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By

**KAH MATTY**

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Speciality: Climate Change and Water Resources

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# IMPACT OF CLIMATE VARIABILITY AND LAND USE/LAND COVER CHANGES ON STREAMFLOW IN THE CONTINENTAL GAMBIA RIVER BASIN

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**Supervisors:**

| | | |
|---|---|---|
| **YALO Nicaise** | Full Professor | Universite d'Abomey-Calavi, Benin |
| **FAYE Cheikh** | Full Professor | Université Assane Seck de Ziguinchor, Senegal |

**German Advisor**

| | | |
|---|---|---|
| **LISCHEID Habil Gunnar** | Full Professor | Leibniz Centre for Agricultural Research (ZALF) & University of Potsdam, Germany |

**Reviewers:**

| | | |
|---|---|---|
| **NDAO Saidou** | Full Professor | University Iba Der Thiam of Thies, Senegal |
| **ALAMOU Adéchina Eric** | Full Professor | UNSTIM, Bénin |
| **JIMOH O. David** | Full Professor | Federal University of Technology, Minna, Nigeria |

**JURY**

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|---|---|---|
| **LAWIN Agnidé Emmanuel** | Full Professor, University of Abomey Calavi, UAC, Benin | President |
| **NDAO Saidou** | Full Professor, University Iba Der Thiam of Thies, Senegal | Reviewer |
| **ALAMOU Adéchina Eric** | Full Professor, UNSTIM, Bénin | Reviewer |
| **JIMOH O. David** | Full Professor, Federal University of Technology, Minna, Nigeria | Reviewer |
| **BOSSA Aymar Yaovi** | Associate Professor, University of Abomey Calavi, UAC, Benin | Examiner |
| **YALO Nicaise** | Full Professor, Universite d'Abomey-Calavi, Benin | Supervisor |
| **FAYE Cheikh** | Full Professor, Université Assane Seck de Ziguinchor, Senegal | Supervisor |
| **LISCHEID Habil Gunnar** | Full Professor, Leibniz Centre for Agricultural Research (ZALF) & University OF Potsdam, Germany | Advisor |

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**THESE**

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***Changements climatiques et Ressources en Eau***

Par

**KAH MATTY**

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Spécialité: Changements Climatiques et Ressources en Eau

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# IMPACT DE LA VARIABILITÉ CLIMATIQUE ET DES CHANGEMENTS D'OCCUPATION ET D'UTILISATION DES SOLS SUR L'ÉCOULEMENT DANS LE BASSIN CONTINENTAL DU FLEUVE GAMBIE

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**Directeurs de thèse:**

| | | |
|---|---|---|
| **YALO Nicaise** | Professeur Titulaire | Universite d'Abomey-Calavi, Benin |
| **FAYE Cheikh** | Professeur Titulaire | Université Assane Seck de Ziguinchor, Senegal |
| **German Advisor** | | |
| **LISCHEID Habil Gunnar** | Professeur Titulaire | Leibniz Centre for Agricultural Research (ZALF) & University Potsdam, Germany |

**Rapporteurs:**

| | | |
|---|---|---|
| **NDAO Saidou** | Professeur Titulaire | University Iba Der Thiam of Thies, Senegal |
| **ALAMOU Adéchina Eric** | Professeur Titulaire | UNSTIM, Bénin |
| **JIMOH O. David** | Professeur Titulaire | Federal University of Technology, Minna, Nigeria |

## JURY

| | | |
|---|---|---|
| **LAWIN Agnidé Emmanuel** | Professeur Titulaire, University of Abomey Calavi, UAC, Benin | Président |
| **NDAO Saidou** | Professeur Titulaire, University Iba Der Thiam of Thies, Senegal | Rapporteur |
| **ALAMOU Adéchina Eric** | Professeur Titulaire, UNSTIM, Bénin | Rapporteur |
| **JIMOH O. David** | Professeur Titulaire, Federal University of Technology, Minna, Nigeria | Rapporteur |
| **BOSSA Aymar** | Associate Professor, University of Abomey Calavi, UAC, Benin | Examinateur |
| **YALO Nicaise** | Professeur Titulaire, Universite d'Abomey-Calavi, Benin | Directeur de thèse |
| **FAYE Cheikh** | Professeur Titulaire, Université Assane Seck de Ziguinchor, Sénégal | Directeur de thèse |
| **LISCHEID Habil Gunnar** | Professeur Titulaire, Leibniz Centre for Agricultural Research (ZALF) & University of Potsdam, Germany | Conseiller de thèse |

WASCAL

**Dedication**

I dedicate this work to Allah Almighty and my parents, who gave me the education that has brought me this far. I also dedicate it to my husband and siblings for their support throughout this journey. I am very grateful.

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To all who contributed directly or indirectly to the success of this work, I am truly grateful.

**Abstract**

This study assessed the impact of climate variability and land use change on streamflow in the Continental Gambia River Basin (CGRB), West Africa using the Soil and Water Assessment Tool (SWAT). The specific objectives were to: (i) analyse recent trends in hydroclimatic time series (rainfall, temperature, and streamflow), (ii) investigate the spatio-temporal changes in land use/land cover over the past three decades, (iii) integrate local perceptions on water use, socio-economic activities, and water management; and (iv) assess the impact of climate variability and land use/land cover changes on streamflow. Data used in the study include hydroclimatic data (observation and satellite) and Landsat images (1988, 2002 & 2022) for LULC mapping. The study found significant hydroclimatic shifts in the CGRB from 1990 to 2022. Precipitation increased notably after 2008, transitioning from predominantly dry conditions to wetter trends, as shown by SPI and SPEI indices. Temperature exhibited a steady rise post-2000 and streamflow trends at Simenti Station followed a similar pattern, with increasing discharge after 2010. In terms of land use, burned areas declined significantly (-88.77%), followed by water bodies (-55.75%) and savanna (-15.85%). Conversely, the Bowe steppe class increased markedly (120.08%), with moderate gains in forest (12.08%) and agricultural/bare soil areas (10.68%) respectively. These changes influenced hydrological processes, with forest recovery generally enhancing streamflow and groundwater recharge, while the expansion of bowe & steppe restricted infiltration and lateral flow. From 1988 to 2002, streamflow and surface runoff slightly decreased due to forest and savanna loss, while from 1988 to 2022, streamflow increased slightly, driven by forest recovery but moderated by bowe & steppe expansion. Climate variability had a more pronounced impact, with streamflow rising significantly between 1990–2000 and 2012–2022 (up to 72%), driven by increased precipitation and extreme weather events. This also led to substantial increases in surface runoff and groundwater recharge. The combined effects of climate and land use change further amplified these trends, with forest regrowth enhancing infiltration, while bowe & steppe expansion limited lateral flow.

**Keywords**: Gambia River Basin, Land Use/Land Cover, Climate Variability, SWAT Model, Water Management, Hydrological Processes

**Résumé**

Cette étude a évalué l'impact de la variabilité climatique et du changement d'utilisation et de l'occupation des terres (LULC) sur le débit des cours d'eau dans le bassin continental du fleuve Gambie (CGRB), en Afrique de l'Ouest, à l'aide de l'outil d'évaluation des sols et de l'eau (SWAT). Les objectifs spécifiques étaient les suivants : (i) analyser les tendances récentes dans les séries temporelles hydroclimatiques (précipitations, température et débit), (ii) étudier les changements spatio-temporels de l'utilisation et de l'occupation des terres au cours des trois dernières décennies, (iii) intégrer les perceptions locales sur l'utilisation de l'eau, les activités socio-économiques et la gestion afin de comprendre les réponses locales aux changements de disponibilité en eau, et (iv) évaluer l'impact de la variabilité climatique et des changements de LULC sur le débit des cours d'eau. Les données utilisées comprennent des données hydroclimatiques (observées et satellitaires) ainsi que des images Landsat (1988, 2002 et 2022) pour la cartographie du LULC. L'étude a révélé d'importants changements hydroclimatiques dans le CGRB entre 1990 et 2022. Les précipitations ont augmenté de manière significative après 2008, passant de conditions majoritairement sèches à des conditions plus humides, comme le montrent l'indice de précipitation standardisé (SPI) et l'indice standardisé de précipitation et d'évapotranspiration (SPEI). La température a augmenté de manière constante après 2000, et les tendances du débit à la station de Simenti ont suivi une évolution similaire, avec une augmentation du débit après 2010. En termes d'occupation des terres, les zones brûlées ont fortement diminué (-88,77 %), suivies par les plans d'eau (-55,75 %) et la savane (-15,85 %). En revanche, les zones de bowé et de steppe ont connu une forte augmentation (+120,08 %), tandis que les forêts (+12,08 %) et les zones agricoles/sols nus (+10,68 %) ont enregistré des hausses plus modérées. Ces changements ont influencé les processus hydrologiques. La régénération des forêts a généralement favorisé le débit des cours d'eau et la recharge des eaux souterraines, tandis que l'expansion des zones de bowé et de steppe a limité l'écoulement latéral. Entre 1988 et 2002, le débit des cours d'eau et le ruissellement de surface ont légèrement dimunié en raison de la perte de forêts et de savanes, ayant impacté les précipitations. Entre 1988 et 2022, le débit a légèrement augmenté sous l'effet de la régénération forestière, mais cette augmentation a été modérée par l'expansion des zones de bowé et de steppe. La variabilité climatique a eu un impact plus prononcé, avec une augmentation du débit pouvant atteindre 72 % entre les périodes 1990–2000 et 2012–2022, principalement due à l'augmentation des précipitations et aux événements climatiques extrêmes. Cette évolution a également entraîné une augmentation du ruissellement de surface et de la recharge des nappes phréatiques. Les effets combinés de la variabilité climatique et des changements de LULC ont amplifié ces tendances. La régénération des forêts a amélioré l'infiltration, tandis que l'expansion des zones de bowé et de steppe a limité l'écoulement latéral.

Mots clés : Bassin continental du fleuve Gambie, utilisation et couverture des terres, variabilité climatique, modèle SWAT, gestion de l'eau, processus hydrologiques.

## Introduction

Les cours d'eau d'Afrique de l'Ouest ont connu des changements hydrologiques importants depuis les années 1970, principalement liés à la baisse des précipitations et à l'augmentation de la variabilité climatique (Bodian et al., 2018 ; Faye et Mendy, 2018 ; Traoré, 2014). Ces évolutions ont entraîné une diminution des débits, un décalage des saisons des pluies et une augmentation des événements extrêmes tels que les sécheresses et les inondations (Oki et Kanae, 2006 ; Niang et al., 2015). Elles ont également affecté la disponibilité des ressources en eau et la productivité agricole.

Outre la variabilité climatique, les changements d'utilisation des terres, notamment l'urbanisation et l'expansion agricole, jouent un rôle majeur dans la modification des processus hydrologiques (Salmoral et al., 2015 ; Mas et al., 2017 ; Das et al., 2018). Le bassin du fleuve Gambie reste relativement peu étudié par rapport à d'autres bassins d'Afrique de l'Ouest, malgré des dynamiques marquées liées aux changements hydroclimatiques et d'utilisation des terres (Faye et Mendy, 2018 ; Mbaye et al., 2015). La plupart des études existantes se concentrent sur les impacts climatiques, sans intégrer pleinement les interactions avec les changements d'utilisation des terres (Thiaw, 2017 ; Faye et al., 2019).

Cette thèse vise à analyser les effets combinés et individuels de la variabilité climatique et des changements d'utilisation et de couverture des terres (LULC) sur le débit des cours d'eau dans le bassin du fleuve Gambie. L'approche repose sur l'analyse des séries temporelles hydroclimatiques, l'évaluation spatio-temporelle du LULC et la modélisation hydrologique à l'aide du modèle SWAT. L'étude intègre également les perceptions locales afin de mieux comprendre les dynamiques socio-environnementales et de rapprocher les résultats scientifiques des réalités du terrain (UN, 1992 ; Hope, 2009).

Les résultats visent à soutenir la gestion durable des ressources en eau en fournissant des éléments sur les tendances passées et les évolutions possibles selon différents scénarios climatiques et d'utilisation des terres (Mbaye et al., 2015 ; Niang et al., 2015 ; Arnell, 2018). Cette recherche contribue ainsi à une meilleure compréhension du fonctionnement hydrologique du bassin du fleuve Gambie et propose des orientations pour une gestion adaptative face aux pressions environnementales actuelles.

## Zone d'étude

Le bassin du fleuve Gambie couvre environ 77 000 km². Il s'étend en latitude de 11°22'N, au Fouta-Djalon, à 14°40'N, au sud-est du Ferlo, et en longitude de 11°13'W à 16°42'W, jusqu'à Banjul où le fleuve se jette dans l'océan Atlantique (figure 1). Le fleuve prend sa source dans les hautes terres du Fouta-Djalon en Guinée, à une altitude d'environ 1 125 mètres, puis traverse trois pays : la Guinée (15,25 % du bassin), le Sénégal (72,30 %) et la Gambie (12,45 %) (Séne et al., 2024). Le bassin est divisé en deux parties selon le régime hydrologique du fleuve : le bassin amont, ou bassin continental, qui s'étend jusqu'à la station de Gouloumbou au Sénégal, et le bief maritime situé en aval. Le fleuve évolue sous un climat tropical caractérisé par une longue saison sèche (novembre à mai) et une saison des pluies plus courte (juin à octobre). La majeure partie du bassin appartient à la zone soudano-guinéenne, avec des précipitations annuelles variant d'environ 600 mm dans le nord à 1 600 mm dans le sud (Faty et al., 2023). La végétation est dominée par des forêts denses dans la partie méridionale, qui évoluent vers des savanes et des steppes arbustives en allant vers le nord. Les activités humaines, notamment la déforestation, l'expansion des zones habitées et la croissance démographique, accentuent la dégradation des sols et la perte de couverture végétale. Ces dynamiques réduisent la capacité de rétention d'eau, augmentent l'érosion et prolongent les périodes d'étiage, en particulier dans les zones septentrionales plus sèches (Lamagat et al., 1990).

