Assessing Impacts of Climate Variability and Land Use/Land Cover Change on the Water Balance Components in the Sahel Using Earth Observations and Hydrological Modelling

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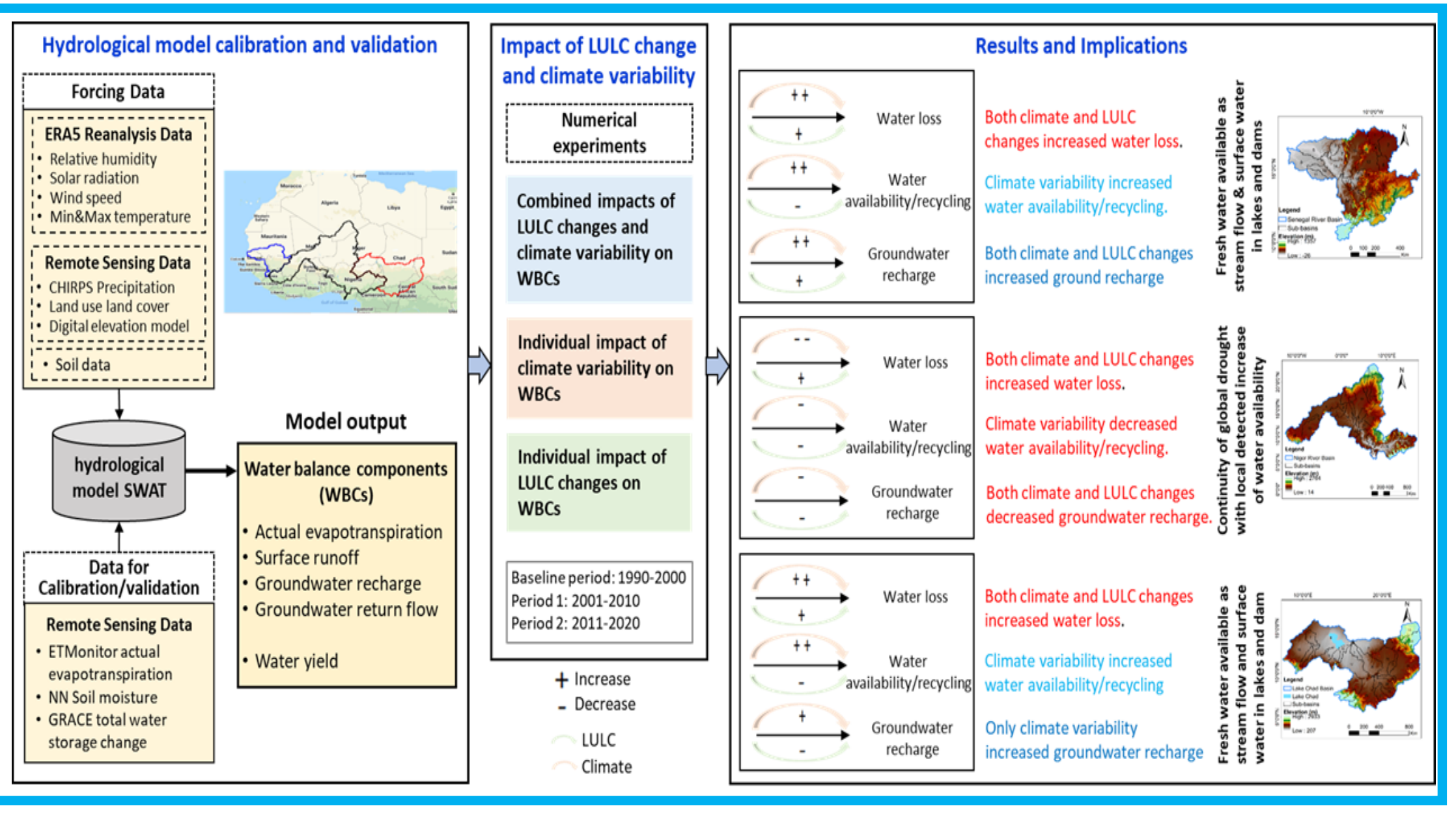
Abstract: The investigation of the hydrological responses to land use/land cover (LULC) change and climate variability is essential for understanding catchment hydrology, particularly in a vulnerable zone to global changes such as the Sahel region. Hence, our study contributed to separating and assessing the impacts of LULC change and climate variability on water balance components in the Sahel at the basin and sub-basin. Three basins were selected as study cases due to their importance in terms of catchment area (i.e. Senegal river, Niger river and Lake Chad basins). In this work, we have applied Soil and Water Assessment Tool (SWAT) model coupled with remote sensing retrievals of actual evapotranspiration (ETa) and surface soil moisture (SSM). To separate the impacts of the two aforementioned factors, two numerical experiments were designed: (i) climate variability effects by applying frozen LULC while changing the climate; (ii) LULC change impacts by applying frozen climate while changing LULC. The results revealed that, overall in the 2010s compared to the 1990s, the combined impact of LULC change and climate variability as well as separate effect of climate showed an increase in surface runoff, groundwater recharge and return flow in Senegal river and Lake Chad basins, while in Niger river basin most of all water balance components were declined. Frozen climate and change in LULC showed that spreading of natural vegetation at the expense of bare land led to an increase in actual ET and a decrease in surface runoff in the three watersheds, while in Senegal river basin it shows a slight increase in groundwater recharge and return flow. At sub-basin level, the analysis of LULC change showed that the gain in cropland and urban areas at the expense of the forest in some sub-basins, led to a local increase in surface runoff. This implies a better redistribution of water downstream and compensates the deficit in surface runoff caused by natural vegetation at the expense of bare land in some other catchments, i.e. a beneficial increase in fresh water availability. These changes at the same time with high intensity and long duration precipitation, this is likely to be a source of inundation and soil erosion in some small catchments in Niger river basin. Globally, the climate variability had a dominant impact on increasing water balance components resulting an increase in fresh water availability, with an extension and recovery of lake area in Lake Chad, which also increased groundwater return flow to rivers and water recycling within Senegal river and Lake Chad basins. In contrast, the LULC change was the major driver of decreasing the surface runoff, which could be a reason for lake area depletion in Lake Chad. At the same time, the two factors led to increasing water scarcity in Niger river basin. These outcomes emphasize the crucial role of water recycling which is the amount of water transferred from a sub-basin upstream to the next downstream within the watershed as well as give a good hydrological insight about water and land management in the study area. These findings are relevant to water resource management and to advance towards water-related Sustainable Development Goals (SDGs).

