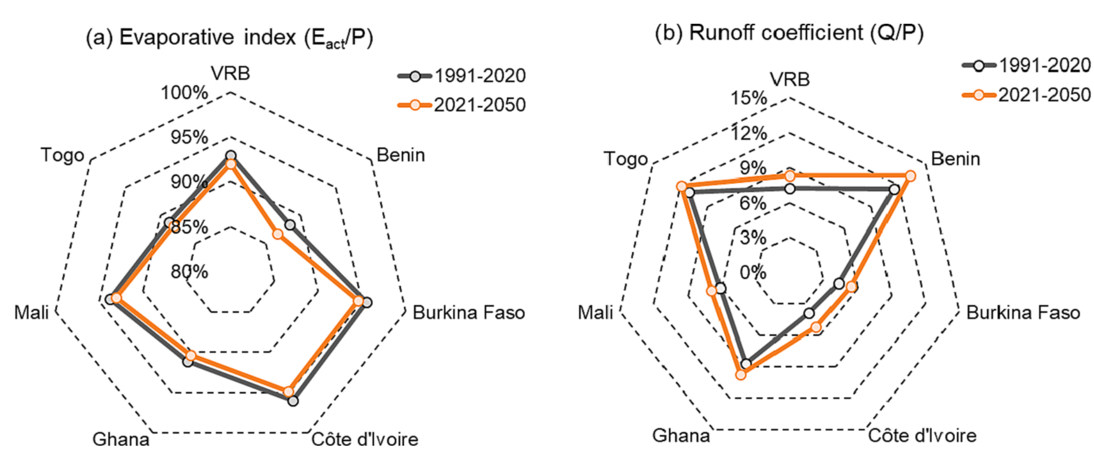

Fig. 15. Long-term average annual evaporative index (a) and runoff coefficient (b) for the VRB and its riparian countries over the historical (1991–2020) and future (2021–2050) periods.

intelligence and digital tools, context-specific and demand-driven cross-sectoral solutions should be developed to support a resilient socio-economic development. However, open access to good quality in-situ data is a prerequisite to calibrating and validating models and tools for water monitoring and management, which can be supported with user-delivered information and citizen science. Additionally,

Table 6
Repartition of key water accounts across spatial domains in the Volta River Basin. The colour scale indicates ranked values from the lowest (red) to the highest (blue).

Long-term average (km^3/year)		Historical period (1991-2020)					Future period (2021-2050)				
Spatial scales / Water accounts		P	E_{act}	E_{green}	E_{blue}	Q	P	E_{act}	E_{green}	E_{blue}	Q
Basin	VRB	419.6	388.8	368.7	20.1	30.3	425.5	390.4	370.4	20.0	35.2
Climatic zones	Sahelian	4.4	4.1	4.1	0.1	0.3	4.4	4.1	4.0	0.1	0.3
	Sudano-Sahelian	114.2	109.5	105.9	3.6	4.6	116.5	110.6	106.9	3.8	5.9
	Sudanian	143.1	134.6	129.1	5.5	8.3	145.3	135.1	129.7	5.4	10.2
	Guinean	157.9	140.6	129.7	10.9	17.2	159.3	140.6	129.8	10.8	18.8
Sub-basins	Black Volta	138.1	131.8	126.2	5.5	6.2	140.9	133.0	127.4	5.7	7.8
	White Volta	103.3	98.4	94.5	3.9	4.8	104.6	98.7	94.8	3.9	5.9
	Oti	83.7	75.4	72.8	2.6	8.2	84.8	75.5	72.9	2.6	9.3
	Lower Volta	94.5	83.2	75.2	8.0	11.2	95.3	83.2	75.3	7.9	12.2
Countries	Benin	18.1	16.0	15.7	0.4	2.1	18.5	16.0	15.7	0.4	2.5
	Burkina Faso	150.2	143.5	138.6	4.9	6.5	153.4	145.1	140.1	5.0	8.3
	Côte d'Ivoire	14.1	13.5	12.7	0.9	0.5	14.3	13.6	12.7	0.8	0.7
	Ghana	194.2	177.0	164.2	12.9	16.9	196.0	177.1	164.3	12.7	19.1
	Mali	10.7	10.0	9.9	0.2	0.7	10.7	10.0	9.8	0.2	0.7
	Togo	32.3	28.7	27.7	0.9	3.6	32.6	28.7	27.7	0.9	3.9

transboundary information exchange among the riparian states of the basin is essential to bolster resilience and foster regional development in the face of the worsening impacts of climate change. Consequently, sustainable progress in water resources management in the region is only possible under a strong collaboration between scientists, development practitioners and policymakers. These efforts will enhance water governance and strengthen water security in the Volta River Basin.

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CRediT authorship contribution statement

Moctar Dembélé: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Elga Salvadore:** Conceptualization, Methodology, Writing – review & editing. **Sander Zwart:** Conceptualization, Writing – review & editing, Funding acquisition. **Natalie Ceperley:** Conceptualization, Writing – review & editing, Funding acquisition. **Grégoire Mariéthoz:** Conceptualization, Writing – review & editing, Resources, Supervision, Project administration, Funding acquisition. **Bettina Schaefli:** Conceptualization, Writing – review & editing, Resources, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.130092.

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