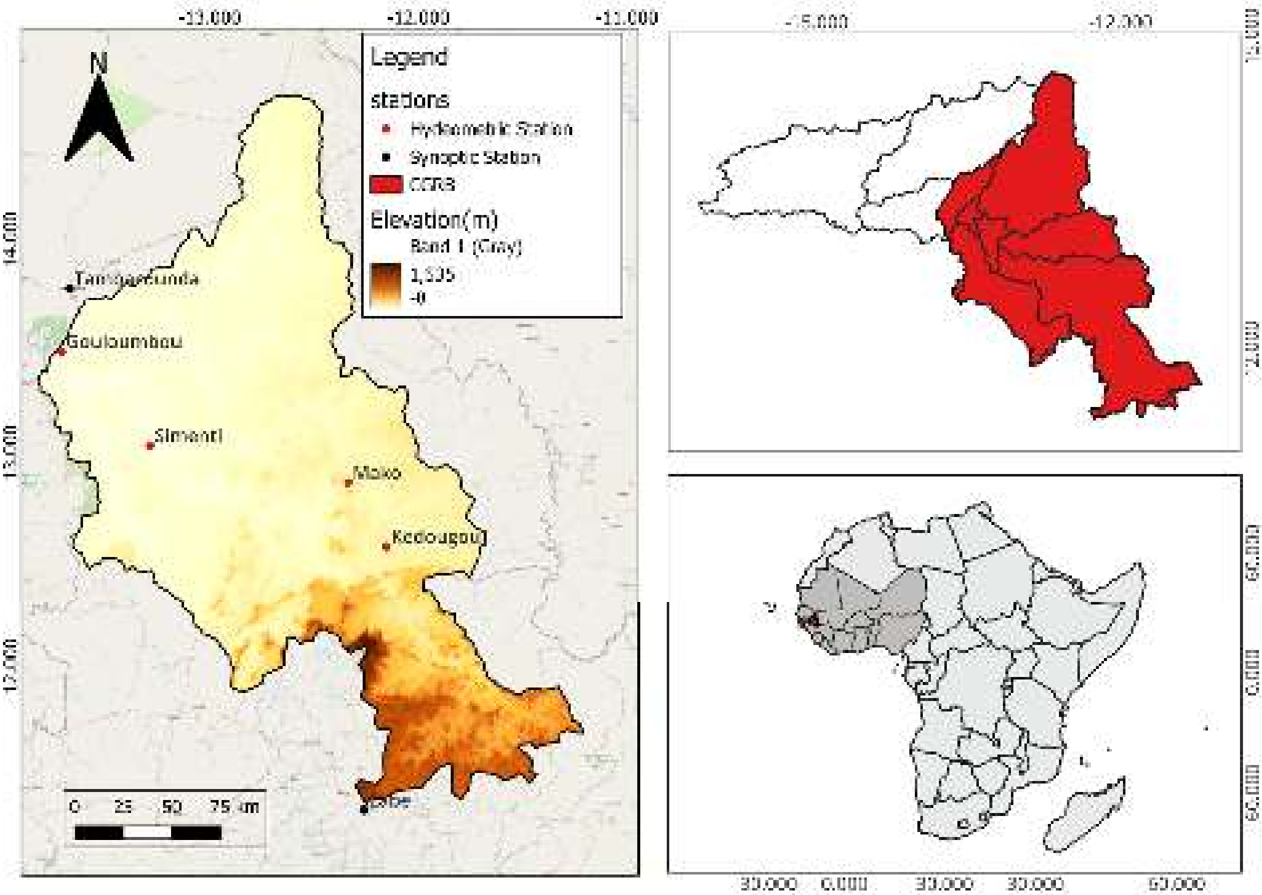


**Figure 1 : Carte de localisation du bassin**

**Matériel et méthodes**

Cette étude repose sur une combinaison de sources de données, de méthodes et d'outils analytiques afin d'évaluer les changements d'utilisation et de couverture des terres (LULC) et les dynamiques environnementales dans le bassin continental du fleuve Gambie (CGRB). Des images satellites Landsat multi-dates (1988, 2002 et 2022) ont été traitées en appliquant des corrections géométriques et radiométriques. Une classification hiérarchique non supervisée a permis d'identifier les différentes catégories de LULC. Les données hydroclimatiques, incluant les précipitations, la température, le débit des cours d'eau et l'évapotranspiration, proviennent de sources telles que CHIRPS et ERA5. Ces données ont été traitées et analysées à l'aide de plusieurs outils, notamment TerrSet, Climate Data Operators (CDO), Grid Analysis Display System (GrADS) et Stata, afin d'assurer leur cohérence et leur fiabilité. Le modèle hydrologique Soil and Water Assessment Tool (SWAT) a été utilisé pour simuler le débit des cours d'eau en fonction de différents scénarios climatiques et de LULC. La mise en place du modèle a inclus la délimitation du bassin versant, la définition des unités de réponse hydrologique (HRU), ainsi que les étapes d'analyse de sensibilité, de calibration et de validation. Un modèle numérique de terrain (MNT) de 30 m de résolution a permis de délimiter 28 sous-bassins couvrant une superficie de 41 806,68 km². Les cartes d'utilisation des terres et des sols ont été reclassées afin d'assurer leur compatibilité avec SWAT. L'évapotranspiration potentielle a été estimée à l'aide de la méthode de Hargreaves, choisie en raison de la disponibilité limitée des données climatiques. L'analyse de sensibilité a été réalisée à l'aide de l'algorithme SUFI-2 dans SWAT-CUP, ce qui a permis d'identifier 19 paramètres influençant significativement le débit des cours d'eau. Le modèle a été calibré à partir des données de débit journalier pour la période 1990–2009, puis validé sur la période 2011–2022 à la station de Simenti. Les performances du modèle ont été évaluées à l'aide de l'efficacité de Nash-Sutcliffe (NSE), du coefficient de détermination ($R^2$) et du biais en pourcentage (PBIAS). Des données spatiales d'évapotranspiration et de hauteur des eaux souterraines ont également été utilisées comme contraintes supplémentaires pour améliorer la robustesse du modèle. Les scénarios ont été élaborés afin d'isoler les effets de la variabilité climatique, des changements de LULC et de leur interaction sur le débit des cours d'eau. Les données climatiques ont été divisées en trois périodes (1990–2000, 2001–2011 et 2012–2022), correspondant aux années d'utilisation des terres (1988, 2002 et 2022). En complément de l'analyse quantitative, une enquête de terrain a été menée dans plusieurs villages situés le long du fleuve Gambie. Les données socio-économiques ont été collectées à travers des entretiens, des discussions de groupe et des observations directes. L'enquête a porté sur les dynamiques démographiques, les activités économiques, les impacts du climat et des changements d'utilisation des terres, ainsi que les stratégies locales de gestion des ressources en eau. Les données ont été collectées à l'aide de l'outil Kobo Collect. Enfin, les tendances hydroclimatiques ont été analysées à l'aide des tests non paramétriques de Mann-Kendall modifié et de Pettitt sur la période 1990–2022, afin d'identifier les tendances et les ruptures dans les séries temporelles. Cette approche intégrée, combinant télédétection, modélisation hydrologique, analyse statistique et données socio-économiques, permet une compréhension globale et cohérente des dynamiques hydrologiques et environnementales dans la zone d'étude.

**Résultats et discussion**

Entre 1990 et 2022, les changements climatiques et d'utilisation des terres dans la région de Gouloumbou ont mis en évidence des tendances marquées des précipitations, de la température et de l'occupation des sols. Les précipitations ont augmenté de manière significative après 2008, avec un passage de conditions majoritairement sèches à des conditions plus humides, accompagné d'une reprise notable après 2015. La température a également montré une augmentation progressive après 2000. Les indices hydrologiques, notamment l'indice de débit normalisé (IDN), ainsi que les tendances de débit, indiquent une évolution vers des conditions plus humides après 2010, caractérisée par une augmentation du débit des cours d'eau. L'évolution de l'occupation des sols entre 1988 et 2022 révèle une expansion des forêts et des zones agricoles, tandis que la savane et les plans d'eau ont régressé. Les zones de bowé et de steppe se sont étendues, en particulier dans les parties centrale et septentrionale du bassin. L'expansion des terres agricoles et des sols nus reflète une intensification des activités humaines. Ces transformations traduisent une dynamique contrastée, avec une tendance vers des conditions plus humides, mais accompagnée d'une dégradation de certaines composantes du paysage, notamment la diminution des masses d'eau et des zones brûlées. L'impact de la variabilité climatique et des changements d'utilisation et d'occupation des terres (LULC) sur les processus hydrologiques a été analysé à l'aide du modèle SWAT à travers neuf scénarios. L'analyse a comparé différentes configurations de LULC (1988, 2002, 2022) et de périodes climatiques (1990–2000, 2001–2011, 2012–2022) afin d'évaluer leurs effets individuels et combinés. Les résultats montrent que les changements de LULC entre 1988 et 2002 ont entraîné une légère diminution du débit des cours d'eau et du ruissellement de surface, principalement en raison de la réduction des surfaces forestières et de la savane. L'expansion des zones de bowé et de steppe a contribué à limiter l'infiltration. En revanche, entre 1988 et 2022, la régénération forestière a légèrement augmenté le débit, bien que cet effet ait été atténué par l'expansion continue des zones de bowé et de steppe. La variabilité climatique apparaît comme le facteur dominant. Entre les périodes 1990–2000 et 2012–2022, des augmentations importantes du débit des cours d'eau, du ruissellement de surface et de la recharge des nappes phréatiques ont été observées, en lien avec l'augmentation des précipitations et la fréquence des événements extrêmes. Les effets combinés de la variabilité climatique et des changements de LULC ont amplifié ces dynamiques, avec une augmentation globale des flux hydrologiques et une diminution relative de l'évapotranspiration.

**Conclusion**

Les analyses de tendances, réalisées à l'aide des tests de Mann-Kendall modifié et de Pettitt sur la période 1990–2022, mettent en évidence des changements significatifs des précipitations et de la température. Les précipitations ont augmenté de manière notable après 2008, traduisant une transition vers des conditions plus humides, tandis que la température a connu une hausse progressive depuis les années 2000. Ces évolutions se reflètent dans les tendances du débit, avec une augmentation significative observée après 2010. Les résultats montrent que la variabilité climatique constitue le principal facteur de modification des régimes hydrologiques dans le bassin du fleuve Gambie. Les changements d'utilisation et d'occupation des terres ont également influencé les processus hydrologiques, notamment en modifiant les capacités d'infiltration, de rétention et de ruissellement, mais leur impact reste secondaire par rapport aux facteurs climatiques. La déforestation, l'expansion agricole et l'extension des zones de bowé et de steppe ont contribué à la dégradation des conditions hydrologiques locales, en particulier sur la période 1988–2002. Toutefois, la régénération forestière observée entre 1988 et 2022 a partiellement compensé ces effets en favorisant une légère augmentation du débit des cours d'eau suite à la hausse des précipitations. Ces résultats soulignent la nécessité d'intégrer conjointement les facteurs climatiques et les dynamiques d'utilisation des terres dans les stratégies de gestion des ressources en eau. Une approche intégrée, fondée sur la gestion durable des terres et l'adaptation aux variations climatiques, est essentielle pour renforcer la résilience hydrologique du bassin et assurer une gestion efficace des ressources en eau à long terme.

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**List of Acronyms**

| | |
|---|---|
| **CHIRPS** | Climate Hazard Group Infrared Precipitation with Station Data |
| **CILSS** | Permanent Interstate Committee for Drought Control in the Sahel |
| **CSE** | Ecological Monitoring Centre |
| **DEM** | Digital Elevation Model |
| **DGPRE** | Directorate of Water Resources Management and Planning |
| **ECMWF** | European Centre for Medium-Range Weather Forecasts |
| **GIS** | Geographic Information System |
| **GCM** | General Circulation Models |
| **GDP** | Gross Domestic Product |
| **GW_Q** | Groundwater Contribution |
| **HRU** | Hydrologic Response Units |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ITD** | Inter-Tropical Discontinuity |
| **IWRM** | Integrated Water Resources Management |
| **k-NN** | k-nearest neighbour algorithm |
| **LAT_Q** | Lateral Flow |
| **LULCC** | Land Use and Land Cover Change |
| **m-MK** | Modified Mann–Kendall |
| **MUSLE** | Modified Universal Soil Loss Equation |
| **NASA** | National Aeronautics and Space Administration |
| **NSE** | Nash-Sutcliffe Efficiency |
| **PET** | Potential Evapotranspiration |
| **PBIAS** | Percentage Bias |
| **SAI** | Standardized Anomaly Index |
| **SFI** | Standardized Streamflow Index |

| | |
|---|---|
| **SPEI** | Standardized Precipitation Evapotranspiration Index |
| **SPI** | Standardized Precipitation Index |
| **SRTM** | Shuttle Radar Topography Mission |
| **SUFI-2** | Sequential Uncertainty Fitting Program |
| **SURF_Q** | Surface Runoff [mm] |
| **SWAT** | Soil and Water Assessment Tool |
| **SWAT-CUP** | SWAT Calibration and Uncertainty Programs |
| **UNCED** | United Nations Conference on Environment and Development |
| **WMO** | World Meteorological Organization |

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# 1 General Introduction

This chapter provides the study's background, outlines the problem statement and objectives, and reviews relevant literature. It examines trend and breakpoint analysis, land use/land cover change assessments, and hydrological modelling of watersheds, focusing on the impacts of climate and land use/land cover changes on water resources.

## 1.1 Context and Problem Statement

Since the 1970s, rivers in West Africa have experienced significant hydrological changes, primarily driven by reduced rainfall, resulting in a substantial decline in water resources (Faye and Mendy, 2018). The region has witnessed long-term reductions in rainfall, a decrease in the contribution of the wettest months to cumulative annual precipitation, shifting rainy seasons, increased frequency of dry spells, declining piezometric levels, and reduced river flows. These changes have had severe implications for the agricultural sector and the availability of natural resources, which are heavily dependent on stable water supplies.

While climate change and variability have long been recognized as critical factors influencing hydrological regimes, effective water resource management and planning require a thorough understanding of how these dynamics evolve over time. This necessitates the use of long-term hydroclimatic datasets, including rainfall and runoff, coupled with robust statistical analyses to identify trends, shifts, and anomalies in these time series (Traoré, 2014). Such analyses provide insights into the changing hydrological behaviour of river basins and inform sustainable water resource management strategies.

Despite the importance of understanding hydroclimatic variability, the Gambia River Basin has received comparatively little attention in recent research, especially when compared to other major West African basins like the Senegal River. Although several studies have examined the basin's hydrology, focusing on hydroclimatic variability and its impacts on water resources, hydrological modelling efforts using tools such as GR4J, GR2M, and BILAN have primarily focused on climatic influences, often overlooking the complex interactions between land use change and hydrology (Traoré, 2014; Thiaw, 2017; Bodian et al., 2018; Faye and Mendy, 2018; Faye et al., 2019). Few studies have examined the combined effects of climate variability and land use change on streamflow in the Gambia River Basin, particularly using integrated modelling approaches and long-term datasets.

## 1.2 Literature Review

Water resource management is one of the world's most pressing problems (Flint, 2004). It is a critical resource that is essential to all ecological and societal activities, such as food and energy production, transportation, waste disposal, industrial development, fish habitat, and human health. To meet their water needs, societies drain massive amounts of water from rivers, lakes, wetlands, and underground aquifers to supply cities, farms, and industry. The demand for the aforementioned purposes continues to rise, increasing the pressure on the freshwater resources of the world (Arnell, 2018; Thomas and Rösch, 2000). Nonetheless, freshwater resources are unevenly and irregularly distributed, with certain parts of the world suffering from severe water scarcity. As the world's population rises, this scenario will intensify, resulting in higher water use and, perhaps, increased contamination of surface and groundwater, not to mention the added threat of climate change. Under these conditions, the world's freshwater resources will become even more valuable than they are now, and may become a source of conflict in some of the world's international river basins. For this reason, the Integrated Water Resources Management (IWRM) strategy was proposed in 1992 during the International Conference on Water and Development in Dublin to avoid possible conflicts and make water resource management viable (UN, 1992). Since then, the IWRM has been seen as a viable option for ensuring long-term water resource management. Knowledge of water quality and quantity is one of the most important aspects of IWRM. Indeed, a balance between demands and available water is required. Knowledge appears to be the basis of the IWRM or a recommendation for its implementation. In West Africa, however, there is a lack of understanding about water resources. Due to a shortage of financial and personnel resources, national hydrological agencies are having trouble ensuring appropriate monitoring of water streams. As a result, West Africa's monitoring network is deteriorating, resulting in significant gaps in stream discharge series. These gaps in the series of hydrological data prevent specialists from having sufficient knowledge of water resources to properly manage and conduct design studies, which are required before constructing hydrological infrastructures (dams, anti-salt dikes, retention basins, and road infrastructure) for the benefit of the population.

At the other side of the hydrological extreme, majority of the world's population is subject to floods, with floods having the highest death and devastation toll of any of the other types of disasters. Floods, avalanches, landslides, and mudslides will become more common as the population grows. Too much or too little water can impede a developing/developed country's progress toward the UN Conference on Environment and Development (UNCED) and its vision of sustainable development. Every strategy aimed at improving water supply, preventing flooding, or meeting other human requirements alters the hydrological cycle in some manner. These changes affect the transportation of materials across the earth through natural geochemical cycles, as well as the numerous living animals that rely on the aquatic environment for survival. They may also be altering energy transport patterns around the world. As a result, it's reasonable to believe that credible information about freshwater supplies and water use would be readily available on a national, regional, and global scale. This is not the case, however. In many cases, the data collection and analysis are inadequate. A handful of countries lack the requisite institutions, while others are poorly equipped. Furthermore, unlike meteorological data, which is collected and exchanged through the World Meteorological Organization's (WMO) 'world weather watch,' there is no operational global system for collecting and exchanging this data for forecasting and other reasons. While a few countries have active systems for collecting statistics on water consumption, the majority do not, and as a result, water use figures are sparingly available. In the face of a future water crisis, it appears critical to increase this knowledge - the crisis could occur in the near future, or it could never occur. There can be no integrated river-basin planning and management without a thorough assessment of water resources, and the pursuit of sustainable development will remain a wild goose chase. For this reason, water management planners are facing significant uncertainties about future water supply and extreme events (such as floods and droughts) around the world.

Because of the increased greenhouse effect, global warming is likely to have significant effects on the hydrological cycle. Observed warming over several decades has been related to changes in the large-scale hydrological cycle, including increased atmospheric water vapour content, altered precipitation patterns, intensity, and extremes; reduced snow cover and extensive ice melting, and changes in soil moisture and runoff (IPCC, 1996). Several studies conducted on the impact of climate change have given evidence that all sectors of water resources have been affected (Oki and Kanae, 2006; Urama and Ozor, 2010; Nan et al., 2011; Faramarzi et al., 2013; Oyebande, 2013; Arnell, 2018). Climate change is having a wide range of current and long-term effects on Africa's water supplies. Flooding, drought, sea-level rise in estuaries, river drying up, poor water quality in surface and groundwater systems, precipitation and water vapour pattern distortions, and snow and land ice mal-distribution are just some of the issues (Urama and Ozor, 2010). When these factors combine, they have severe repercussions on ecosystems and populations, ranging from economic and social effects to health and food shortages, all of which put many African regions at risk of continued existence. Due to its high exposure and little adaptive capacity, Africa as a whole is one of the most susceptible continents in the world (Niang et al., 2015), although it is the least contributor to factors that result in global climatic changes (Hope, 2009). The persistent drop in rainfall in the Sahel since the late 1960s has been one of the most significant climate variations (Dore, 2005).

The decreasing rainfall and resultant devastating droughts are regarded as being amongst the largest climatic changes in the world. Declining rainfall, which is very variable in time and space, has led to a substantial reduction in streamflow and a fall in freshwater levels. As a result of this condition, groundwater levels have dropped and the desertification process has intensified, resulting in huge food insecurity crises and enormous migration, which frequently leads to war. Many other issues, such as regional demographic dynamics, non-existent or inadequate water regulations, ineffective management practices, and a lack of trustworthy and adequate data, compound the problems and uncertainties connected with potential climate change impacts on water resources in West Africa. The prolonged drying trend has raised concerns among development planners about how to deal with food production losses, food insecurity events, population displacements, water scarcity, and hydroelectricity limitations.

### 1.2.1 Impacts of Climate Change in Africa

Climate change according to the IPCC refers to "A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer". Climate change can be caused by natural internal processes, external forcings, or long-term anthropogenic changes in atmospheric composition or land use. From this definition, we can deduce that climate change can result from natural internal processes, external forcings or from persistent anthropogenic changes in the atmospheric composition or land use. The climate varies by latitude, distance from the sea, vegetation, the presence or absence of mountains, and other topographical factors. Climate changes over time, from season to season, year to year, decade to decade, and even over far longer timescales, such as the Ice Ages. The prospect of human-induced climate change has been considered by many as a matter of concern. Externally induced climate changes and change may be partly predictable, especially at larger spatial scales such as continental and global. Because human activities such as greenhouse gas emissions and land-use change create external forcing, it is thought that large-scale features of human-induced climate change are partly predictable. However, we cannot precisely predict population change, economic change, technology advancement, and other relevant characteristics of future human activity, therefore our ability to do so is restricted. In reality, this means relying on carefully designed human behaviour scenarios and determining climate projections based on these scenarios.