Graphical Abstract


Hydrological model calibration and validation

Forcing Data
- ERA5 Reanalysis Data
  - Relative humidity
  - Solar radiation
  - Wind speed
  - Min&Max temperature
- Remote Sensing Data
  - CHIRPS Precipitation
  - Land use land cover
  - Digital elevation model
- Soil data

hydrological model SWAT

Model output
Water balance components (WBCs)
- Actual evapotranspiration
- Surface runoff
- Groundwater recharge
- Groundwater return flow
- Water yield

Data for Calibration/validation
Remote Sensing Data
- ETMonitor actual evapotranspiration
- NN Soil moisture
- GRACE total water storage change

Impact of LULC change and climate variability

Numerical experiments
Combined impacts of LULC changes and climate variability on WBCs
Individual impact of climate variability on WBCs
Individual impact of LULC changes on WBCs

Baseline period: 1990-2000
Period 1: 2001-2010
Period 2: 2011-2020

+ Increase
- Decrease
LULC
Climate

Results and Implications

Water loss: Both climate and LULC changes increased water loss.
Water availability/recycling: Climate variability increased water availability/recycling.
Groundwater recharge: Both climate and LULC changes increased ground recharge
Fresh water available as stream flow & surface water in lakes and dams

Water loss: Both climate and LULC changes increased water loss.
Water availability/recycling: Climate variability decreased water availability/recycling.
Groundwater recharge: Both climate and LULC changes decreased groundwater recharge.
Continuity of global drought with local detected increase of water availability

Water loss: Both climate and LULC changes increased water loss.
Water availability/recycling: Climate variability increased water availability/recycling
Groundwater recharge: Only climate variability increased groundwater recharge
Fresh water available as stream flow and surface water in lakes and dam

Keywords: African Sahel, SWAT model, ETMonitor, remote sensing soil moisture, LULC change, climate variability.

Introduction:

Understanding the response of a watershed to climate variability is complex because it is non-linear due to the concurrent response of LULC to the same variability, response modulated by anthropic interventions. The non-linearity is due to the modification of a watershed hydrological properties because of LULC changes. This process is particularly relevant and complex under arid and semi-arid conditions such as in the Sahel, where changes in water availability lead to large and rapid changes in LULC, through the natural response of ecosystems to water and to the efforts. A better understanding of the separate impacts of LULC and climate variability on water balance components is needed to develop effective land management policies towards sustainable water security

Several studies paid attention to investigating the effects of LULC change and climate variability on hydrological response in the Sahel region using hydrological models or remote sensing data:

- Some studies have investigated the hydrological response to LULC change and climate variability in the Sahel before and during the drought **[1]**.
- Some studies have reported a recovery in vegetation and rainfall in the Sahel **[2]**.
- Some studies have investigated the hydrological response to LULC change and climate variability in the Sahel before the drought and in the post-drought period **[3]**.

Almost of all previous studies were not able to separate the impacts of LULC change and climate variability due to the type of the used data (remote sensing data (NDVI) and ground observations data (precipitation and surface runoff)). Some other studies have applied hydrological models to separate the contribution of the two factors in changing hydrological response but in small catchments (<1000 km2).
Most of the studies focused on surface runoff and streamflow, while other water balance components are equally important such as groundwater recharge and groundwater return flow. Moreover, water recycling as a consequence of LULC change was not evaluated. Most studies compared the drought period (1970s and 1980s) with the years past the drought till 2010.
A study at basin level and sub-basin level, after the last recovery of vegetation and rainfall, has not been done yet.

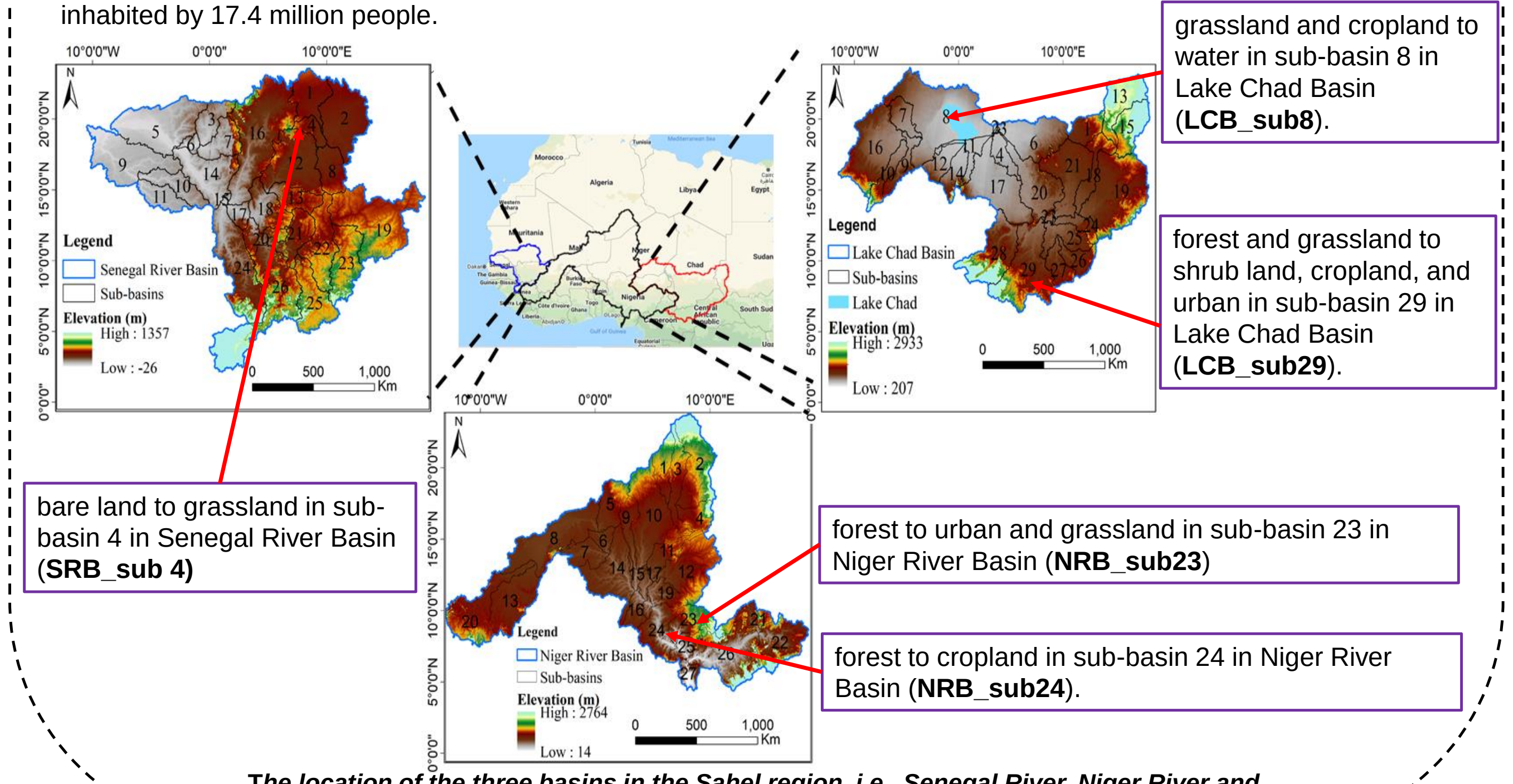
Objective:

The objectives of this study are:

1) to evaluate the separate impacts of climate variability and LULC on water balance components using a physically-based hydrological model
2) to estimate the responses of different water balance components to climate variability and LULC changes at basin and sub-basin scale
3) to compare the relative contributions of these different factors and identify which one has the dominant impacts

Study area

The Senegal River basin (SRB) is located in the western part of the Sahel region, with a total drainage area of approximately 375,000 Km2 and a length of 1800 km. The region is inhabited by 3.5 million people.
The Niger River basin (NRB) has a catchment area of 2.1x106 km2 and a length of 4200 km. This region is inhabited by more than 100 million people and spans nine countries.
The Lake Chad basin (LCB) is the largest endorheic lake basin in the world, and it is located in the center of the African Sahel between 5.19–25.29°N latitude and 6.85–24.45°E longitude with an area of 2,5 106 km2. The region is inhabited by 17.4 million people.


grassland and cropland to water in sub-basin 8 in Lake Chad Basin (**LCB_sub8**).

forest and grassland to shrub land, cropland, and urban in sub-basin 29 in Lake Chad Basin (**LCB_sub29**).

bare land to grassland in sub-basin 4 in Senegal River Basin (**SRB_sub 4)**

forest to urban and grassland in sub-basin 23 in Niger River Basin (**NRB_sub23**)

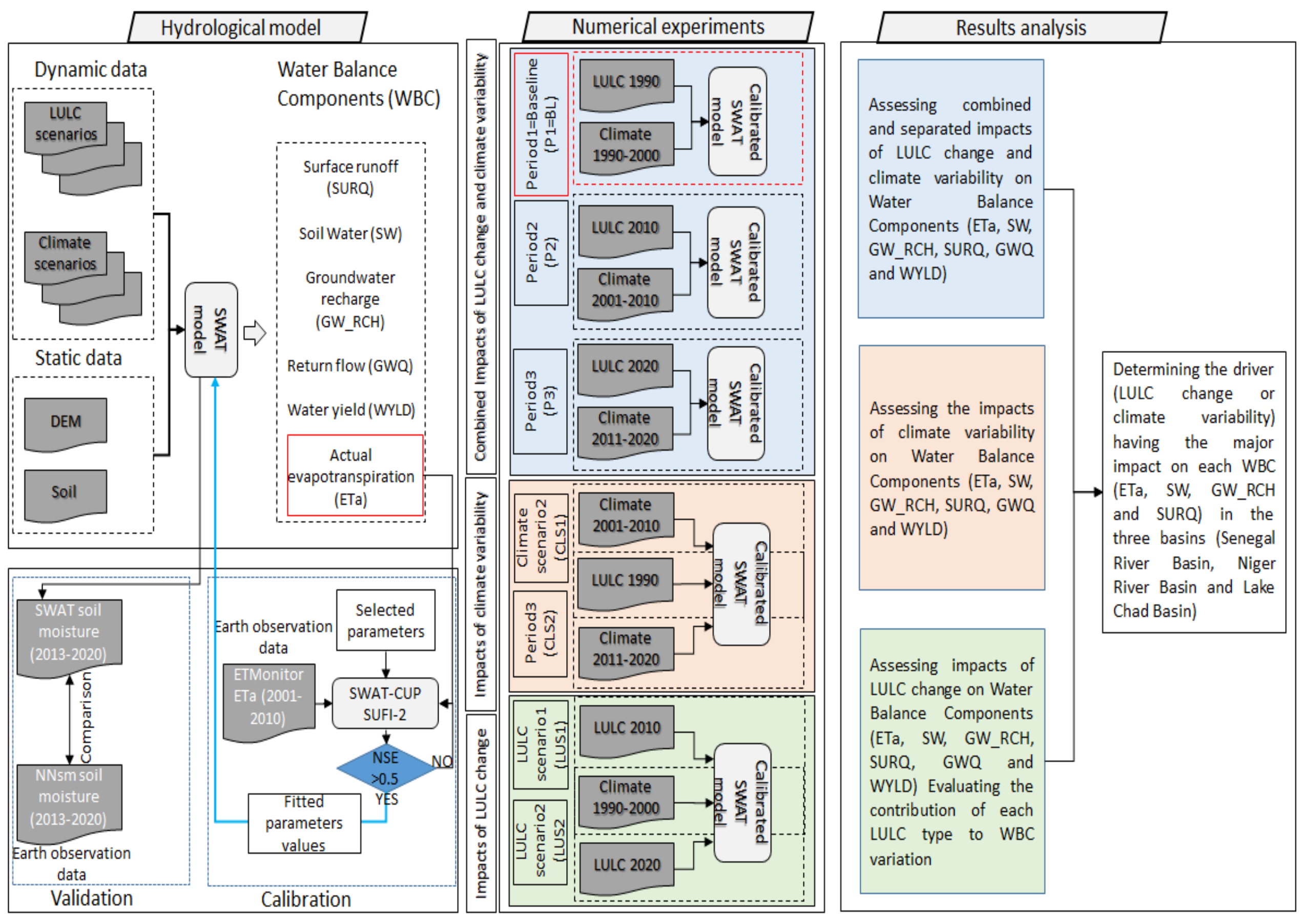
forest to cropland in sub-basin 24 in Niger River Basin (**NRB_sub24**).

The location of the three basins in the Sahel region, i.e., Senegal River, Niger River and Lake Chad basins.

Method

Hydrological model: Soil and Water Assessment Tool (SWAT) **[4]** which was calibrated and validated by using remote sensing data, and this was well described in our previous paper **[5].**
Then the calibrated SWAT was used to separate and assess the impacts of LULC change and climate variability on WBCs. The study period was split into 3 sub periods:

Period 1 =Base Line (P1=BL)= Climate 1990–2000 with LULC1990, Period 2 (P2)= Climate 2001–2010 with LULC2010 and Period 3 (P3)= Climate 2011–2020 with LULC2020.
Three climate scenarios were used in this study, Climate 1990–2000=base line (BL), Climate 2001–2010=Climate Scenario 1 (CLS1) and Climate 2011–2020= Climate Scenario 2 (CLS2).
Three LULC scenarios were used in this work, LULC1990=base line (BL), LULC2010=Land Use Scenario 1 (LUS1) and LULC2020= Land Use Scenario 2 (LUS2).