The majority of Africa’s population lives in rural areas and relies mostly on agriculture, with water availability being one of the most limiting constraints. Long-term observational data and climate projections have shown that freshwater resources are vulnerable to climate change and have the potential to be severely impacted, with far-reaching implications for both human societies and ecosystems. In arid and semiarid climate regions, such as West Africa, the impacts are more severe (Mbaye et al., 2015). Numerous studies over West Africa have highlighted that water resources in the region have been enormously impacted by the effects of climate change (Tall et al., 2017; Mbaye et al., 2015, 2019, 2020; Faye, 2022). Knowledge about recent climate change events in most parts of Africa is limited due to the weaknesses in climate monitoring practices and gaps in data coverage that still exist. Since water is the driving agent for the most important economic sectors like agriculture, energy, transport, etc., it is vital to investigate the ways climate change will impact this valuable natural resource in the future.

### 1.2.2 Climate Change Impacts on Water Resources and Streamflow

Climate change is anticipated to have a net negative impact on water resources and freshwater ecosystems in nearly all parts of the world, according to the Intergovernmental Panel on Climate Change (IPCC, 2007). Over the last few decades, many rivers around the world have experienced significant streamflow reductions. Climate change (CC), land use and land cover changes (LULCC), water transfers, and river impoundment are all factors that have contributed to the observed streamflow variations (Salmoral et al., 2015). It is difficult to ascertain each driver’s impact individually as they all interact simultaneously. The streamflow is one of the most important factors in determining water availability (Bodian et al., 2018). It varies greatly from river to river and is primarily affected by local seasonal cycles of precipitation and evaporation demand, snowmelt timing (if any), and travel times of the groundwater runoff component (Barberis et al., 2023). As a result, understanding streamflow is critical in order to better determine the quantity of available water for numerous purposes. Human activity and climate change, however, have disrupted the hydrological cycle through activities like reservoir construction, abstractions of groundwater and irrigation. It therefore has theoretical and practical implications to study the effects of climate change on hydrology and water resources in order to address key issues such as water resource planning, operations management, environmental protection, and ecological balance. Industry, agriculture, urban development, and other economic sectors all have a direct interaction with hydrology and water resource systems (Yang et al., 2011). Widespread activities such as the construction of reservoirs, abstractions of groundwater, and irrigation, do impact the global hydrological cycle, but these direct effects, however, are minor in comparison to the fluctuations induced by climate oscillations (Klate and Kuchment, 2004). As a result, water inflow must be accounted for in order to ensure proper water monitoring and assessment for multipurpose reservoirs or river basins.

Using a wide range of hydrological models, several studies were conducted around the world to estimate the impact of climate change on streamflow under various climatic models and scenarios (Eckhardt and Ulbrich, 2003; Liew et al., 2012; Ficklin et al., 2013; Tan and Gan, 2015; Eisner et al., 2017; Teuling et al., 2019; Gulakhmadov et al., 2020; Awotwi et al., 2021; Li and Fang, 2021). These studies showed that climate change will have a significant impact on the availability of water resources around the world. The magnitude and severity of the impact are determined by the geographical location and context. Climate change and its impact on the availability of water resources in space and time in Africa have posed complicated difficulties to African countries in their efforts to better manage water resources and increase food security.

Agriculture is the largest use of freshwater in West Africa, followed by domestic, industrial, and hydroelectric power (Oyebande, 2013). Rivers, lakes, and marshes comprise the region's surface water resources. West Africa has a considerable number of river basins and the major rivers cross multiple hydrogeological regions and are transboundary, necessitating cooperation among riparian states in water resource management. The series of droughts in the Sudano-Sahelian zone of West Africa, particularly the Niger, Volta, and Senegal basins, have impacted the water resources, ecosystems, and fragile economies of at least 13 of the region's 16 countries over the last three decades (Gachon et al., 2007; Oyebande, 2013). The shortage of electricity that affected huge coastal capitals like Abidjan and Cotonou during the summers of 1984 and 1998, following the dryness of the prior rainy seasons, is an example of the effect of the drought on the more humid parts of West Africa. Because of the lack of rain, the reservoirs remained dry, forcing the hydroelectric units to shut down (Le Barbé et al., 2002). In 1985 for example, the Niger River, Western Africa's greatest river, dried up for several weeks in Malanville, Benin Republic. This was due to a one-year lag in the lowest rainfall and runoff (1984) in the upper basin since the beginning of the century.

The Senegal River Basin has also experienced the droughts of the 1970s resulting in reduced average streamflow at Bakel from 1374 m3/sec in 1903-1950 to 419 m3/sec in the period 1973-2002. Such water shortage has clearly impacted the basin's principal operations (agriculture, fishery, hydropower generation, etc.) (Mbaye et al., 2015). Climate change predictions forecast decreased rainfall and increased evaporation in Africa's Sudano Sahelian zones (Niang et al., 2015), where the majority of the basin is located. Shifts in seasonality may be linked to changes in the rainfall regime within the basin. Annual precipitation is likely to decrease under both 1.5°C and 2.0°C degree ("The Paris Agreement | UNFCCC," 2015) warming of the atmosphere. This reduction in precipitation amounts is confirmed during the July-September season especially under the 2.0°C (Mbaye et al., 2019). Several studies have investigated the impact of climate change on water resources in the basin and confirmed streamflow reductions. Mbaye et al. (2015) documented that a general decrease of streamflow, runoff, actual evapotranspiration, soil moisture is expected by the end of the twenty-first century, and that the available water resources will decrease by more than 50% in majority of the basin especially under the RCP8.5. Elevated warming of temperatures is also projected over the whole of Senegal under RCP4.5 and RCP8.5 which will result in a significant increase in the atmospheric water demand (Tall et al., 2017). High variability in precipitation and temperature will result in frequent changes in agro-climatic characteristics and an increase in crop yield variability across ecological zones. As a result, this circumstance will have a significant influence on the Gross Domestic Product (GDP) of some of the basin's countries. Climate change will have a significant impact on agricultural systems, ultimately affecting crop calendars and growing season lengths. Extreme events like strong rains and droughts would diminish crop production in the basin since water surpluses and deficits have detrimental effects on plant growth.

A series of studies have been conducted over West Africa where the Gambia river basin is located, in order to assess the capabilities of climate models to simulate the climate of the region, as well as to quantify projected climate changes and identify potential climate change impacts. Ardoin-Bardin et al. (2009) evaluated the ability of the four Global Circulation Models (CSIRO-Mk2, ECHAM4, HadCM3 and NCAR-PCM) that were used in the third Assessment Reports of the IPCC. The authors discovered the inability of the models to simulate the volume of rainfall in the Sahelian zone and the seasonal dynamics of the two rainy seasons in the Guinean zone. The authors also documented that future runoff variations are highly dependent on rainfall and, thus, on the quality of a given GCM's output.

Bodian et al. (2018) studied the impacts of climate change on the streamflow of the Senegal and Gambia river basins using projected temperature from six General Circulation Models (CanESM2, CNRM, CSIRO, HadGEM2-CC, HadGEM2-ES, and MIROC5) and two scenarios (RCP4.5 and RCP8.5) to force the GR4J model. The studies found that the near future projections (2050) compared to the 1971-2000 reference period show a decrease in streamflow in the basins which is more pronounced in the Gambia river basin especially in the RCP8.5 (26%) scenario suggesting that climate change will have a greater impact on the Gambia river basin. Faye and Mendy (2018) on the other hand used observed data from six stations in the Basin to analyse changes induced by rainfall variability on the basin's hydrological behaviour. They observed that a downward trend and deficit exist in the hydrological parameters that were analysed [average rainfall (-14.2%), effective rainfall (-27 %), runoff potential (-49.8%) and infiltration potential (-11.4%)].

### 1.2.3 Land Use and Land Cover Change

Land is the most basic life-sustaining natural resource for humans and the majority of other living organisms in terms of providing habitat, energy, and nutrition. Land can be classified into natural land and land that has been transformed to fit a variety of human requirements and desires. In this respect, land quality is determined by its natural suitability for a particular human activity, which then dictates land use. Land has been utilized for a variety of human needs and wants throughout history, ranging from non-destructive activities such as landscape observation and traditional herb gathering to highly destructive activities such as heavy machinery application and industrial land use. Land use and cover changes are mostly caused by rising socioeconomic development. This is connected to rapid population expansion and increased consumption, which is a major driver of environmental and water resource changes. This has had a tremendous impact on the weather and climate in the area. For example, increased population growth/density and the resulting socioeconomic development desire, technological advancements, and climate change have all been identified as major causes of rapid land use/cover changes. Only few landscapes on the planet's surface have not been drastically affected or are currently being transformed by humans in some way. Land-use planning is a vital strategy for long-term advantages of societal improvements while ensuring that natural resources are being protected, especially in emerging nations where demand for socioeconomic activities is high. Land-use planning, on the other hand, is essentially unknown in most developing countries in Sub-Saharan Africa, including The Gambia.

Human presence on the planet and landscape alteration have had a significant impact on the natural environment. As land use and land cover (LULC) change is becoming recognized as a key driver of environmental change and has sparked global concern, anthropogenic activities such as agriculture, mining, deforestation, and construction have an impact on shifting patterns of land use, they are a primary component of many current environmental concerns. These LULC changes are prevalent, accelerating, and can have negative consequences on a local, regional, and global scale. Land use and land cover are important components of climatic fluctuation and change since it defines the lower boundary of the atmosphere through the modification of carbon, water, and energy cycles (Mas et al., 2017). By altering mass and energy fluxes between an ecosystem and the atmosphere, human modification of the land surface has an impact on regional to global climate processes. Land use/cover changes have consequences that extend beyond climatic changes to the temporal and spatial determination of the state of water resources at the river catchment level. The consequences of land use/cover changes on the hydrologic system and the resulting massive potential repercussions on water supplies are well documented. This occurs on multiple levels, including the impact on runoff and streamflow caused by induced climate system changes.

Land use/cover changes (LULLC) caused by human activities have also been identified as a primary driving reason behind excessive water resource utilization. Anthropogenic interferences in the form of LULLC alters the balance between rainfall, evaporation, and runoff response in a watershed, modifying hydrological processes (Salmoral et al., 2015). Changes in land use/cover are also among the primary causes of soil erosion, which can result in siltation of water bodies and worsening of water quality. "Introduction of nitrogen compounds and other biologically active solutes" and "large-scale adjustment of sediment budgets" are two effects of land use/cover changes on water quality. Information on land use/cover has thus become crucial for developing educated natural resource management policies at all levels, from global to local.

Aside from anthropogenic LULCC, climate change and disturbance regimes like forest fires may create complicated and large-scale direct and indirect biophysical watershed responses, as well as socio-economic consequences and feedbacks. At catchment level, land use and land cover change (LULCC) has a significant impact on the hydrological cycle (Das et al., 2018). Any change in land use/cover has the potential to impact water yield in a watershed, and thus the catchment's hydrological regime. Increased soil water retention is linked to forest cover and is important in a watershed because the stored water feeds streamflow during low flow periods during the dry season, as well as increased evapotranspiration and infiltration rates. Any significant land cover changes in a catchment could result in siltation of water bodies. Furthermore, changes in land use/cover have an impact on evaporative water losses and evapotranspiration variations, which are major challenges in irrigated agriculture. Lesch and Scott (1997) documented that forest cover loss is found to increase low flows, while forest cover gain decreases low flows.

Understanding the human-nature link necessitates a thorough examination of land use and land cover change (Chughtai et al., 2021). Remote sensing technology and GIS tools have made monitoring changes in land use and land cover (LULC) from the past to the present much easier. This technology has shown regional and worldwide changes, as well as providing significant benefits to the scientific community. The process of determining changes related with land use and land cover properties using geo-registered multi-temporal remote sensing data is known as digital change detection (Yacouba et al., 2010).

Watershed hydrology is being impacted by uncontrolled LULCC, particularly in tropical watersheds in developing countries (Ewane and Lee, 2020). Overgrazing, soil erosion, and intense farming have all contributed to the degradation of upland watershed ecosystems. The effects of heavy demand on land resources, rapid population increase, and frequent droughts have thrown the development process into disarray. Erosion, siltation, and sedimentation caused by upland deterioration threaten lowland ecosystems and riverine wetlands. Aridity in the uplands and acidity/salinity of soils in the lowlands have both grown as rainfall has decreased over the previous 40 years. The Gambia River's decreasing flow causes saline water intrusion into the river basin. Loss of natural land productivity, loss of native biological diversity and resilience, increased carbon dioxide emissions, reduced carbon sequestration, and degradation of watershed function, including destabilization of sediment storage and release are examples of the consequences of the land degradation. Increased food poverty and diminishing access to natural resources have resulted from the gradual degradation of these ecosystems across the country.

Overall, existing research demonstrates significant hydroclimatic variability and widespread land use change across West Africa. However, limited studies integrate these drivers to assess their combined influence on streamflow, particularly in the Gambia River Basin. This study addresses this gap by applying an integrated modelling framework alongside socio-hydrological analysis. Understanding the combined effects of climate variability and land use change in the Gambia River Basin is essential for improving land resource monitoring, watershed planning, and sustainable water management.

### 1.2.4 Hydrological Modelling in West Africa and the Gambia River Basin

Hydrological modelling has been widely used to assess the impacts of climate variability and land use change on water resources. In West Africa and the Gambia River Basin, a range of models have been applied, including lumped, conceptual, and distributed models. However, differences in model structure, spatial representation, and scope have resulted in varying levels of understanding of basin hydrology. To better position this study within existing research, a comparative summary of previous modelling studies is presented in Table 1.

**Table 1: Summary of Previous Hydrological Modelling Studies in West Africa and the Gambia River Basin**

| Study | Basin/Region | Model Used | Focus | Key Limitations / Gaps |
|---|---|---|---|---|
| Traoré (2014) | Gambia River Basin | GR4J | Climate variability & streamflow | No land use change considered |
| Thiaw (2017) | Gambia River Basin | GR2M | Rainfall–runoff relationship | Limited spatial representation |
| Bodian et al. (2018) | Senegal & Gambia Basins | GR4J | Climate change projections | No LULC integration |
| Faye & Mendy (2018) | Gambia River Basin | Statistical analysis | Hydroclimatic variability | No modelling framework |
| Faye et al. (2019) | Gambia River Basin | BILAN | Water balance | Limited scenario analysis |
| Awotwi et al. (2021) | West Africa | SWAT | Climate change impacts | Limited socio-hydrological integration |
| Other global SWAT studies | Various | SWAT | Climate/LULC impacts | Rarely applied to GRB with integrated approach |
| Perez (Year) | Kedougou (Upper Gambia sub-catchment, Senegal) | GSSHA | LULC impacts on inundation and hydrology | Limited to a small sub-catchment; not representative of the entire basin; no climate variability integration; no basin-scale |

| | | | | |
|---|---|---|---|---|
| | | | | analysis; no socio-hydrological component |

The comparison presented in Table 1 highlights important gaps in existing hydrological modelling studies in the Gambia River Basin and surrounding regions. Most studies have relied on lumped models such as GR4J, GR2M, and BILAN, primarily focusing on climate variability and rainfall–runoff relationships, with limited spatial representation and no explicit integration of land use change. Although distributed modelling approaches, such as the GSSHA model applied in Kedougou (Perez, 2019), provide improved spatial detail, they are restricted to small sub-catchments and do not represent the hydrological behaviour of the entire upstream (continental) Gambia River Basin.

Furthermore, existing studies often assess climate variability or land use change independently, with very few adopting an integrated approach. In addition, socio-hydrological aspects, including local perceptions and water use practices, are largely overlooked.

These limitations highlight a critical research gap, which this study addresses by applying a basin-scale SWAT model to assess the combined and individual impacts of climate variability and land use change, while also integrating local perceptions to provide a more comprehensive understanding of water resource dynamics.

### 1.3 Research Questions

1. What are the recent trends and patterns in hydroclimatic variables (e.g., rainfall, temperature, and streamflow) in the Gambia River Basin from 1990 to 2022, and how have extreme events like droughts and floods evolved over this period?
2. What are the key spatio-temporal land use and land cover (LULC) changes over the past three decades, and how have vegetation shifts and agricultural expansion affected different parts of the Gambia River Basin?
3. How do local communities perceive the impacts of climate and land use changes on water availability and quality, and what are the key socio-economic activities and traditional water management practices shaping local adaptation?
4. How have climate variability and land use changes individually and jointly affected streamflow in the Gambia River Basin, and what management strategies can enhance water sustainability in response to these pressures?

### 1.4 Thesis Objectives

#### 1.4.1 Main Objective

The main objective of this study is to assess the combined and individual impacts of land use change and climatic variability on streamflow in the Gambia River Basin. The study aims to provide actionable insights for sustainable land use planning and water resource management in the context of ongoing climate and land use pressures.