Hydrological model
Dynamic data: LULC scenarios; Climate scenarios
Static data: DEM; Soil
SWAT model
Water Balance Components (WBC): Surface runoff (SURQ); Soil Water (SW); Groundwater recharge (GW_RCH); Return flow (GWQ); Water yield (WYLD); Actual evapotranspiration (ETa)
Validation: SWAT soil moisture (2013-2020); Comparison; NNsm soil moisture (2013-2020); Earth observation data
Calibration: Earth observation data; ETMonitor ETa (2001-2010); Selected parameters; SWAT-CUP SUFI-2; NSE >0.5; NO; YES; Fitted parameters values

Numerical experiments
Combined Impacts of LULC change and climate variability: Period1=Baseline (P1=BL): LULC 1990, Climate 1990-2000, Calibrated SWAT model; Period2 (P2): LULC 2010, Climate 2001-2010, Calibrated SWAT model; Period3 (P3): LULC 2020, Climate 2011-2020, Calibrated SWAT model
Impacts of climate variability: Climate scenario2 (CLS1): Climate 2001-2010; LULC 1990; Period3 (CLS2): Climate 2011-2020; Calibrated SWAT model
Impacts of LULC change: LULC scenario1 (LUS1): LULC 2010; Climate 1990-2000; LULC scenario2 (LUS2): LULC 2020; Calibrated SWAT model

Results analysis
Assessing combined and separated impacts of LULC change and climate variability on Water Balance Components (ETa, SW, GW_RCH, SURQ, GWQ and WYLD)
Assessing the impacts of climate variability on Water Balance Components (ETa, SW, GW_RCH, SURQ, GWQ and WYLD)
Assessing impacts of LULC change on Water Balance Components (ETa, SW, GW_RCH, SURQ, GWQ and WYLD) Evaluating the contribution of each LULC type to WBC variation
Determining the driver (LULC change or climate variability) having the major impact on each WBC (ETa, SW, GW_RCH and SURQ) in the three basins (Senegal River Basin, Niger River Basin and Lake Chad Basin)

Study workflow: 1) Hydrological modeling including Calibration/Validation of SWAT model; 2) Numerical Experiments including assessment of the combined impact of LULC and climate change, the impact only by climate change and the impact only by LULC change on each of the simulates water balance components; 3) Results Analysis

(1) The combined impacts by LULC change and climate variability on WBCs
It is calculated following the following equation: $\Delta \mathbf{WBC_{Pi}} = \mathbf{WBC_{Pi}} - \mathbf{WBC_{BL}}$
ΔWBC_{Pi} is the change in a water balance component between the corresponding period (Pi = P2 or P3) and the baseline period (P1), WBC_{Pi} is the value of the water balance component in the corresponding period, WBC_{BL} is the value of the water balance component in the baseline period
(1) The impacts of climate variability on WBCs
It is calculated following the following equation: $\Delta \mathbf{WBC_{CLi}} = \boldsymbol{WBC_{CLSi}} - \boldsymbol{WBC_{BL}}$
$\Delta \mathrm{WBC_{CLi}}$ is the change in a water balance component between the corresponding period (CLS1 or CLS2) and the baseline period, WBC_{CLSi} is the value of the water balance component for either CLS1 or CLS2, WBC_{BL} is the value of a water balance component in the baseline period.
(1) The impacts of LULC changes on WBCs
It is calculated following the following equation: $\Delta \boldsymbol{WBC_{LUi}} = \boldsymbol{WBC_{LUSi}} - \boldsymbol{WBC_{BL}}$
$\Delta WBC_{\mathrm{LUi}}$ is the change in a water balance component between the corresponding period (LUS1 or LUS2) and the baseline period, WBC_{LUSi} is the value of a water balance component for either LUS1 or LUS2, WBC_{BL} is the value of a water balance component in the baseline period.

An indicator of water recycling: the ratio of Water outflow to Water inflow

The SWAT provides options to describe the use of streamflow in the river channels and allows inter-sub-basin water transfers **[6]**. We proposed to use the ratio of WYLD/PREC as an indicator for potential water recycling, i.e. the ratio of out/in-recycling (R_{oiR}), calculated as: $R_{oiR} = WYLD/PREC$
where R_{oiR} is the ratio of out/in recycling, $PREC$ is the sum of precipitation over all sub-basins (km3), $WYLD$ (km3) is the net amount of water that leaves the sub-basin and contributes to streamflow in the reach and calculated as:

$$WYLD = SURQ + LATQ + GWQ - Q_{TLOSS}$$

where $LATQ$ (km3) is the lateral flow contribution to streamflow; and Q_TLOSS (km3) is the transmission loss.

Impact score of LULC change and climate variability on water balance components

To identify which factor dominated the impact, we calculated the impact scores of LULC change and climate variability following the

$$\mathrm{CR\_WBC_{CLi}} = \Delta\mathrm{WBC_{CLi}} / \Delta\mathrm{WBC}$$
$$\mathrm{CR\_WBC_{Lui}} = \Delta\mathrm{WBC_{Lui}} / \Delta\mathrm{WBC}$$

$\mathrm{CR\_WBC_{CLi}}$ and $\mathrm{CR\_WBC_{LUi}}$ are the separate impact scores on water balance components, i.e., actual ET, SW, GW_RCH, and SURQ, caused by climate variability and caused by LULC change, respectively; $\Delta\mathrm{WBC}$ is the change in a water balance component caused by the combined impact of LULC change and climate variability relative to baseline.

Calibration/validation Performance metrics

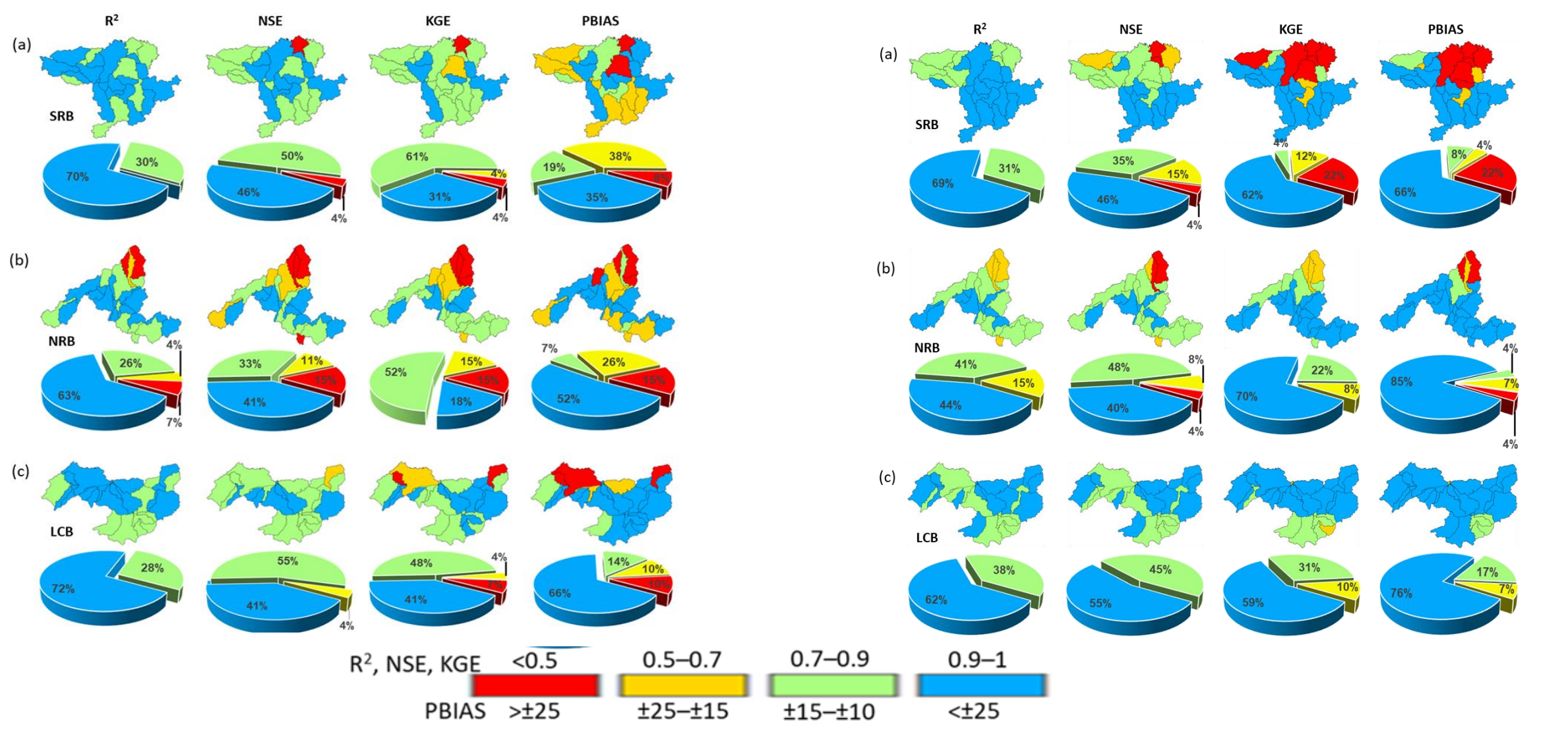
***Performance metrics used to evaluate the calibration and validation* [7]**

Performance Metrics	Equations	Descriptions
Coefficient of determination	$R^2 = \frac{[\sum_i (ET_{Rs,i} - \overline{ET_{Rs}})(ET_{s,i} - \overline{ET_s})]^2}{\sum_i (ET_{s,i} - \overline{ET_s})^2 \sum_i (ET_{Rs,i} - \overline{ET_{Rs}})^2}$	where ET_{Rs} represents satellite-based ETa values; ET_s represents simulated ETa values; $\overline{ET_{Rs}}$ represents mean satellite-based ETa values; $\overline{ET_s}$ represents mean simulated ETa values. r is the Pearson product correlation coefficient between satellite-based ETa and the simulated ETa; α is the standard deviation of the simulated ETa over the standard deviation of the satellite-based ETa; β is the ratio of the mean simulated ETa to the satellite-based ETa.
Nash–Sutcliffe Efficiency	$NSE = 1 - \frac{\sum_i (ET_{Rs} - ET_s)_i^2}{\sum_i (ET_{s,i} - \overline{ET_s})^2}$	
Kling–Gupta Efficiency	$KGE = 1 - \sqrt{(r-1)^2(\alpha-1)^2(\beta-1)^2}$	
Percent bias	$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(ET_{Rs} - ET_s)i}{\sum_{i=1}^{n}(ET_{Rs})}$	

Results

Calibration based on actual evapotranspiration and validation by using soil moisture

In the three basins, the calibration using monthly ETMonitor retrievals of actual ET indicated a good performance with values of R2, NSE, and KGE greater than 0.7 and PBIAS values lower than ±15%. The validation for the three basins using monthly NNsm soil moisture showed that R2, NSE, and KGE were higher than 0.7 and PBIAS lower than ±15%.

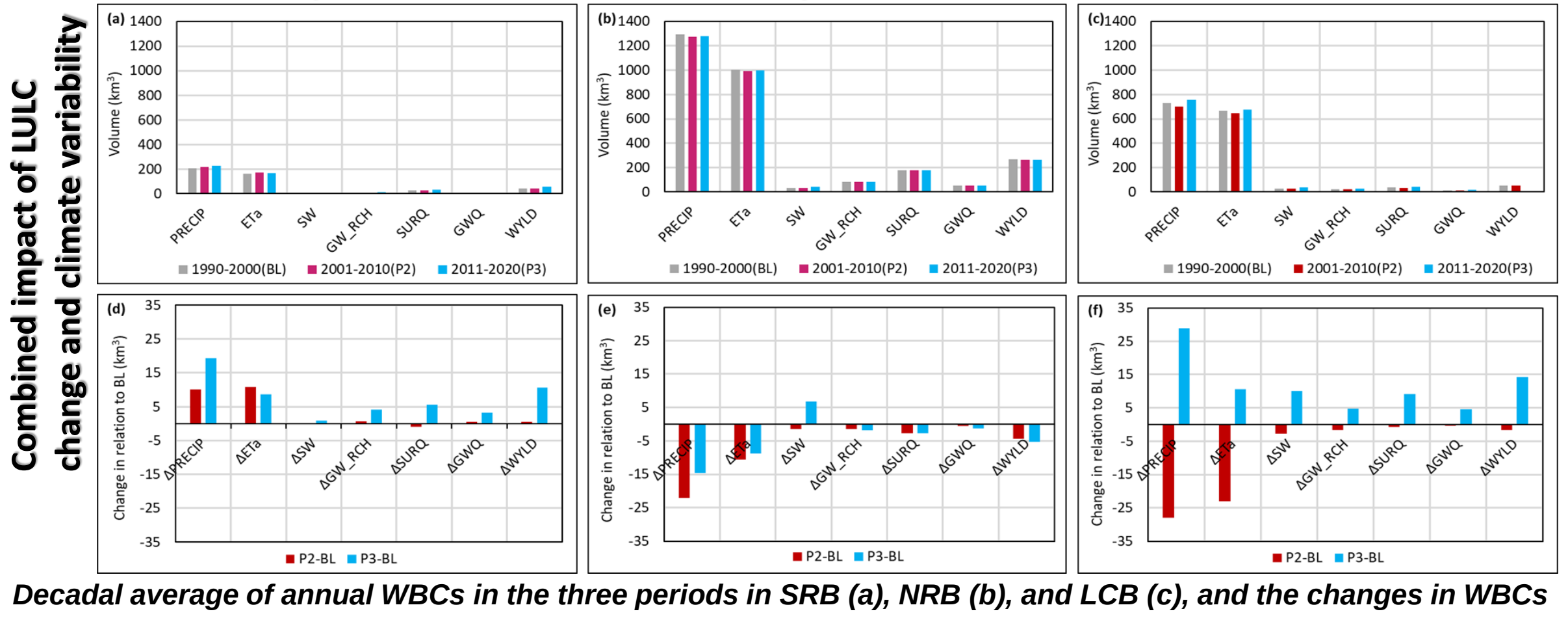


Spatial distribution of performance metrics (R², NSE, KGE, and PBIAS) of calibration of the SWAT model using ETa of ETMonitor product for SRB (a), NRB (b), and LCB (c) from 2001 to 2010.