### 1.4.2 Specific Objectives

1. Analyse recent trends in hydroclimatic time series (rainfall, temperature, and streamflow) to provide updated insights into the evolving climate and hydrology of the Gambia River Basin.
2. Conduct a spatio-temporal assessment of land use and land cover changes over the past three decades to identify critical areas of transformation and their potential impacts on the hydrology of the watershed.
3. Integrate local perceptions on water use, socio-economic activities, and water management to bridge the gap between scientific research and community needs, and to understand how local populations perceive and respond to changes in water availability.
4. Quantify the individual and combined impacts of climate and land use changes on streamflow using the Soil and Water Assessment Tool (SWAT).

## 1.5 Hypothesis

1. Significant trends in hydroclimatic variables (e.g., rainfall, temperature, and streamflow) have occurred over the past three decades, indicating shifts in the hydrological regime of the Gambia River Basin, with implications for water resource availability and management.
2. The Gambia River Basin has experienced substantial land use and land cover changes, primarily driven by deforestation and agricultural expansion, leading to altered hydrological processes.
3. Local communities perceive climate variability and land use changes as major factors affecting water availability, influencing socio-economic activities and traditional water management practices in the basin.
4. The SWAT model reliably simulates the impacts of climate and land use change on streamflow.

## 1.6 Novelty

Despite previous modelling efforts, existing studies remain limited either in spatial scale (e.g., sub-catchment analyses), modelling approach, or scope, with little integration of climate variability, land use change, and socio-hydrological dimensions at the scale of the entire Gambia River Basin. This study contributes new insights into the combined impacts of climate variability and land use change on streamflow in the Gambia River Basin, an area that has been underexplored in recent research compared to other West African basins. The key innovative aspects of this research include:

I. **Comprehensive Hydroclimatic Analysis**: By analysing long-term hydroclimatic time series, this study provides updated insights into the evolving climate patterns and hydrological regime of the basin, highlighting shifts in rainfall, temperature, and streamflow over the past three decades. This approach adds to the limited body of knowledge on hydroclimatic trends in the Gambia River Basin.

II. **Spatio-temporal Land Use Assessment:** The study conducts a thorough spatio-temporal analysis of land use changes in the basin, identifying critical transformation areas that have significant impacts on hydrological processes. This adds a new dimension to existing studies by providing detailed insights into land cover changes and their influence on water resources.

III. **Incorporating Local P**erceptions**:** Unlike previous studies, this research integrates the perceptions of local communities in the Gambia River Basin regarding water use, socio-economic activities, and water management. Understanding these local perceptions is essential for bridging the gap between scientific research and the needs of rural populations, thus ensuring that water resource management strategies are more effective and community-driven.

IV. **SWAT Model Application for Impact Quantification:** The study employs the SWAT model to assess the individual and combined effects of climate and land use changes on streamflow, offering a more accurate understanding of how these factors interact and influence water availability. This novel application of SWAT will provide a clearer picture of the contributions of climate and land use changes to river flow variability, and offer projections of future scenarios under continued trends.

By addressing these gaps, this study will contribute new knowledge on the hydrological dynamics of the Gambia River Basin and provide actionable recommendations for sustainable water resource management in the face of climate change and increasing land use pressures.

### 1.8 Expected Results and Benefits

The study aims to provide a detailed understanding of the combined and individual impacts of climate and land use changes on streamflow in the Gambia River Basin. The expected results will not only contribute to scientific knowledge of hydrological dynamics but also offer practical solutions and recommendations for sustainable water resource management. The key expected outcomes and their associated benefits are as follows:

1. **Comprehensive Analysis of Hydroclimatic Trends:** The study will identify significant trends in hydroclimatic variables, such as rainfall, temperature, and streamflow, over the past three decades. By offering updated insights into the evolution of the basin's hydrological regime, this research will enhance the ability to predict future water availability. This will improve water resource management and allow for better adaptation strategies to changing climate conditions in the Gambia River Basin.

2. **Spatio-temporal Assessment of Land Use Changes:** A detailed analysis of land use and land cover changes will highlight areas impacted by climate or human-related activities. This will inform land use planning, taking into account the impact of these changes on hydrological processes like streamflow. The study will promote sustainable development and improve land use planning that considers the effects on water resources in the Gambia River Basin.

3. **Integration of Local P**erceptions **on Water Use and Management:** The inclusion of local community insights into water use and management practices will provide a holistic understanding of the challenges faced by rural populations. This will ensure that future water management strategies are relevant to community needs and grounded

in local realities. The study will empower local communities by making water management decisions more inclusive and ensuring more effective governance.

4. **Impact Simulation Using the SWAT Model:** The SWAT model will quantify the impacts of climate and land use changes on streamflow, providing valuable insights into water availability. These results will guide water resource management, particularly concerning reductions in river flow and the impacts on agricultural and domestic water use. This will lead to evidence-based recommendations for managing the combined impacts of climate and land use changes, helping secure water resources in the future.

5. **Contribution to Policy Development and Water Resource Management:** Findings from this research will contribute to the development of policies that address the impacts of climate change and land use on streamflow. This will be crucial for ensuring water security in the Gambia River Basin, particularly in the context of population growth and climate variability. The study will support the creation of adaptive water management policies that promote water security and resilience to climate change in the basin.

6. **Strengthened Capacity for Hydrological Research:** This study will fill critical gaps in hydrological research for the Gambia River Basin and provide new data and methodologies for future studies. This will strengthen local capacity for hydrological research and decision-making. By building capacity for local researchers and institutions, the study ensures a stronger foundation for future hydrological studies and better data collection in the basin.

In summary, this study will offer valuable insights into the combined effects of climate and land use changes on streamflow. The expected benefits include improved water resource management, informed policy decisions, and sustainable development in the Gambia River Basin, enhancing water security, improving community resilience, and supporting climate adaptation strategies.

### 1.9 Outline of the Thesis

The thesis is structured into eight chapters. Chapter 1 offers an introduction, presenting the study background, research problem, a review of relevant literature, the research objectives, the novelty of the study, its scope, and the expected outcomes. Chapter 2 provides an in-depth overview of the Gambia River Basin, including its location, climate, land use/land cover types, and topography. Chapter 3 outlines the data collected, along with the tools and methods used for data analysis. It also details the SWAT model, covering input data preparation, model setup, calibration, and validation, and provides a thorough discussion of water balance components like streamflow, evapotranspiration, and groundwater recharge estimations from the SWAT model. Chapter 4 presents the results and discussion on hydroclimatic trend analyses. Chapter 5 examines the changes in land use/land cover within the basin. In Chapter 6, community perceptions on socio-economic activities, climate and land use changes, and water resource management are explored. Chapter 7 focuses on the outputs from SWAT simulations, highlighting the individual and combined effects of climate variability and land use change on streamflow. Finally, Chapter 8 concludes the thesis with the study's findings and perceptions.

### 1.7 Scope of the Thesis

This thesis focuses on the impact of climate and land use changes on streamflow in the Gambia River Basin, aiming to understand trends in hydroclimatic variables, land use changes, and the socio-economic factors influencing water use and management. The study will analyse long-term hydroclimatic data to assess changes in rainfall, temperature, and streamflow, providing insights into the evolving hydrological regime in the basin. It also includes a detailed spatio-temporal analysis of land use and land cover changes, focusing on drivers such as climate change and human activities. Local community perceptions on water availability and traditional management practices will be incorporated to bridge scientific findings with local needs. The study will use the SWAT model to quantify the impacts of climate and land use changes on streamflow.

## Chapter 2: Study Area

### 2.1 Location

The Gambia River Basin spans approximately 77,000 km² and extends, in latitude, from 11°22'N in Fouta-Djalon to 14°40'N in southeastern Ferlo; in longitude, from 11°13'W in Fouta-Djalon to 16°42'W in Banjul, where the river meets the Atlantic Ocean (Figure 1). Originating in the Fouta Djalon Highlands in Guinea at an altitude of 1,125 meters, the river crosses three countries: Guinea, which makes up 15.25% of the basin area, Senegal (72.30%), and The Gambia (12.45%) (Mory et al., 2023).

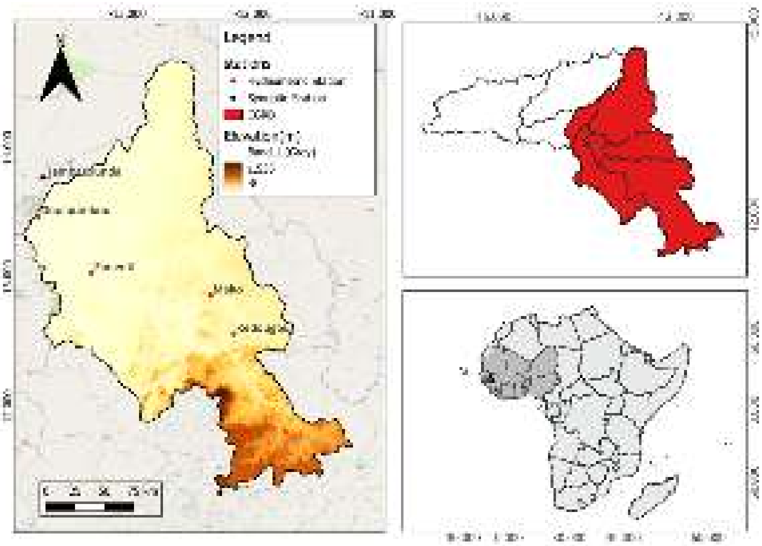


*Figure 1: Map of the Continental Gambia River Basin Showing Elevation, Stations, and Location within the Gambia River Basin and Africa*

### 2.2 Relief

The relief of the basin is dominated by the Fouta-Djalon, often referred to as the "water tower of West Africa". Several tributaries of major rivers, such as the Niger, Senegal, Konkouré, and Corubal, also originate here. The highest point in the basin is located on the water divide with the Corubal River, at the Tamgué or Mali massif, which is also the highest peak of Fouta-Djalon, standing approximately at 1500 meters. As the Gambia River exits Guinean territory around the 12°20'N parallel, the terrain transitions from medium mountains to hills and plateaus. The hills in this region can locally reach up to 400 meters, while the plateaus do not exceed 200 meters. This area, known as Eastern Senegal, constitutes more than half of the Gambia River basin. Finally, just before entering The Gambia, the river reaches almost sea level (with the riverbed at a negative elevation at the Gouloumbou bridge). The remaining 500 km of the river's course is influenced by tidal forces (Lamagat et al., 1990). The basin is divided into two sections based on the river’s regime: the upstream basin, extending to the Gouloumbou station in Senegal near the Gambian border, known as the continental basin, and the maritime reach, located downstream from this station, where the river is at sea level.

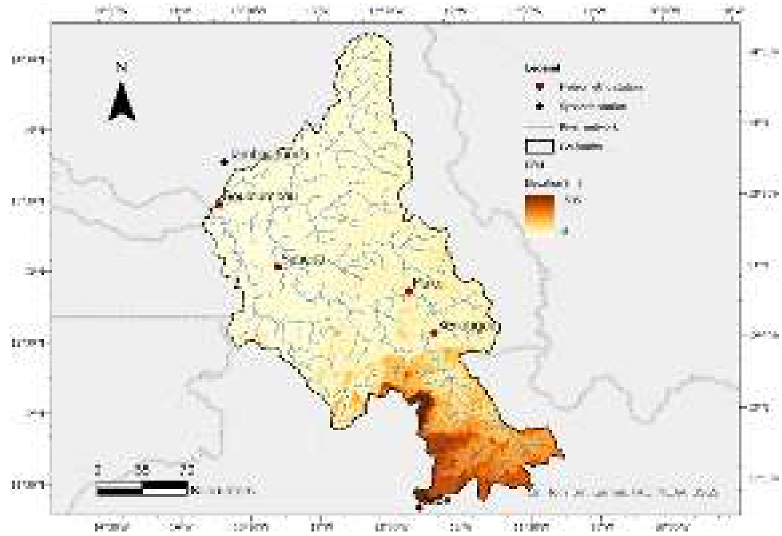

*Figure 2: Drainage Network of the Continental Gambia River Basin*

## 2.3 Vegetation

The Gambia River Basin is characterized by dense vegetation composed of tree species, shrubs, and herbs, supporting a diverse range of ecosystems, including estuaries, marshes, swamps, and mudflats, along with a rich variety of flora and fauna. The southern part of the basin is dominated by thick forests, while the northern region transitions into smaller and more spaced-out woody species savannas and shrub steppes (Lamagat et al., 1990), with the vegetation thinning out and becoming sparser. Dry forests and woodland savannas cover the hills, and gallery forests are found along riverbanks. However, this vegetation has shown signs of deterioration due to a combination of natural factors such as drought and erosion, and human-induced pressures such as deforestation, bush fires, over-exploitation of forest resources, and over-grazing (Bodian et al., 2018). Like other parts of the Sahel, the Gambia Basin faces significant pressures from human settlement and growing populations, leading to the degradation of vegetation and soil. Human activities such as land conversion for agriculture and grazing, as well as the extraction of wood and charcoal, have been major contributors. Bushfires, common in Sudanian savannas, shorten the growing season for many tree species, favouring fire-resistant plants while disadvantaging annuals, which leads to a shift in plant communities. These fires also exacerbate soil degradation by increasing surface runoff and erosion. Deforestation for charcoal production and grazing, combined with destructive grazing practices, especially by goats, has further altered the landscape, with areas like the plateaus of Fouta Djallon being entirely cleared for cultivation. Alongside these human pressures, the impacts of climate change, including reduced rainfall, have worsened the situation, resulting in problems with water retention, more severe erosion, and prolonged low-flow periods, particularly in the northern, drier regions of the basin.

## 2.4 Climate

The climate in the basin is controlled by the Inter-Tropical Discontinuity (ITD), which is the boundary in the lower troposphere where two contrasting air masses meet: the tropical maritime (mT) air mass from the Southern Hemisphere, characterized by a cool, moist south-westerly monsoon flow, and the tropical continental (cT) air mass from the Northern Hemisphere, distinguished by a dry, warm northeasterly Harmattan flow (Bou Karam et al., 2008; Lélé and Lamb, 2010; Pospichal et al., 2010; Nicholson et al., 2018). These two air masses govern the onset, retreat, and length of the rainy season in the region. The beginning of the rainy season is marked by the movement of the ITD from the Gulf of Guinea coast towards the north in the months of March and April (Sultan and Janicot, 2003). Over the next few months, the ITD continues inland until the months of July and August when it reaches its northernmost climatological location. The basin experiences a tropical climate, which is characterized by a unimodal rainfall regime (Figure 3) with a long dry season from November to May and a short rainy season from June to October (Fall et al., 2006)

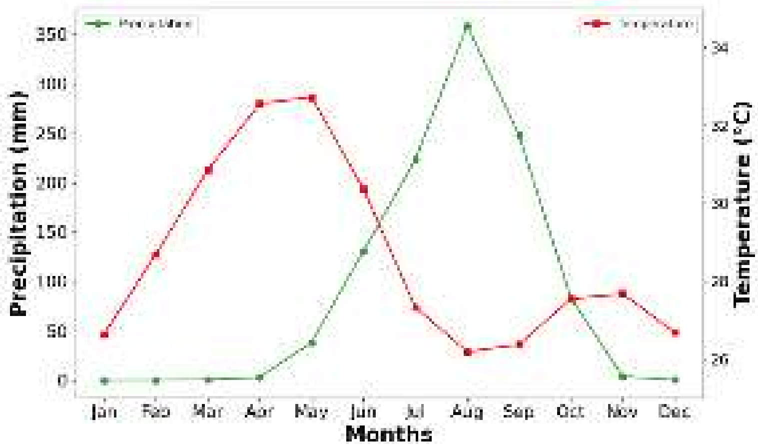


*Figure 3: Seasonal Cycle of Precipitation and Temperature*

The rainfall in the basin exhibits a distinct north-to-south gradient, with annual totals ranging from over 1500 mm on the Fouta plateaus to around 500 mm in the southern Ferlo, placing most of the basin within the Sudano-Guinean climatic zone (Figure 4). The dry season, corresponding to the boreal winter, lengthens as one moves northward, from 3-4 months in the Fouta-Djalon to 7-8 months in the southern Ferlo. As one moves north, rainfall decreases, while average and maximum temperatures rise, leading to increased evaporation and solar radiation. Due to worsening climate conditions, the northernmost areas (southern Ferlo) are increasingly exhibiting characteristics of the Sahelian climate. This "dryness," which accelerates environmental degradation and desertification, becomes more pronounced towards the north, where the regions already have lower rainfall. From 1990 to 2022, this gradient has persisted, but a clear temporal increase in precipitation is observed. Rainfall was relatively lower during 1990–2000, particularly in the central and northern regions, but increased during the 2001–2011 period and further in 2012–2022. The high-rainfall southern zone expanded over time, while the drier zones gradually receded northward.