Spatial distribution of performance metrics (R2, NSE, KGE, and PBIAS) of validation of the simulated soil moisture by the calibrated SWAT model against NNsm-SM (a2, b2, and c2) for SRB (a), NRB (b), and LCB (c) from 2013 to 2020.

Combined Impacts of LULC changes and climate variability on water balance components

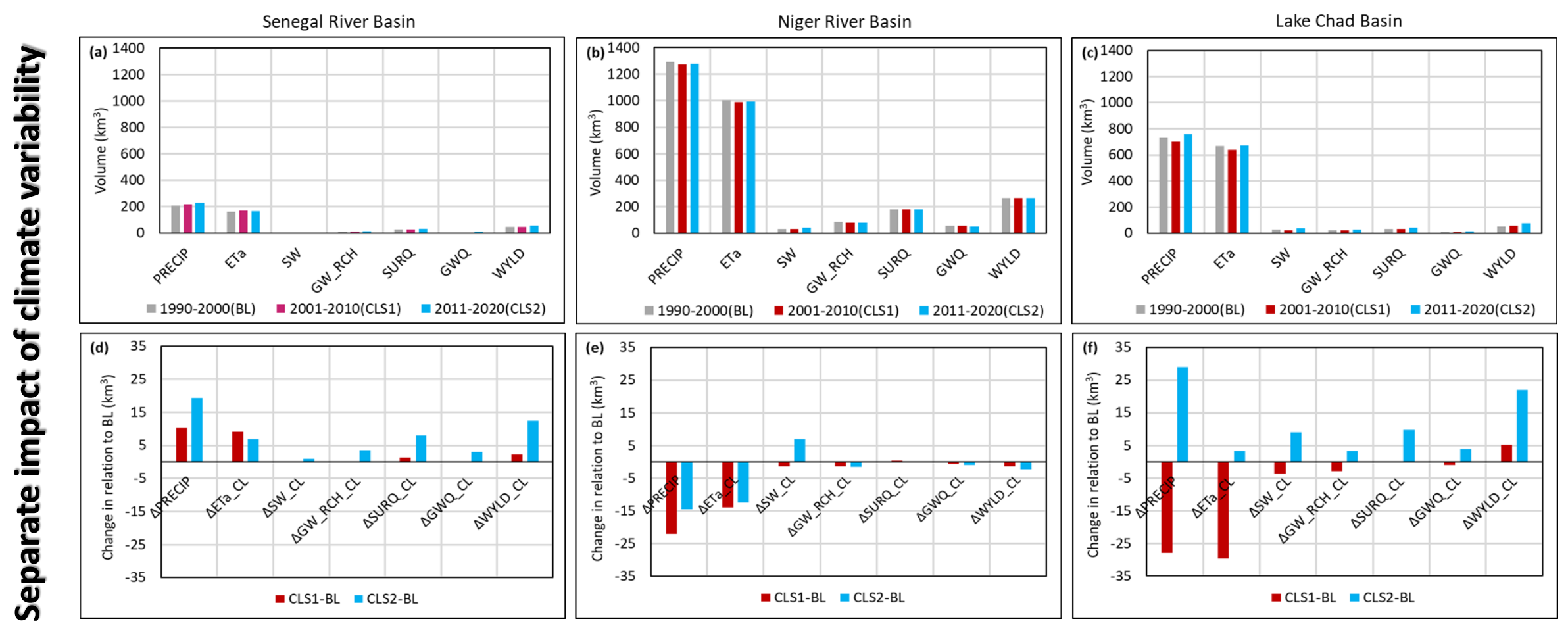
The change in WBCs were evaluated during P2 (2001-2010) and P3 (2011-2020) compared to P1=BL (1990-2000). In P2 (2001-2010), all WBCs decreased in NRB and LCB, while in contrary in SRB most WBCs increased except for surface runoff. In P3 (2011-2020), all WBCs increased in SRB and LCB, while in NRB most WBCs decreased except for soil water content (SW).



Decadal average of annual WBCs in the three periods in SRB (a), NRB (b), and LCB (c), and the changes in WBCs caused by combined impacts of LULC and climate variability in P2 and P3 relative to the baseline period in SRB (d), NRB (e) and LCB (f).

separate impacts of climate variability on water balance components

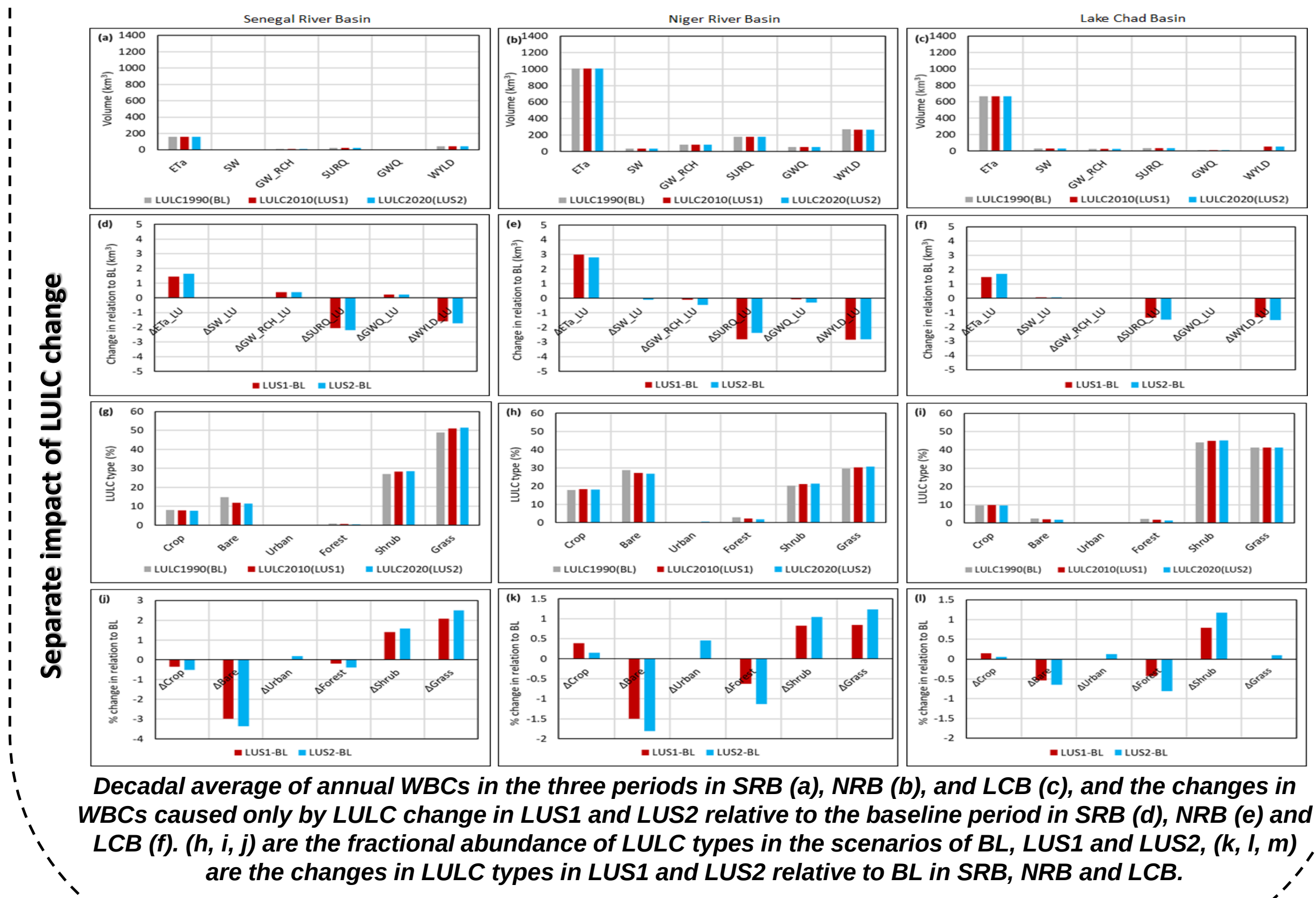
The increase in rainfall in SRB and LCB led to an increase in most of all WBCs specifically fresh water availability and water recycling.
In NRB the decrease in rainfall led to fresh water scarcity which may led to the desertification.



Decadal average of annual WBCs in the three periods in SRB (a), NRB (b), and LCB (c), and the changes in WBCs caused only by climate variability in CLS1 and CLS2 relative to the baseline period in SRB (d), NRB (e) and LCB (f).

separate impacts of LULC changes on water balance components

In the three watersheds the increase of natural vegetation at the expanse of bare land led to an increase in ETa which triggered a decline in surface runoff.
An increase in crop land in NRB and LCB minimized the decline of surface runoff compared to the decrease of this latter in SRB.



Decadal average of annual WBCs in the three periods in SRB (a), NRB (b), and LCB (c), and the changes in WBCs caused only by LULC change in LUS1 and LUS2 relative to the baseline period in SRB (d), NRB (e) and LCB (f). (h, i, j) are the fractional abundance of LULC types in the scenarios of BL, LUS1 and LUS2, (k, l, m) are the changes in LULC types in LUS1 and LUS2 relative to BL in SRB, NRB and LCB.

An indicator of water recycling: the ratio of Water outflow to Water inflow

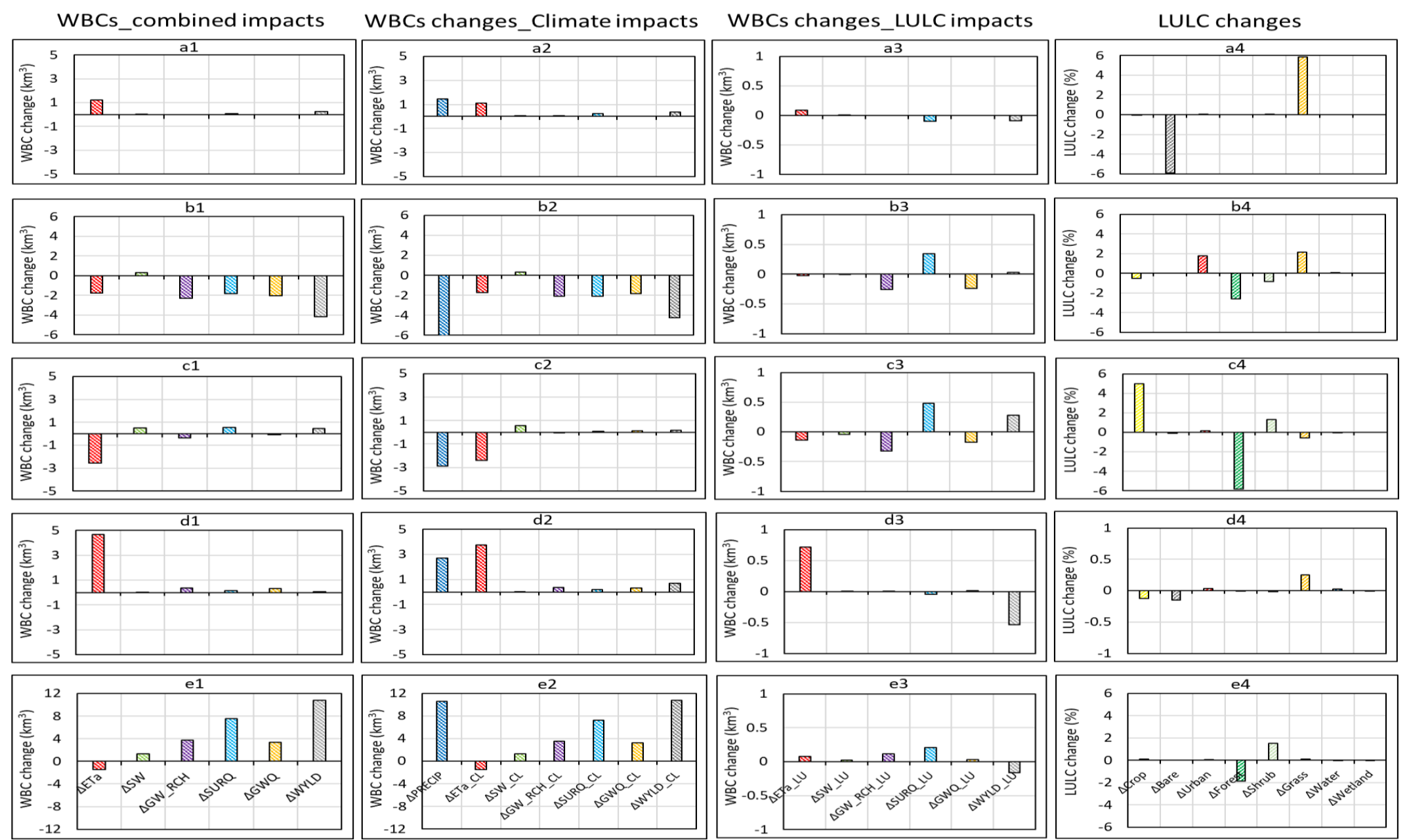
Water yields from the watershed were about 20%, 7% and 20% of the precipitation in SRB, LCB and NRB respectively.
An amount of water is transferred from sub-basins upstream to the next sub-basin downstream within the watershed, water recycling.
Water recycling provides an additional volume of water which could be diverted for irrigation or to another reservoir from upstream to downstream.

Sum of annual precipitation and water yield (km3/year) in each period in the three watersheds and the ratio of water in and water out. It is assumed that Q_TLOSS = 0 on annual basis.