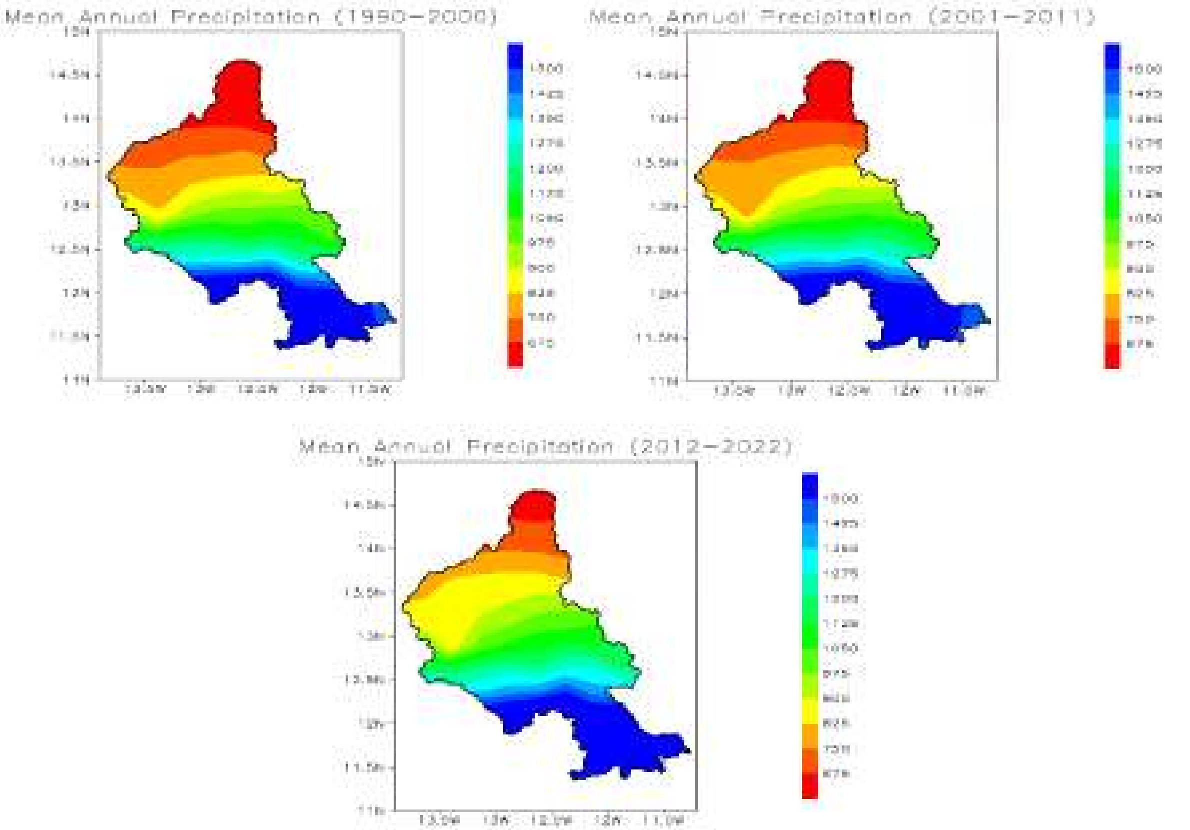


*Figure 4: Spatial Distribution of Annual Precipitation over the Continental Gambia River Basin*

Figure 5 illustrates the spatial distribution of mean annual temperature across the basin for three time periods: 1990–2000, 2001–2011, and 2012–2022. Warmer regions are shown in red, predominantly located in the northern and western parts of the basin, where average temperatures exceed 28.5°C. Conversely, cooler areas appear in yellow, mainly concentrated in the southern and southeastern zones, where temperatures drop below 26.5°C. A clear warming trend is observed over the three decades. From 1990–2000 to 2012–2022, the extent of high-temperature zones has expanded, particularly in the central and northern regions, indicating a consistent rise in temperatures. In the most recent period (2012–2022), nearly the entire basin, especially the north, experiences temperatures exceeding 28.8°C, with some areas surpassing 30°C. The maps also highlight a persistent north-south temperature gradient, where the northern areas remain consistently hotter and the southern regions cooler. This spatial pattern reflects the inverse relationship between rainfall and temperature across the basin. As observed in the corresponding precipitation maps, the wetter southern zones are cooler, while the drier northern parts are warmer. This pattern is characteristic of tropical climates, where increased cloud cover and rainfall in the south limits solar radiation, reducing heat absorption and resulting in relatively lower temperatures. Overall, the spatial patterns in Figure 5 underline the intensifying warming across the basin, which is crucial for understanding water resource availability, and potential hydrological impacts in the region.

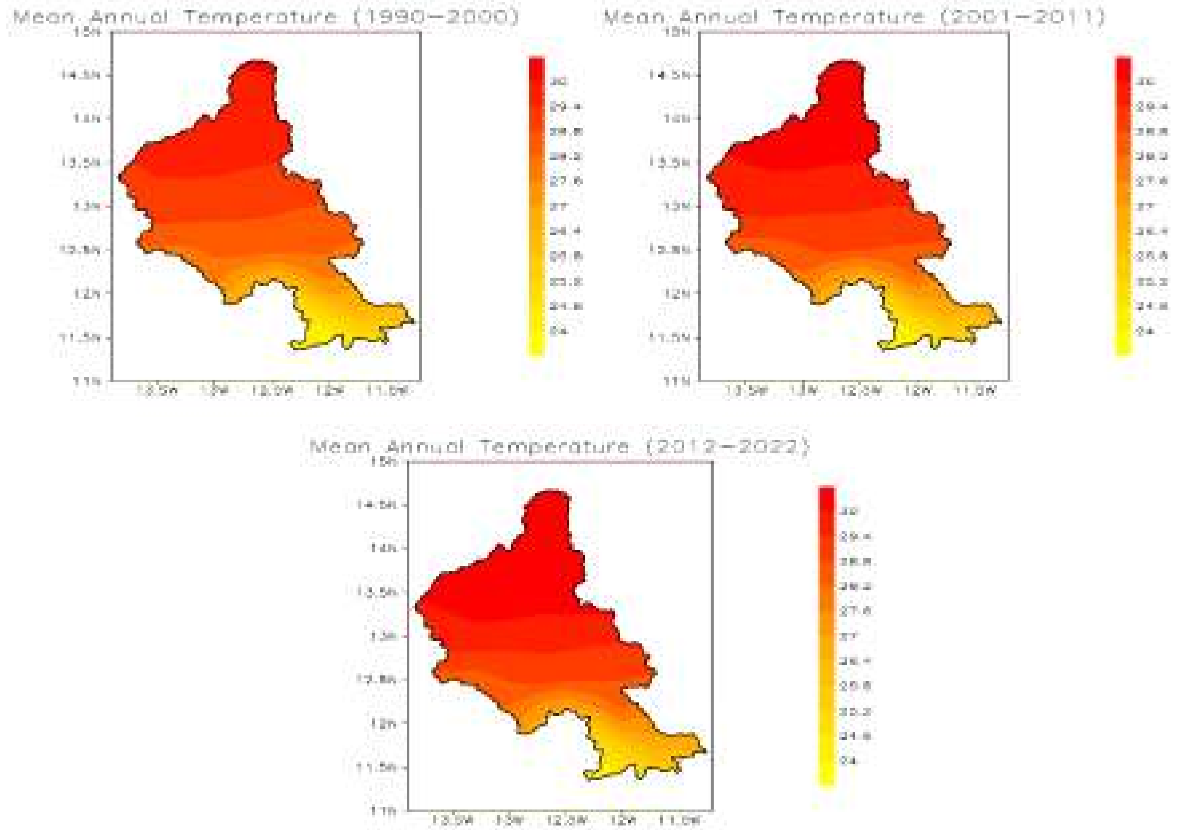


*Figure 5: Spatial Map of Annual Mean Temperature*

### 2.5 Hydrography

The Gambia River's flow is divided into two sections: a continental and a maritime reach. In the continental reach, the river flows predominantly in a southeast-to-northwest direction, traversing the upstream region characterized by mountainous terrain and significant rainfall during the wet season, often exceeding 1500 mm. This area supports a well-structured hydrographic network, with tributaries being more densely distributed due to the topographical and climatic conditions. There is a clear differentiation between the left tributaries, originating from the Fouta-Djalon highlands, and the right tributaries, which drain the Sudanian plateaus of the Continental Terminal.

As the river approaches Gouloumbou and enters the maritime section, its flow orientation shifts to an east-to-west direction. In this section, the basin narrows considerably, and the influence of tributaries diminishes. Rainfall that falls directly onto the river itself becomes the dominant hydrological input, as opposed to contributions from upstream tributaries. This transition reflects a significant hydrological shift in the river's behaviour and its dependence on local precipitation.

The Gambia River exhibits a pure tropical hydrological regime, which is shaped by the spatio-temporal distribution of precipitation and the natural characteristics of the basin. This regime is marked by a single, brief high-water period lasting from mid-July to mid-October, corresponding to the rainy season. During this period, streamflow increases rapidly due to intense rainfall and runoff from the impermeable basin surfaces, which limit infiltration. This high-water phase is followed by a swift decline in flow rates, culminating in a prolonged low-water season from December to June, during which discharge is extremely low.

The seasonality of the Gambia River's flow reflects the broader climatic and topographical patterns of the region. The upstream portions of the basin, with their steep slopes, high rainfall, and dense tributary network, contribute significantly to the river's discharge during the wet season. However, downstream, the narrowing of the basin and the reduced influence of tributaries result in a hydrological regime heavily dependent on rainfall directly over the river. These distinct characteristics make the Gambia River both unique and representative of the broader hydrological patterns seen in tropical rivers with pure tropical regimes.

Despite the variability in flow, the Gambia River holds significant economic and ecological potential, particularly for irrigation and other water-resource-based activities. The river's seasonal behaviour and its reliance on precipitation make understanding its hydrology crucial for sustainable water management in the region (Ardoin-Bardin Sandra, 2004).

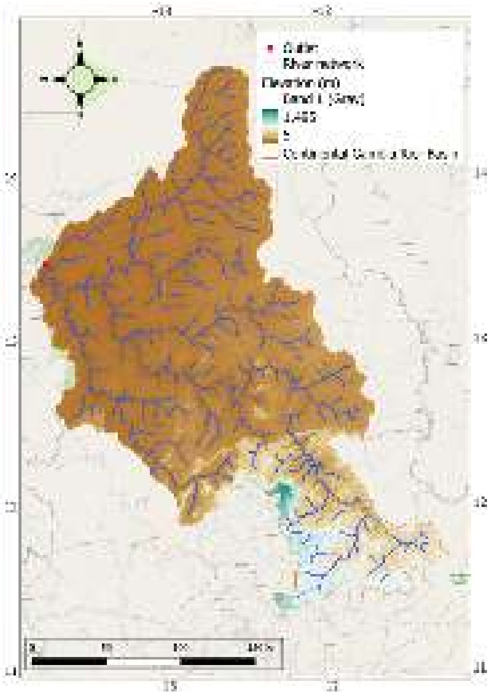

*Figure 6: Hydrographic Network of the Continental Gambia River Basin*

**2.6 Soil and Land Use**

**2.6.1 Soil**

The soil map of the study area (Figure 7) was obtained from the Food and Agriculture Organization's Digital Soil Map of the World, with a spatial resolution of 10 km, based on derived soil properties version 3.6. The dominant soil groups found in the basin are Vertic Cambisols (Bv), lithosols (I), Eutric Fluvisols (Je), Ferric Luvisols (Lf), Eutric Gleysols (Re), and Solodic Planosols (Ws). Cambisols, characterized by early horizon differentiation, typically exhibit changes in structure, colour, clay content, or carbonate levels and are formed from medium and fine-textured parent materials derived from various rocks. These soils are moderately weathered and lack significant illuviated compounds, commonly occurring in temperate, boreal, and some dry regions, especially where young parent materials or slow soil formation prevail. High base saturation Cambisols are highly productive for agriculture, while those on steep slopes or in humid tropics are less fertile, being more suitable for forestry or grazing.

Lithosols, on the other hand, are shallow soils found over continuous rock or unconsolidated materials with minimal fine earth, predominantly in mountainous or eroded regions. Their parent materials include continuous rock or weathered materials with less than 20% fine earth. While Lithosols are valuable for grazing and forestry, they are highly prone to erosion, especially in temperate zones. Fluvisols, being young azonal soils, develop in alluvial, lacustrine, and marine deposits, typically in environments like river plains, deltaic areas, and tidal marshes. These soils are characterized by weak horizon differentiation and often display redoximorphic features, particularly in the lower profile. Formed from fluvial, lacustrine, and marine parent materials, Fluvisols are widely distributed across all continents and climates, particularly in the tropics. They are extensively used for paddy rice and dryland crops, though some areas face salinity or acidity issues.

Luvisols are distinct for their paedogenetic clay differentiation, where subsoils have a higher clay content than topsoils due to clay migration, forming an argic horizon. These soils, developed from various unconsolidated materials such as glacial till, alluvial, aeolian, and colluvial deposits, are typically found in temperate or Mediterranean regions with alternating wet and dry seasons. Fertile and well-suited for agriculture, Luvisols require careful management to prevent erosion and structural deterioration, particularly in sloping areas. Gleysols, often found in low-lying areas with shallow groundwater, are wetland soils characterized by prolonged saturation, leading to distinctive gleyic colour patterns such as reddish, brownish, yellowish, and greyish/bluish hues. Formed from unconsolidated materials like fluvial, marine, and lacustrine sediments of Pleistocene or Holocene origin, Gleysols are used for agriculture and horticulture after drainage. However, improper cultivation under wet conditions can damage their structure, necessitating practices such as liming and deep drainage for optimal use.

Planosols, commonly found in seasonally waterlogged areas of subtropical and temperate regions, are characterized by a light-coloured surface horizon overlying a dense, clay-rich subsoil. These soils form primarily from clayey alluvial and colluvial deposits, with water stagnation near the textural boundary creating reducing conditions. They are mostly used for extensive grazing, paddy rice cultivation, and irrigated grasslands. However, due to poor drainage and restricted root development in the dense subsoil, crop yields are generally low, making Planosols less suited for intensive agriculture (WRB, 2023).

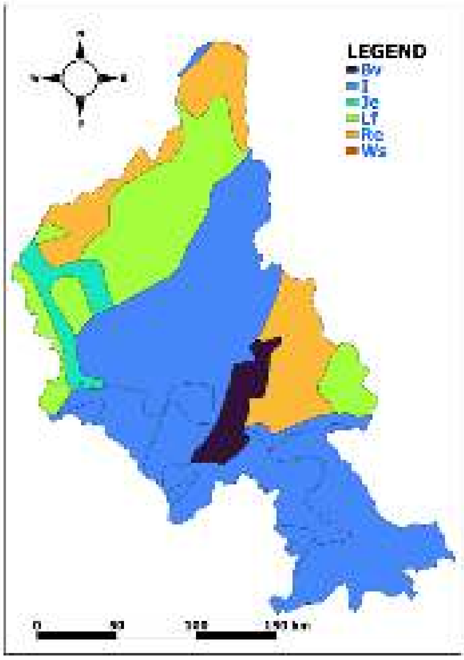


*Figure 7: Soil Map of the Continental Gambia River Basin. The soil types are represented by letter codes: BV – Vertic Cambisols, I – Lithosols, Je – Eutric Fluvisols, Lf – Ferric Luvisols, Re – Eutric Gleysols, Ws – Solodic Planosols*

### 2.6.2 Land Use

The land use of the basin is dominated by savanna, which features significant tree and shrub layers and is a combination of wooded savanna, where trees and shrubs form an open canopy; tree savanna, characterized by scattered trees and shrubs within a grassy layer; and shrubby savanna, which consists of a continuous herbaceous layer with sparsely distributed shrubs. Forest follows as a major land cover, consisting of open forest, an ecosystem with small to medium-sized trees forming a loose canopy that allows ample light penetration, supporting a mix of grasses and shrubs; gallery forest, a dense vegetative formation lining watercourses, benefiting from consistent moisture; and dense forest, a closed-canopy system with high tree density, limiting undergrowth due to restricted light penetration.  Next is the bowe and steppe, characterized by grassy bowe, which are marked by outcrops of impermeable laterite that restrict root penetration and result in open, often treeless meadows.  During the dry season, the laterite crusts are completely bare, and during the rainy season, they are covered by a carpet of grasses, which are later burned by bushfires. When the laterite crust is locally dismantled, bushes and shrubs settle in, and trees may take root at the edges. Steppes are discontinuous or sparse herbaceous ground cover, often with scattered shrubs, and are the primary land cover type that has replaced the once-extensive riverine woodlands.  Agricultural areas, bare soils, and built-up areas are key land uses within the basin.  Agriculture, which includes the cultivation of annual crops such as maize (Zea mays), peanut (Arachis hypogaea), millet (Pennisetum glaucum), okra (Abelmoschus esculentus), pepper (Capsicum spp.), tomatoes (Solanum lycopersicum), rice (Oryza sativa), cotton (Gossypium spp.), banana (Musa spp.), and lettuce (Lactuca sativa), as well as some tree crops like banana and cowpea, plays a major role in shaping the landscape and land use patterns in the area. Bare soils refer to land that has been cleared for cultivation or remains devoid of vegetation, typically resulting from overexploitation or degradation. Bare soils are particularly vulnerable to erosion and can exacerbate water runoff and sedimentation. Following agricultural areas, bare soils, and built-up areas, burned areas emerge as a significant land use type in the basin. These areas are commonly found in the shrubland or wooded savannas of the Sudanian region, where frequent and prolonged bushfires occur. These fires reduce the growing season for many trees, as they are still retaining their leaves when the grasses dry out. This results in a selective process where only fire-resistant plants thrive, while less resilient species fade away. The herbaceous layer is also negatively impacted by the fires, with annual plants being outcompeted by more fire-resistant perennials. This ongoing degradation of the vegetation cover affects the landscape, increasing runoff and causing erosion. The soil becomes depleted, and the intensity of water impact on the surface (splash) is heightened. Figure 8 illustrates the different land use/land cover (LULC) types in the catchment. A comprehensive description of the land use and land cover in the study area is provided in Chapter 5.

Gallery Forest (Solly, 2021)

Wooded savanna (Solly, 2021)

Tree savanna (Solly, 2021)

Burn (Solly Boubacar, 2021)

Banana plantation Water

*Figure 8: Various LULC types in the study region*

**2.7 Demography, Environmental, Social, and Economic Activities**

The living standards in the Gambia River Basin mirror the overall conditions in the surrounding countries. According to the United Nations Human Development Index, Senegal and The Gambia, which share the basin, rank among the poorest nations with low development indicators. Population density in the region varies, with 61 people per km² in Guinea, 98 per km² in Senegal, and 279 per km² in The Gambia (Worldometer). Approximately 50% of the rural population is estimated to live below the poverty line. Economic difficulties remain prevalent, with poverty rates reaching 55% in Guinea and as high as 80% in Senegal's Kedougou region (UCAD Team, 2019; OMVG, 2020).

The region has distinct wet and dry seasons, with annual rainfall ranging from 1,000 mm in the north to 2,200 mm in the south. Vegetation varies, with forests in Guinea while savannas dominate in the Senegalese part of the Basin. Shifting cultivation, deforestation, and frequent bushfires contribute to environmental degradation. Additionally, human activities such as extensive slash-and-burn agriculture, increasing firewood demand, and expansion of grazing and farmland place further strain on natural resources. Migration patterns, influenced by urbanization, desertification, economic instability, and conflicts, complicate demographic projections and resource management. Water resources are irregular, requiring regulation for sustainable agricultural and hydroelectric use (OMVG, 2020; Team UCAD, 2019).

Agriculture, livestock rearing, and fishing are the dominant socio-economic activities. The river supports irrigation, with an estimated 93,000 hectares of irrigable land, including 4,100 hectares in Senegal recognized for good irrigation potential (Team UCAD, 2019). Agriculture employs between 70–90% of the active population and contributes 30–50% of national GDP, depending on the country. The sector is divided into subsistence farming, which supports local food demand, and cash crops intended for export. Key crops include rice, groundnuts, cotton, maize, millet, and sorghum, though agriculture remains largely rain-fed. Traditional slash-and-burn farming contributes to land degradation, and livestock farming follows a transhumant system but faces challenges such as bushfires, farmer-herder conflicts, and limited infrastructure (OMVG, 2020; Team UCAD, 2019).

The industrial sector in the region is underdeveloped, mainly focused on agro-industrial activities such as sugar production, breweries, and food processing. Despite its abundant natural resources, the basin remains underdeveloped, requiring strategic planning to enhance economic growth while ensuring environmental sustainability. Hydraulic infrastructure plays a crucial role in supporting agriculture, irrigation, and access to drinking water, making it central to development strategies in the region.

### 2.8 Conclusion

The Gambia River Basin, spanning approximately 77,000 km² across Guinea, Senegal, and The Gambia. It encompasses diverse landscapes, climates, and ecosystems shaped by its relief, climate, hydrology, soil characteristics, and land use. Originating in the Fouta-Djalon Highlands, the river transitions from a mountainous landscape to a tidal-influenced reach near the Atlantic Ocean. The basin exhibits a unimodal tropical climate, with rainfall decreasing northward, leading to increasing aridity and environmental stress. Hydrologically, the river follows a distinct seasonal pattern, with high flows during the rainy season and prolonged low-flow periods, highlighting its dependence on precipitation.

Vegetation and land use reflect these climatic and topographical variations, ranging from dense forests in the south to savannas and steppes in the drier north. Agricultural expansion, deforestation, and recurrent bushfires have intensified land degradation. Soil diversity, including fertile Cambisols and Luvisols, supports agriculture but is threatened by erosion and unsustainable land management. The interplay of climate change, human activities, and natural factors continues to shape the basin's hydrological and ecological dynamics, emphasizing the need for sustainable management strategies to balance environmental conservation with socioeconomic development.

## Chapter 3: Data, Materials and Methods

This study relies on multiple datasets to analyse the hydrological and climatological dynamics within the Gambia River Basin. This chapter provides details of the datasets, their sources, temporal and spatial coverage, and any preprocessing steps undertaken to address missing data.

### 3.1 Data

#### 3.1.1 Landsat Images

To analyse land use changes in the CGRB, multi-date images from the Landsat satellite are used (Table 1). The Landsat satellite has the advantage of providing free images (http://earthexplorer.usgs.gov/) with a sufficient resolution (30 m) to study changes in land use. Three image acquisition dates were selected: 1988, 2002, and 2022. These dates were chosen based on image availability and quality. A temporal gap of at least ten (10) years between successive dates was chosen based on image availability, justifying the selection of the year 2002.

*Table 2: Landsat Satellite Images Used*

| Date | Acquisition date | Satellite | Path/Row | Spatial resolution |
|---|---|---|---|---|
| **1988** | 1988/12/03 | Landsat 5 | 201/052 | 30m |
| | 1988/12/10 | | 202/050 | |
| | 1988/12/10 | | 202/051 | |
| | 1988/12/10 | | 202/052 | |
| | 1988/11/15 | | 203/050 | |
| | 1988/12/01 | | 203/051 | |
| **2002** | 2002/12/18 | Landsat 7 | 201/052 | 30m |
| | 2002/12/25 | | 202/050 | |
| | 2002/12/25 | | 202/051 | |
| | 2022/12/25 | | 202/052 | |
| | 2002/12/16 | | 203/050 | |
| | 2003/01/01 | | 203/051 | |
| **2022** | 2022/12/25 | Landsat 9 | 201/052 | 30m |
| | 2022/12/24 | Landsat 8 | 202/050 | |

| | | |
|---|---|---|
| 2022/12/24 | Landsat 8 | 202/051 |
| 2022/12/24 | Landsat 8 | 202/052 |
| 2022/12/23 | Landsat 9 | 203/050 |
| 2022/12/23 | Landsat 9 | 203/051 |

The images used in this study were provided by four satellites and sensors: Landsat 5 (TM), 7 (ETM+), 8 (OLI-1), and 9 (OLI-2). For each image, the multispectral bands (Blue, Green, Red, NIR, SWIR1, and SWIR2) with a spatial resolution of 30m were selected for processing. A total of six (6) scenes were required to cover the entire basin. Additionally, the images were acquired between late November and early January, a period considered more suitable for this study. This timing coincides with the end of the rainy season, during which photosynthetic activity decreases, and the presence of clouds in the images is minimized (Solly, 2021). To account for radiometric differences between acquisition dates, the images were collected within very close time intervals. The processing of these images was performed using the TerrSet software.

#### 3.1.1.1 Processing Method

The image processing involved four main steps. The first step consisted of geometric and radiometric correction. These corrections are essential in multi-date analyses, as uncorrected images can lead to erroneous interpretation of land use/land cover changes and hydrological impacts. Geometric correction was performed to ensure accurate spatial alignment of the images. This process corrects distortions caused by sensor geometry, satellite motion, and terrain effects. Images were georeferenced to a common coordinate system using ground control points and standard correction models, ensuring that features are correctly positioned and comparable across different time periods. The accuracy of the correction was assessed using Root Mean Square Error (RMSE), following established approaches in remote sensing studies (Gill et al., 2010). Radiometric correction was applied to ensure consistency in pixel values across multi-temporal images. This step removes the effects of atmospheric conditions, sensor differences, and illumination variability, allowing meaningful comparison of land surface characteristics over time. Relative radiometric normalization techniques were used to standardize image reflectance, ensuring that observed changes are due to actual land cover variations rather than external distortions (Janzen et al., 2006; Paolini et al., 2006; Andrieu and Mering, 2008; Solly, 2021).

The second step involved mosaic creation using the six scenes, followed by the construction of a false-colour infrared composite. This relied on the strong reflection of near-infrared radiation by vegetation (Girard & Girard, 2010). The resulting composite for each date enabled the identification of different land use units through photo-interpretation. These land use units were grouped into six categories: water (water bodies), forest (dense forest, gallery forest, and woodland), savanna (wooded savanna, tree savanna, and shrubby savanna), bowe and steppe, agricultural areas and bare soils, and "burn". The vegetation class nomenclature is primarily based on the Yangambi classification, a global reference adapted for West Africa (CSE, 1996; Stancioff and Tappan, 1986; CILSS, 2016). The "burn" category refers to surfaces affected by fires at the time of image acquisition.

The third step focused on image classification. The method used was unsupervised hierarchical classification, as outlined by (Andrieu and Mering, 2008; Diédhiou et al., 2020; Solly, 2021; Diéye et al., 2022). This method has the advantage of grouping image pixels into spectral classes based on their signatures, which depend on the spectral signature of the thematic classes making up the surface to be mapped. The classification process was carried out in several steps: an initial classification into 10 classes using the k-means clustering algorithm, which incorporated all bands from blue to mid-infrared; interpretation of the spectral signatures of the resulting classes; reclassification based on the chosen nomenclature; creation of thematic masks; hierarchical classification on the masks; and final reclassification. The k-means algorithm, based on aggregate pixel analysis, requires specifying the number of classes to be extracted, initializing centroids, and iteratively updating them until optimal spectral separation is achieved (MacQueen, 1967). This method classifies each pixel to the nearest class (Ducrot, 2005).

The final step involved validating the classified land use maps. Ground control points, collected during a field survey mission, were used for validation. In addition, several studies conducted in the region at various scales were consulted (Tappan et al., 2004; CILSS, 2016; Solly et al., 2022). These GCPs were recorded using handheld GPS devices across representative land cover types, including agricultural land, savanna, burned areas, forest patches, inhabited areas, and bodies of water identified through direct field observations. The points were used to validate the satellite-based land use/land cover (LULC) classification through visual comparison and expert knowledge. In addition to the collection of GPS coordinates and field observations, structured interviews were conducted with local farmers, herders, and community members to gather socio-economic data relevant to land use practices. The survey captured trends in population, crop and livestock farming activities, and the factors behind the perceived trends. These local perceptions provided valuable context for interpreting the socio-economic aspects related to LULC changes.

To observe land use evolution, change maps were created. These maps were generated by comparing results from different dates (1988-2002, 2002-2022, and 1988-2022). Three major types of changes were analyzed based on the resulting data and statistical analysis: regressions, which correspond to a decrease in one class in favour of others (negative change); progressions, which correspond to an increase in one class at the expense of others (positive change); and stability, which refers to a class that underwent no change during the study period.

*Table 3: Land Use/ Land Cover Classes and their Definitions*

| **LULC Classes** | **Description** |
|---|---|

| | |
|---|---|
| **Water** | Natural water bodies such as rivers, lakes, and wetlands. |
| **Forest** | Dense vegetation dominated by trees, forming a continuous canopy. It includes dense forest, gallery forest, and woodland |
| **Savanna** | Mixed vegetation with scattered trees and a dominant grass layer, structurally between forest and steppe. It includes the wooded savanna, tree savanna and shrubby savanna |
| **Bowe and steppe** | Bowes are open herbaceous formations that occur on shallow, lateritic soils with poor water retention, while Steppe consists of grasslands with sparse or no tree cover, often found in drier conditions. |
| **Agricultural area and bares soils** | Land modified by human activities, including croplands and barren, non-vegetated surfaces. |
| **Burn** | Areas recently affected by fire, characterized by scorched vegetation and exposed soil. |

### 3.1.2 Precipitation Data

Precipitation data for this study is sourced from the Climate Hazard Group Infrared Precipitation with Station (CHIRPS) version 2 (Funk et al., 2015), covering the period from 1990 to 2022. The CHIRPS dataset spans 1981 to 2022 and provides a quasi-global rainfall record with a spatial resolution of 0.05°×0.05°. By combining satellite imagery with in-situ station data, CHIRPS creates gridded rainfall time series, ideal for trend analysis and drought monitoring. Due to the absence of extensive ground-based data, satellite estimates like CHIRPS are often used as alternatives or supplements. The dataset has been validated against daily rain gauges in the Sahel and Guinea Coast, showing good correlation with seasonal precipitation trends. Data is available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/.

### 3.1.3 Temperature Data

The study utilizes ERA5 temperature data, which is the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data for global climate and weather. This data is generated by integrating a numerical weather prediction model with observational data from satellites and ground-based measurements. The data used in the study is at a daily timescale and has a spatial resolution of 0.25° x 0.25°. More information about the dataset can be found at https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview.

### 3.1.4 Streamflow Data

Streamflow data for the period 1990–2022 were obtained from the Directorate of Water Resources Management and Planning (DGPRE) at the Simenti station on the Gambia River Basin. This station was selected for the analyses as the main outlet of the basin (Gouloumbou Station) could not be used due to tidal influence, which prevents continuous measurement. The Simenti station provides a continuous, year-round discharge record, making it suitable for hydrological modelling. The availability of continuous discharge observations at this station enables robust calibration and validation of the SWAT model and ensures reliable simulation of streamflow dynamics. Furthermore, its location upstream of tidal influence allows accurate assessment of streamflow responses to climate variability and land use change without interference from marine processes.

### 3.1.5 Digital Elevation Model (DEM)

The elevation data used in the study is from the Shuttle Radar Topography Mission at a spatial resolution of 30 meter (Farr et al., 2007). The DEM was used to delineate watershed boundaries, derive the stream network, and compute topographic parameters such as slope, flow direction, and flow accumulation, which are essential for representing runoff routing and watershed hydrological connectivity within the SWAT model.

### 3.1.6 SWAT Model Input Data

The SWAT model requires input data including a Digital Elevation Model (DEM), daily meteorological data, and soil and land use/cover maps. The specifics of the datasets used and their sources are presented in Table 3. Due to the cost of daily climatic data, daily precipitation data from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) and temperature data from ERA5, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), were used. The CHIRPS daily precipitation data was extracted for the hydroclimatic stations within the CGRB. The discharge data for the study comes from the Simenti Station, covering the period from 1990 to 2022. This data was supplied by Directorate of Water Resources Management and Planning (DGPRE) in the Republic of Senegal. The land use/land cover (LULC) maps were derived from a k-means clustering classification of Landsat images from 1988, 2002, and 2022.

*Table 4: SWAT Input Data and Sources*

| Data | Source | Spatial Resolution | Temporal Resolution |
|---|---|---|---|
| **Digital Elevation Model** | Shuttle Radar Topography Mission. | 30m | - |
| **Land use Data** | Landsat Mission | 30m | 1988, 2002 & 2022 |

| | | | |
|---|---|---|---|
| **Soil Data** | FAO Soils | 10km | - |
| **Daily Precipitation** | Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) | 0.05º | 1990 - 2022 |
| **Daily Temperature** | European Centre for Medium-Range Weather Forecasts (ERA5) | 0.25º | 1990 - 2022 |
| **Discharge** | Direction de la Gestion et de la Planification des Ressources en Eau (DGPRE) | Station Data | 1990 - 2022 |

*Table 5: SWAT Reclassified Land use/ Land Cover Classes*

| LULC Class | Adapted LULC for SWAT Database | SWAT Code |
|---|---|---|
| **Water** | Water | WATR |
| **Forest** | Forest-Mixed | FRST |
| **Savanna** | Range-Brush | RNGB |
| **Bowe and steppe** | Range-Grasses | RNG |
| **Agricultural area and bare soils** | Agricultural Land-Generic | AGRL |
| **Burn** | Barren | BARR |

## 3.2 Materials

### 3.2.1 Climate Data Operators (CDO)

The Climate Data Operator (CDO) software is a comprehensive toolset for processing and analysing climate and numerical weather prediction (NWP) model data. It supports standard file formats like GRIB and NetCDF, enabling functions such as statistical analysis, arithmetic operations, data selection, spatial interpolation, and climate index calculations. Designed for efficiency, many of its 100+ functions can be combined in a singlecommands to leverage modern computing hardware. CDO supports a variety of grid types, including Gaussian, latitude-longitude, and unstructured grids, alongside some institution-specific binary formats. However, GRIB datasets must be consistent, and NetCDF is limited to classic models with up to four dimensions. More detailed information about CDO can be found at https://code.mpimet.mpg.de/projects/cdo.

### 3.2.2 Grid Analysis Display System (GrADS)

The Grid Analysis and Display System (GrADS) is an interactive desktop tool for accessing, analysing, and visualizing earth science data. It supports multiple data formats, including GRIB, NetCDF, HDF, and BUFR, across various operating systems. Using a 5-dimensional framework (longitude, latitude, vertical level, time, and an optional ensemble dimension), GrADS organizes data through descriptor files and allows for overlaying datasets with proper spatial and temporal alignment. Interactive commands enable data manipulation using built-in or custom functions. Visualization options include line graphs, bar charts, contours, wind vectors, and more, with outputs in formats like PostScript and images. A scripting interface supports advanced applications, user interaction through buttons and menus, and automated batch processing, making GrADS a robust tool for geoscientific workflows. More information about GrADS and its features can be found at http://cola.gmu.edu/grads/.

### 3.2.3 Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) is a continuous, long-term, distributed-parameter model capable of simulating various processes such as surface flow, subsurface flow, soil erosion, sediment deposition, and nutrient movement within watersheds (Arnold et al., 1998; Neitsch et al., 2011; Srinivasan et al., 2012). The model was developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS). Currently, SWAT stands as one of the most widely utilized hydrological models worldwide. The widespread use of the SWAT model may have been attributed to its availability as open-source code and its seamless integration with GIS platforms for easy application. The model operates on a process-based approach, demonstrating computational efficiency while enabling continuous simulation over long time periods. Key components of the model encompass hydrology, erosion/sedimentation, plant growth, nutrient dynamics, pesticide behaviour, land management practices, stream routing, and pond/reservoir routing. The hydrologic processes simulated by SWAT encompass a range of phenomena, including canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, and recharge via seepage from surface water bodies, ponds, and tributary channels. The SWAT modelling tool encompasses simulations of various factors including climate variations, hydrological processes, land use changes, management of water usage, and evaluations of water quality and quantity. It has demonstrated its versatility in exploring diverse hydrologic and water quality issues across various watershed scales. It is highly adaptable for applications demanding enhanced simulation capabilities, particularly in the realm of hydrology and related fields. SWAT requires basin-specific input data covering various components including weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, channel routing, and pond/reservoir routing. Weather inputs, including precipitation, maximum and minimum temperature, relative humidity, wind speed, and solar radiation, are necessary at a daily temporal resolution. However, newer versions of the model permit the use of hourly input files.