Basin	Scenario	PREC = W_{in} (km³)	SURQ (km³)	GWQ (km³)	LATQ (km³)	WYLD = W_{out} (km³)	R_{oiR} (km³)
LCB	BL	728.82	35	11	6.5	52.5	0.07
	LUS1	728.82	33.68	10.95	6.49	51.12	0.07
	LUS2	728.82	33.53	10.93	6.50	50.96	0.07
SRB	BL	206.69	26.30	4.31	12.92	43.53	0.21
	LUS1	206.69	24.25	4.53	13.14	41.92	0.20
	LUS2	206.69	24.11	4.53	13.14	41.78	0.20
NRB	BL	1294.54	180.21	54.73	28.00	262.94	0.20
	LUS1	1294.54	177.41	54.65	28.04	260.10	0.20
	LUS2	1294.54	177.83	54.45	27.88	260.16	0.20

Impacts of LULC changes and climate variability on water balance components at sub-basin level

The increase in most of all WBCs in different sub-basins was mainly caused by climate variability.
The sub-basin 24 and 23 in NRB showed an increase in surface runoff, despite the rainfall deficit, due to the increase in cropland and urban at the expense of forest.



Average annual water balance components in the study area in the Lake Chad Basin based on SWAT-simulated output before (Uncalibrated) and after (Calibrated) calibration. (ETa: actual evapotranspiration; SW: soil water content; PERC: perception; SURQ: surface runoff; GW_Q: groundwater recharge; WYLD: water yield; LATQ: lateral runoff.

Impact score of LULC change and climate variability on water balance components

Over all in the three watersheds the climate has the major impact on increasing/ decreasing all water balance components.
LULC change has the dominant impact in decreasing the surface runoff.

The impact scores of LULC change (CR_LU) and climate variability (CR_CL) on WBCs in the P2 (2001–2010) and P3 (2011–2020) for the basins of SRB, NRB, and LCB in the Sahel. Numbers in bold indicate the dominant impacts.

Basin	Period	CR	Actual ET	SW	GW_RCH	SURQ
SRB	P1	CR_CL	**0.85**	**1.15**	0.40	**-1.53**
		CR_LU	0.13	-0.21	0.57	**2.35**
	P2	CR_CL	**0.79**	**0.96**	**0.87**	**1.45**
		CR_LU	0.19	0.04	0.09	-0.40
NRB	P1	CR_CL	**1.32**	**0.95**	**1.01**	-0.09
		CR_LU	-0.29	0.00	0.06	**1.01**
	P2	CR_CL	**1.43**	**1.02**	**0.82**	0.02
		CR_LU	-0.32	-0.01	0.24	0.86
LCB	P1	CR_CL	**1.05**	**0.99**	**0.94**	-0.64
		CR_LU	-0.06	-0.02	-0.01	**1.78**
	P2	CR_CL	**0.83**	**0.97**	**0.98**	**1.15**
		CR_LU	0.16	0.01	0.00	-0.16

Discussion

- In the SRB, the rise in SURQ, GW_RCH, and return flow (GWQ), during both CLS1 (2001–2010) and CLS2 (2011–2020) compared to baseline (1990–2000), Oyebande and Odunuga (2010) **[8]**.
- In the NRB, the decline in SURQ, GW_RCH, and GWQ caused by the deficit in rainfall during both CLS1 and, Descroix et al. (2018) **[9]**.
- In LCB, the decline in SURQ during CLS1 was clearly caused by rainfall deficit, Mahmood and Jia (2019).
- The re-greening of the region by expansion of grassland and shrub land led to an increase in actual ET and a decrease in SURQ, Yonaba et al. (2021) and Ogutu et al. (2021). This vegetation recovery played a major role in increasing GW_RCH and soil water content (SW), Marshall et al. (2012). This finding applied to three watersheds, but the change was larger in NRB and LCB than that in SRB, Mahmood and Jia (2019).
- Both climate variability and LULC change had nearly similar impacts on the hydrological response in the SRB. The LCB was more sensitive to the LULC change during P2. This process significantly reduced water availability by decreasing the SURQ and increasing the water loss via evapotranspiration, because of the higher actual ET. In contrast, climate variability was the main driver of increasing SURQ during P3, Pham-Duc et al. (2020) **[10]**.

Conclusions

- An increase in rainfall in both the SRB and the LCB, leading to a rise in freshwater availability and water recycling because of the increase in water yield. In the NRB, the shortage of water supply continued, resulting in the continuation of the drought in the basin, which showed that the Sahelian hydrological paradoxes did not apply at basin level.
- In LCB and SRB, the increase in water yield, caused by climate variability, played an important role in improving water availability in the basin.
- The man-made extension of cropland at the expense of the forest loss had an important role in mitigating the decrease in surface runoff.
- The continuous population growth led to an increase in the cultivated area at the expense of forest loss, i.e., a further increase in surface runoff. The latter may contribute to water recycling through water transfer from a sub-basin upstream to the next sub-basin downstream. These findings emphasized the crucial role of water recycling within the watershed, as well as giving a good hydrological insight into the interrelation of water and land management in the study

Major references:

1. Albergel, J., 1987. Sécheresse, dbsertification et ressources en eau de surface - Application aux petits bassins du Burkina Faso, The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. no. 168, 1987.
2. Jiang, M., Jia, L., Menenti, M., Zeng, Y., 2022. Understanding spatial patterns in the drivers of greenness trends in the Sahel-Sudano-Guinean region. Big Earth Data: 1-20. DOI:10.1080/20964471.2022.2146632
3. Dardel, C. et al., 2014. Rain-Use-Efficiency: What it Tells us about the Conflicting Sahel Greening and Sahelian Paradox. Remote Sensing, 6(4): 3446-3474. DOI:10.3390/rs6043446
4. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modeling and assessment part I: Model development. Journal of the American Water Resources Association 1998, 34, 73-89, doi:10.1111/j.1752-1688.1998.tb05961.x.
5. Bennour, A. et al., 2022. Calibration and Validation of SWAT Model by Using Hydrological Remote Sensing Observables in the Lake Chad Basin. Remote Sensing: 14,1511. DOI:https://doi.org/10.3390/rs14061511.
6. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. Soil & Water Assessment Tool Theoretical Documentation Version 2009; Texas Water Resources Institute; Texas, USA, 2011.
7. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of* Agricultural *and Biological Engineers* **2007**, *50*, 885-900, doi:10.13031/2013.23153.
8. Oyebande, L., Odunuga, S., 2010. Climate Change Impact on Water Resources at the Transboundary Level in West Africa : The Cases of the Senegal , Niger and Volta Basins. 163-172.
9. Descroix, L. et al., 2018. Evolution of surface hydrology in the Sahelo-Sudanian Strip: An updated review. Water, 10. DOI:10.3390/w10060748.
10. Pham-Duc, B. et al., 2020. The Lake Chad hydrology under current climate change. Scientific Reports, 10: 1-10. DOI:10.1038/s41598-020-62417-w