SWAT is integrated into multiple GIS interfaces like ArcGIS, OpenMap, and Grass, enabling the partitioning of a basin into sub-basins. Each sub-basin encompasses river reaches and a single set of weather inputs, further subdivided into hydrological response units (HRUs) based on similar land use, soil type, and slope characteristics (Van Griensven et al., 2012). The HRU serves as the basic unit for defining the water balance, with processes being computed within each sub-basin before being routed through the channels (Arnold et al., 2012).

The HRUs are expressed as a percentage of the sub-watershed area and may not be contiguous or spatially delineated in a SWAT simulation. Alternatively, the watershed can be divided into sub-watersheds based solely on dominant land use, soil type, and management practices. Water balance serves as the fundamental factor governing all processes within the SWAT model, because it influences plant growth and the transport of sediments, nutrients, pesticides, and pathogens. The simulation of watershed hydrology in SWAT is divided into two phases: the land phase, which regulates the input of water, sediment, nutrients, and pesticides into the main channel within each subbasin, and the in-stream or routing phase, which involves the movement of water, sediments, etc., through the channel network of the watershed towards the outlet. SWAT employs a unified plant growth model to simulate various land cover types, distinguishing between annual and perennial plants. This model is utilized to evaluate processes such as water and nutrient uptake from the root zone, transpiration, and biomass or yield production. SWAT utilizes the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977) to forecast sediment yield from the landscape. It also simulates the transport and transformation of various substances including nitrogen, phosphorus, pesticides, and sediment within the watershed. Additionally, SWAT provides the flexibility for users to specify management practices occurring within each Hydrologic Response Unit (HRU). After establishing the loadings of water, sediment, nutrients, and pesticides transitioning from the land phase to the primary channel, these loadings are subsequently channelled through the streams and reservoirs across the watershed. The reservoir water balance comprises factors such as inflow, outflow, surface rainfall, evaporation, seepage from the reservoir bed, and diversions. It is computed as:

$$SW_t = SW_o + \sum_{\{i=1\}}^{t} R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \qquad (1)$$

Where $SWt$ represents the final soil water content (mm), $SWo$ denotes the initial soil water content on day $i$ (mm), $t$ is the time in days, $Rday$ refers to the precipitation amount on day $i$ (mm), $Qsurf$ is the surface runoff amount on day $i$ (mm), $E$a is the evapotranspiration amount on day $i$ (mm), $Wseep$ is the water volume moving into the vadose zone from the soil profile on day $i$ (mm), and $Qgw$ is the return flow amount on day $i$ (mm).

**Surface Runoff**: This refers to flow along a sloped surface and occurs when the rate of water applied to the ground surface surpasses the rate of infiltration. In this study, surface runoff generation was estimated using the Soil Conservation Service (SCS) curve number equation, which depends on land use and soil types. The SCS curve number equation is given as:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{R_{day} + 0.8S} \qquad (2)$$

Where $R_{day}$ represents daily precipitation (mm) and S is a retention parameter which is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (3)$$

Here, CN refers to the curve number, which is influenced by land use and soil type. The CN value dictates the portion of rainfall that contributes to surface runoff and the amount that is absorbed by the soil.

**Actual Evapotranspiration**

ET represents the volume of water that is removed from a surface through evaporation and transpiration. SWAT calculates the actual evapotranspiration after determining the potential evapotranspiration (PET). In this study, SWAT estimated the PET using the Hargreaves method (Hargreaves and Samani, 1985), which relies solely on air temperature as the input data.

**Lateral flow ($Lt_{flow}$)**

In SWAT, lateral flow occurs when the soil's water content surpasses its field capacity, and it is calculated as:

$$L_{tflow} = 0.024\left(\frac{2 \cdot SW_{ly,\,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}}\right) \qquad (4)$$

Where $SW_{ly,\,excess}$ represents the drainable volume of water stored in the saturated zone of the hillslope per unit area (mm), $K_{sat}$ is the saturated hydraulic conductivity of the soil (mm $h^{-1}$), slp is the elevation change per unit distance, $\phi_d$ is the drainable porosity of the soil (mm $mm^{-1}$), and $L_{hill}$ is the length of the hillslope (m).

**Water yield (WYLD)**

This refers to the total contribution to streamflow, which includes surface runoff (Q_surf), lateral flow (Ltflow), and groundwater flow (Q_gw).

**Groundwater Recharge**

SWAT models two aquifers in each subbasin. The shallow aquifer is unconfined and contributes to the flow in the main channel or within the subbasin, while the deep aquifer is confined. Water entering the deep aquifer is assumed to contribute to streamflow outside the watershed (Arnold et al., 1993). In this study the groundwater recharge is calculated as:

$$W_{rchg,i} = \left(1 - exp\left(-\frac{1}{\delta_{gw}}\right)\right) W_{seep} + exp\left(-\frac{1}{\delta_{gw}}\right) W_{rchg,i-1} \qquad (5)$$

Here, $W_{\text{rchg},i}$ denotes the recharge amount entering the aquifers on day i (mm), $\delta_{\text{gw}}$ represents the delay or drainage time of the overlying geologic formations (days), $W_{\text{seep}}$ is the total water exiting the bottom of the soil profile on day *i* (mm), and $W_{\text{rchg},i-1}$, is the recharge entering the aquifers on day *i-1* (mm).

The total recharge, once determined, is divided between the shallow and deep aquifers. The water entering the shallow and deep aquifers, as simulated by SWAT, is described by equations 6 and 7 respectively.

$$D_{p\_rech} = \beta_{deep} W_{rchg} \quad (6)$$

$$W_{rchg,\, sa} = W_{rchg} - D_{p\_rech} \quad (7)$$

Where $D_{\text{p\_rech}}$ represents the volume of water percolating into the deep aquifer on day i (mm), $\beta_{\text{deep}}$ is the aquifer percolation coefficient, and $W_{\text{rchg, sa}}$ is the recharge entering the shallow aquifer on day i (mm).

Detailed information regarding these processes can be found in the theoretical documentation of SWAT, accessible at http://swatmodel.tamu.edu.

### 3.3 Methods

#### 3.3.1 Drought Indices

Three indices such as Standardized Anomaly Index (SAI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI) and Standardised Precipitation Evapotranspiration Index (SPEI), are used to evaluate the drought conditions in the study area.

##### 3.3.1.1 SAI

The Standardized Anomaly Index (SAI) is utilized to assess the annual rainfall and discharge variability over the study area. The SAI allows the estimation of the dry and wet years in the record and is used to analyse the frequency and severity of droughts. It is calculated as:

$$SAI = \frac{X - \bar{X}}{\sigma} \quad (8)$$

where $X$ is the annual rainfall of the particular year, $\bar{X}$ is the long-term mean of annual rainfall over the observation period, and σ is the standard deviation of annual rainfall during the observation period. When compared to the chosen reference period, negative values indicate a drought, while positive values indicate a wet scenario.

##### 3.3.1.2 SPI and SPEI

The SPI, derived solely from precipitation data (McKee et al., 1995) as a drought index, has been modified into the SPEI (Vicente-Serrano et al., 2010), which incorporates both precipitation and evapotranspiration data. The SPEI therefore effectively captures the main influence of rising temperatures on water demand. This approach not only detects the anticipated influence on precipitation but also integrates the predicted drought severity resulting from temperature variability. Hence, the index proves particularly suitable for detecting, monitoring, and exploring the influence global warming on drought patterns. Additionally, the SPEI offers the benefit of being a statistically based index, relying solely on climatic data without presumptions about the underlying system's characteristics. This could represent a significant advancement in drought monitoring, particularly in western Africa, where temperatures have increased more than the global average (Calvin et al., 2023). The SPI and SPEI are computed at a 12 & 24-month scale using the SPEI package available in the R statistical software available at (http://sac.csic.es/spei/).

Potential evapotranspiration (PET) was calculated using the Hargreaves–Samani approach (Hargreaves and Samani, 1985), which utilizes daily minimum and maximum temperatures along with latitude. This method is particularly suited for regions with limited data availability, as it requires fewer inputs than more complex models like Penman–Monteith, which depend on additional variables such as solar radiation, wind speed, and humidity. In addition to capturing atmospheric conditions through temperature, the Hargreaves–Samani method indirectly accounts for land surface characteristics, such as soil moisture and surface reflectivity, via the diurnal temperature range, making it more sensitive to surface changes. Several global studies have demonstrated that this method maintains strong performance across a range of climatic zones, including arid, semi-arid, temperate, cold, and polar areas, highlighting the importance of temperature in PET estimation (Almorox et al., 2015; Li et al., 2018; Zarei and Mahmoudi, 2020; Ortiz-Gómez et al., 2022).

However, because PET was estimated using CHIRPS precipitation and ERA5 temperature data within the Hargreaves–Samani framework, some level of uncertainty in the resulting SPEI values is unavoidable, particularly due to the lack of solar radiation and wind speed data. To address this, future research should explore the sensitivity of PET estimates by testing alternative models, such as Penman–Monteith or Thornthwaite, and integrating satellite-derived parameters when available. Where ground-based evaporation data are accessible, validating the PET estimates can also improve the robustness of drought analyses. Such methodological enhancements would contribute to more accurate and reliable interpretations of hydroclimatic trends in data-limited regions like the Gambia River Basin.

#### 3.3.1.3 Standardized Streamflow Index (SSI)

In addition to SPEI, the Standardized Streamflow Index (SSI) was used to evaluate hydrological drought conditions in the study area. The SSI was calculated from annual mean discharge data, following a process similar to the calculation of the Standardized Precipitation Index, but using discharge data instead of precipitation (Barker et al., 2016). This index helps monitor the impact of hydrological conditions on drought severity, offering insights into changes in streamflow over time. The Gouloumbou station, located at the basin outlet, was excluded from the analysis due to the influence of tides and the fact that discharge data is only recorded during the rainy season. This seasonal limitation prevents the availability of continuous, year-round data, making the station unsuitable for reliable trend detection or drought analysis.

### 3.3.2 Trend Analysis

Various statistical techniques, generally categorized into parametric and non-parametric methods, have been used to identify trends and other changes in hydroclimatic data. Parametric approaches presuppose a normal distribution for the relevant variables and must adhere to both distributional and independent assumptions. In contrast, non-parametric methods lack fixed parameters or a specific distribution and only require adherence to the independent assumption. The non-parametric Mann–Kendall test is one of the most widely used methods in detecting increasing or decreasing trends in time series data in recent years. This is attributed to its capability to perform tests without the assumption of normal distribution in datasets and its reduced sensitivity to abrupt breaks caused by inhomogeneous time series (Yue and Wang, 2004; Shahid, 2010). The only prerequisite for trend tests is the independence of data. However, the presence of positive serial autocorrelation in the data can increase the likelihood of detecting significance in the trend. To eliminate the effect of autocorrelation, one can either eliminate serial correlation from the data prior to applying trend tests or adjust the original trend tests to accommodate serial correlation (Hamed, 2008). Hamed and Rao (1998) and Yue and Wang (2004) introduced the modified Mann–Kendall (m-MK) trend test to account for the effects of serial correlation. In addition to autocorrelation, the significance of hydroclimatic trends over time is highly sensitive to assumptions regarding whether the underlying data exhibit short-term or long-term persistence (Sa'adi et al., 2019). Trend analyses in this study were tested with the modified Mann-Kendall trend test and Sen's slope estimator available in the R package, modifiedmmk. The null hypothesis (H0) in this test is that there is no trend in the data over time whilst the alternative hypothesis (H1) indicates there is a trend (increasing/decreasing) over time. All trend results in this study have been assessed at the 5% level of significance to ensure thorough examination of the trends. The test statistic for the modified Mann-Kendall (m-MK) test is given by:

$$\boldsymbol{S_m = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \cdot w_i \cdot w_j} \quad \textbf{(9)}$$

Here, $x_i$ and $x_j$ are the data values at time points *i* and *j (with i < j), n* is the number of data points, *sgn (·)* is the sign function (returns -1 for negative values, 0 for zero, and 1 for positive values), and

$W_i$ and $w_j$ are weights introduced to account for the autocorrelation.

The weights $w_i$ and $w_j$ are calculated based on an autocorrelation function, typically using the following formula:

$$w_i = \frac{1-\rho_i}{1+\rho_i} \quad (10)$$

Where $\rho_i$ is the sample autocorrelation at lag *i*. This weight adjustment helps to mitigate the impact of autocorrelation on the test statistic.

The standard error of $S_m$ is then calculated as:

$$Var(S_m) = \frac{1}{18} n(n-1)(2n+5) - \sum_{i=1}^{t} \frac{g_i \cdot (g_i - 1) \cdot (2g_i + 5)}{18} \quad (11)$$

where $g_i$ is the number of tied groups of data values of size *i,* and *t* is the number of tied group sizes.

Finally, the Z statistic is computed as:

This Z statistic is then compared to critical values from the standard normal distribution to determine the significance of the trend. The modification introduced by Yue and Wang helps account for autocorrelation effects in the data when assessing the significance of trends using the Mann-Kendall test.

#### 3.3.2.1 Spatial and Temporal Aggregation of Gridded Data

Hydroclimatic analyses were conducted using gridded datasets (CHIRPS precipitation and ERA5 temperature). Two complementary approaches were applied. First, spatial trend analysis was performed at the grid-cell level. Each pixel was treated as an independent time series, and the modified Mann–Kendall test and Sen's slope estimator were applied to detect trends and their magnitude. This approach allowed the generation of spatial maps showing the distribution of hydroclimatic trends across the basin. Second, temporal trend analysis at the basin scale was conducted by computing spatial averages of the gridded data. The Climate Data Operators tool (CDO) was used, specifically the 'fieldmean' function, to aggregate all grid cells within the study area into a single representative time series. Trend analysis was then applied to this basin-averaged series using the same statistical methods. This combined approach ensures consistency between spatial variability and overall basin-scale behavior, while avoiding the need for geostatistical interpolation methods such as kriging.

### 3.3.3 Breakpoint Analysis

The objective of pursuing such an analysis is to identify the number of break points within a dataset and the location of the detected break point. In this study, the Pettitt test embedded in the R software is utilized. The Pettitt test (Pettitt, 1979) is a nonparametric test that does not require prior knowledge about the distribution of the dataset and is used to test the departure of homogeneity in the time series. It is an adaptation of the rank-based Mann-Whitney test that allows us to identify the time at which a shift occurs in the dataset. The null hypothesis in this test is that the annual values Yi of the testing variable Y are independent and identically distributed. Under the alternative hypothesis, it is assumed that a step-wise shift in the mean (a break) is present (Wijngaard et al., 2003). The test is capable of locating the year where a break is likely and enables us to identify regime shifts in hydroclimatic data. The Pettitt test holds an edge over alternative homogeneity tests by not relying on the assumption of normal distribution for Yi values. This is because the Pettit test ranks the elements of a series rather than directly analysing their values. This ranking methodology of the Pettitt test further implies a reduced sensitivity to outliers compared to other tests. Given a time series data ($x_1, x_2, x_3$, ……, $x_n$), the ranks $r_1, r_2, r_3, \ldots, rn$ are used to calculate the statistic $X_k$ (Wijngaard et al., 2003).

$$X_k = 2\sum_{i=1}^{k} r_i - \frac{k(n+1)}{2}, \quad k = 1, \ldots, n \quad (12)$$

The tests statistic is calculated as,

$$K = \max_{1 \le k \le n} |X_k| \quad (13)$$

If a break occurs in year K, then the statistic is maximal or minimal near the year k = K. Therefore, if the break occurs, then $U_K = \max Uk$.

To assess the statistical significance of an identified breakpoint, the computed value of K is compared to its corresponding theoretical value at a probability level α.

### 3.3.4 SWAT Model Setup, Calibration, and Validation

#### 3.3.4.1 Watershed Delineation and Hydrologic Response Unit Definition

The SWAT model setup (Figure 9) involved catchment delineation, Hydrological Response Unit (HRU) definition, sensitivity analysis, calibration, and validation. The 30m DEM was utilized to delineate the Upper Gambia Basin, stream networks, sub-basins, and topographic features (such as slopes and elevation) using the SWAT plugin in ArcMap. The delineation resulted in 28 sub-basins, covering a total area of 41,806.68 km². The land use/land cover (LULC) and soil maps were reclassified into SWAT-compatible LULC/soil types (Table 4), and a user-defined lookup table was created to assign SWAT codes to the different LULC/soil categories as required. The LULC and soil maps were then used to define the catchment's HRUs. The Hargreaves method, which requires only minimum and maximum temperature as input, was selected for calculating potential evapotranspiration based on data availability. The model simulation covered the period from 1990 to 2010, with the first two years (1990-1991) used as the model warm-up period.


*Figure 9: Flowchart of the SWAT Processing Steps for the CGRB*

#### 3.3.4.2 Climate Data Preparation for SWAT Model

Climate input data required for SWAT simulation were derived from gridded datasets due to the limited availability of continuous ground observations in the study area. Precipitation data were obtained from the CHIRPS dataset, while temperature data (minimum and maximum) were derived from ERA5 reanalysis products. Since SWAT requires station-based time series, the gridded datasets were processed to extract point-based climate data corresponding to selected stations within the basin, namely Gouloumbou, Kédougou, Mako, Simenti, Tambacounda, and Labé.

The extraction was performed using Climate Data Operators (CDO). For each station, geographic coordinates (longitude and latitude) were specified, and the nearest-neighbour remapping method (remapnn) was applied to extract the value of the closest grid cell from the gridded datasets. This approach preserves the original dataset values without introducing interpolation smoothing, making it suitable for hydrological Modeling applications. The extraction process was implemented using automated Bash scripts to ensure consistency across all stations and time periods. Prior to extraction, CHIRPS data were regridded using bilinear interpolation (remapbil) to harmonize spatial resolution and ensure compatibility with other datasets. This preprocessing step reduced spatial inconsistencies and improved integration of climate variables within the SWAT model framework. The resulting station-based time series of precipitation and temperature were formatted according to SWAT input requirements and used as climate inputs for model simulation, calibration, and validation.

#### 3.3.4.3 SWAT Model Parameter Sensitivity Analysis

Sensitivity analyses refer to the Identification of the most sensitive parameters that significantly impact the SWAT model's performance for a specific catchment. This is the first step in the calibration and validation process. Understanding parameter sensitivity serves two key purposes. It highlights the most influential processes in the study area by analysing how different parameters impact the model. Additionally, it enhances the efficiency of the calibration process by removing parameters that have little to no effect, allowing for a more focused adjustment of the model (Abbaspour et al., 2017). This analysis plays a crucial role in guiding the calibration and validation process, enhancing accuracy by minimizing parameter uncertainty (Lenhart et al., 2002). The Sequential Uncertainty Fitting Program (SUFI-2) algorithm in the SWAT-CUP (SWAT Calibration and Uncertainty Programs) software was used for the sensitivity analyses, calibration and validation analyses (Abbaspour, 2007). The sensitivity analyses for this study were performed on 19 initial parameters (Table 15), which were selected based on past research (Schuol et al., 2008; Wambura et al., 2018) and recommendations from the SWAT documentation about parameters sensitive to streamflow (Neitsch et al., 2011).

#### 3.3.4.4 SWAT Model Calibration, Validation, and Impact Assessment

Calibration is the process of adjusting a model to reduce discrepancies between simulated and observed data. The goal is to ensure that the regional model accurately represents real-world physical processes. The SWAT model for the Continental Gambia River Basin was calibrated using daily observed discharge data from January 1990 to December 2009 and validated with data from January 2011 to October 2022 at the Simenti station. The main outlet of the basin could not be used for the analyses due to the unavailability of discharge data during the dry season. Data here is collected only during the rainy season due to tidal influence of the sea. To ensure that the basin's water balance was well represented, parameter ranges were set based on other studies performed in the region (Schuol et al., 2008; Anoh et al., 2017; Lèye et al., 2020; Sane et al., 2020).

The performance of the calibrated and validated SWAT model was assessed using three metrics: Nash-Sutcliffe model efficiency (NSE), coefficient of determination ($R^2$), and percentage bias (PBIAS) (equations 30-32). PBIAS (Yapo et al., 1996) assesses whether the simulated values tend to be higher or lower than the observed values. Positive PBIAS values suggest that the model overestimates the observations, while negative values indicate an underestimation. NSE values, proposed by (Nash and Sutcliffe, 1970), span from negative infinity to 1, with 1 indicating a perfect model. A value of zero suggests that the observed mean is as accurate as the predicted model, while values less than zero indicate that the observed mean is a better predictor than the model. $R^2$, as described by Krause et al. (2005) , measures the goodness of fit between the simulated and observed data, ranging from 0 to 1, with 1 representing the best fit. Additionally, spatial patterns of remote sensing data of evapotranspiration and groundwater height were used as extra constraints for the model.

Scenarios of land use and climate variability were applied to evaluate how changes in climate, land use, and their combined influence affect streamflow. The climate data from 1990 to 2022 was divided into three 12-year intervals: 1990–2000, 2001–2011, and 2012–2022. Each of these periods corresponds to the respective land use years of 1988, 2002, and 2022.

The scenarios were designed as follows:

1) Climate data was varied while keeping the three land use periods unchanged to evaluate the effect of climate variability on streamflow.
2) Land use was altered while maintaining constant climate data to determine the influence of land use changes on streamflow.
3) In the final step, both climate data and land use were varied simultaneously to assess their combined impact on streamflow.

### 3.3.5 Field Survey

A field survey was conducted to collect socioeconomic data in 15 villages across the rural municipalities of Nettéboulou, Missirah, and Dialacoto, all hydrologically connected to the Gambia River. The selected villages were chosen due to their high reliance on the Gambia River for livelihoods, irrigation, and domestic water use, with seasonal fluctuations in river flow exerting a direct influence on agricultural practices and household activities. The study area includes a mix of long-established settlements and resettled communities, some of which were displaced from Niokolo-Koba National Park (Larrue, 2002), while others migrated southward during the droughts of the 1970s in search of more favourable agricultural conditions (Ndione, 2018). Over time, these settlements became integrated into a large-scale banana production zone along the riverbanks, established to provide farming households with more stable and reliable income opportunities. This expansion of irrigated agriculture has intensified pressure on local water resources, highlighting the growing importance of effective and inclusive water governance. The region's prominence in banana cultivation and market gardening further emphasizes the central role of water in sustaining local livelihoods. These selection criteria ensured that the study sites were representative of river-dependent communities, making them well suited for examining the socio-economic and environmental dynamics shaped by the Gambia River.

The sample size was determined using the total number of households (1,347) and calculated in accordance with Cochran's 1963 sample size formula for finite populations. The applied equation is presented below:

$$n = \frac{Z^2 Np(1-p)}{d^2(N-1)+Z^2 p(1-p)} \quad \textit{(14)}$$

In this equation, n denotes the required sample size, N represents the total population of households (1,347), Z corresponds to the Z-score associated with the selected confidence level (1.96 for 95%), p is the estimated population proportion, assumed to be 0.5 to maximize variability, and d indicates the acceptable margin of error (0.05). Applying these parameters resulted in a sample size of approximately 300 respondents. Data on village population sizes were obtained from the National Agency for Statistics and Demography (ANSD), Senegal.

The number of households to be interviewed per village was calculated as follows:

$$\frac{\textit{Number of households in the village x } 300}{\textit{Total number of households in the } 15 \textit{ villages}} \quad \textit{(15)}$$

*Table 6: Sampling Distribution in the Three Municipalities*

| **Municipality** | **Village** | **No. of Households** | **Uncertainty interval** | **Sampling** | **Percentage** |
|---|---|---|---|---|---|
| **Dialacoto** | Bady | 49 | 5% | 11 | 3.6 |
| **Dialacoto** | Nionghani | 32 | 5% | 7 | 2.4 |
| **Dialacoto** | Ouassadou Depot | 256 | 5% | 57 | 19.0 |
| **Dialacoto** | Ouassadou Village | 20 | 5% | 4 | 1,5 |
| **Dialacoto** | Damantan | 15 | 5% | 3 | 1.1 |
| **Missirah** | Gouloumbou | 201 | 5% | 45 | 14.9 |
| **Missirah** | Koar | 189 | 5% | 42 | 14.0 |

| | | | | | |
|---|---|---|---|---|---|
| **Missirah** | Nguene Sérère | 102 | 5% | 23 | 7.6 |
| **Missirah** | Saal | 103 | 5% | 23 | 7.6 |
| **Missirah** | Sankagne I | 142 | 5% | 32 | 10.5 |
| **Netteboulou** | Bantantinti | 115 | 5% | 26 | 8.5 |
| **Netteboulou** | Faraba | 59 | 5% | 13 | 4.4 |
| **Netteboulou** | Guenetto | 17 | 5% | 4 | 1.3 |
| **Netteboulou** | Koulare | 33 | 5% | 7 | 2.4 |
| **Netteboulou** | Mawadou Touremane | 14 | 5% | 3 | 1.0 |
| **Total** | | **1347** | **5%** | **300** | **100** |

This method was adopted to acquire comprehensive data within the region under investigation rather than relying solely on remote sensing analysis or pre-existing data from the authorities. The choice of methodology was motivated by several reasons. Firstly, it provided us with a detailed understanding of the local environment, including the perceptions and beliefs held by the local population. This is an aspect that could have eluded us if we relied solely on remote sensing data or official statistics. Moreover, the interviews allowed us to be flexible with the questions enabling deeper exploration of relevant topics that were of interest to us. Engaging directly with the local communities through interviews also gave the natives the opportunity to contribute their knowledge and perceptions and hence creating a collaborative research environment.

Prior to the full survey, a pilot study was carried out in two villages to assess the clarity, relevance, and cultural suitability of the questionnaire. Following minor revisions, the finalized structured questionnaire was administered using the Kobo Collect Toolbox (www.kobotoolbox.org). The questionnaire was divided into five sections. The first section focused on demographic characteristics, while the second examined the socioeconomic activities of residents in the selected villages, including population trends and water use. The third section assessed climatic and land use trends and their effects on hydrological processes, whereas the fourth addressed water resource management, covering awareness, attitudes, conflicts, and management strategies. The final section sought recommendations from respondents for sustainable water resource management. Data from the first three sections were used to validate the results of the land use analysis, while the final two sections assessed participants' knowledge of key dimensions of water governance, including awareness of regulations, perceptions of institutional effectiveness, participation in local decision-making, and experiences of water-related conflicts.

Data collection was conducted by a team of six trained enumerators proficient in local languages, including Mandinka, Fulani, Wolof, Diola, and Soninke. Of the 300 households initially targeted, 290 completed responses were successfully obtained, yielding a response rate of over 96%, which is considered strong for social science field research (Babbie, 2010).

### 3.3.6 Chi-Square Test

The chi-square test was employed to examine associations between key categorical variables. This test was selected to assess whether statistically significant relationships exist between these variables. The chi-square test is a commonly used statistical method for determining whether a significant association exists between two categorical variables (Tang et al., 2012; Unguryanu and Grjibovski, 2014; Azen and Walker, 2021). The test is appropriate when the expected cell counts in the contingency table are sufficiently large, generally considered to be five or more in each cell.

## 3.4 Partial Conclusion

This study utilized a combination of advanced data sources, methods, and tools to assess land use changes and environmental dynamics in the CGRB. Multi-date Landsat satellite images from 1988, 2002, and 2022 were processed with rigorous geometric and radiometric corrections, and image analysis using unsupervised hierarchical classification enabled the identification of land use categories. Environmental data on precipitation, temperature, streamflow, and evapotranspiration from sources such as CHIRPS and ERA5 provided a comprehensive understanding of the area's hydrological behaviour. These datasets were analysed using tools like TerrSet, CDO, GrADS, and Stata to ensure reliability and accuracy.

Furthermore, the Soil and Water Assessment Tool (SWAT) was employed to simulate various hydrological processes in the Upper Gambia Basin. Through careful model setup, calibration, and validation, SWAT proved to be an effective tool for assessing streamflow under changing land use and climate scenarios. Sensitivity analyses highlighted the most influential parameters, enhancing the model's performance and accuracy. The integration of field surveys and socio-economic data further enriched the study by offering insights into local dynamics and fostering a collaborative approach to water resource management. The combination of these methodologies ensures a robust, multidimensional understanding of the study area's environmental and hydrological conditions.

## Chapter 4: Hydroclimatic Trends

### 4.1 Standardized Anomaly Index of Precipitation (SAI)

The results of the modified MK trend test for the annual precipitation sum (1990-2022) showed a significant increasing trend, with a breakpoint in 2008 (Figure 10). All P-values were below the 5% significance level. The Standardized Precipitation Index (SPI), constructed for the same period reveals that prior to 2008, conditions were predominantly dry, apart from the exceptionally wet year in 1999. Post-2008, the region shifted toward wetter conditions, indicating a rainfall recovery. The SPI graph shows significant variability, with extreme dry years observed in the early 1990s and 2000s, and extreme wet years in the later part of the study period, especially in 2015.

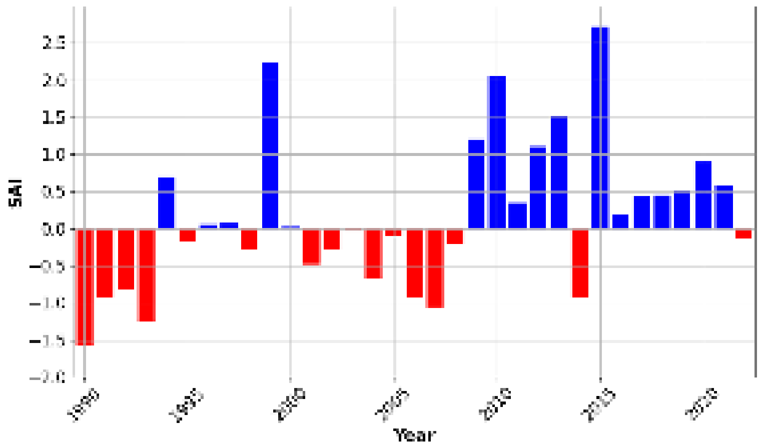


*Figure 10: Standardized Anomaly Index of Precipitation*

### 4.2 Trend Analysis of Precipitation

#### 4.2.1 Spatial Precipitation Trends over the Continental Gambia River Basin

Figure 11 presents the spatial trend in annual precipitation across the CGRB between 1990 and 2022, with areas of statistical significance overlaid. The results indicate a clear north–south gradient in precipitation trends. The northern part of the catchment experienced a statistically significant increase in annual precipitation, with changes reaching up to 35%. In contrast, the southern region exhibited a decreasing trend, with reductions of up to 10%, although these declines were generally not statistically significant. The central portion of the basin remained relatively stable or experienced moderate increases.

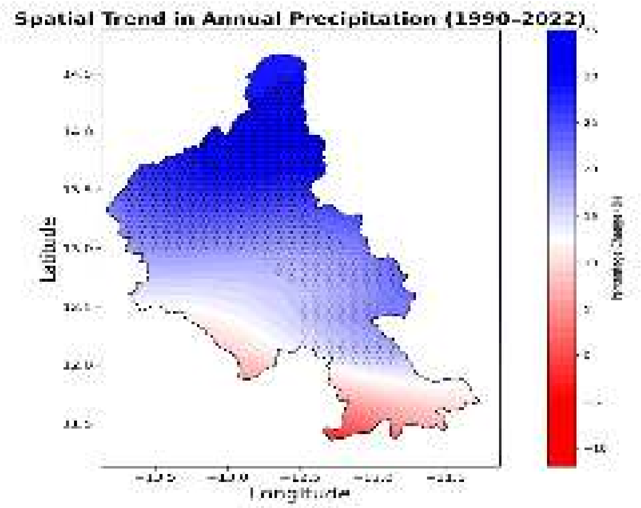


*Figure 11:* Spatial Precipitation Trends over the CGRB

### 4.2.2 Temporal Precipitation Trends over the Continental Gambia River Basin

The precipitation trend in the Gouloumbou from 1990 to 2022 is presented in Figure 12. It shows a significant (at α=5 %) shift in precipitation patterns, with a notable increase after the year 2008. Before 2008, precipitation values ranged from approximately 900–1300 mm/year. Between 1990 and 2010, precipitation values peaked at 1300mm per year in 2000. After 2010, precipitation values are observed to increase with the highest peak observed in 2016.

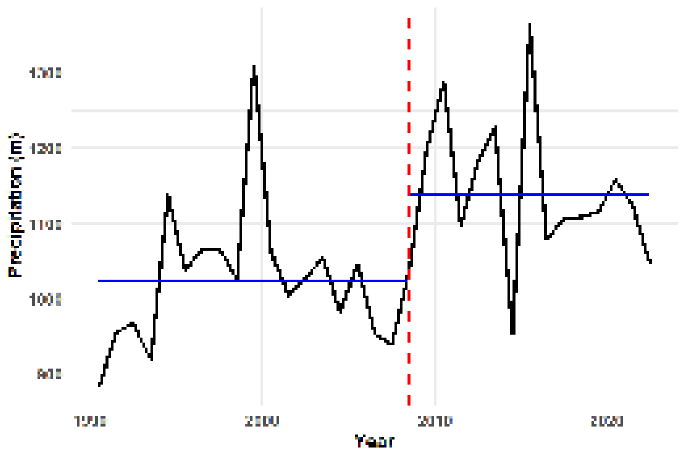


*Figure 12: Temporal Precipitation Trends over the CGRB*

### 4.3 Temperature Trend

The temperature trend in Gouloumbou from 1990 to 2022 is presented in Figure 14. It reveals a significant (at α=5 %) shift in climate patterns, with a notable increase in average temperatures after the year 2000. Between 1990 and 2000, temperatures fluctuated between approximately 28°C and slightly above 29°C, with an overall stable average around 28.5°C. However, after 2000, a clear upward trend is observed, as temperatures rise steadily, and higher temperature peaks become more frequent, especially in the years after 2015. The post-2000 period is marked by fewer fluctuations below 28.5°C and several instances where temperatures exceed 29°C, indicating a sustained warming trend. This increase suggests the potential influence of regional or global climate change, which could have significant implications for local ecosystems, water availability, and agricultural productivity in the CGRB.

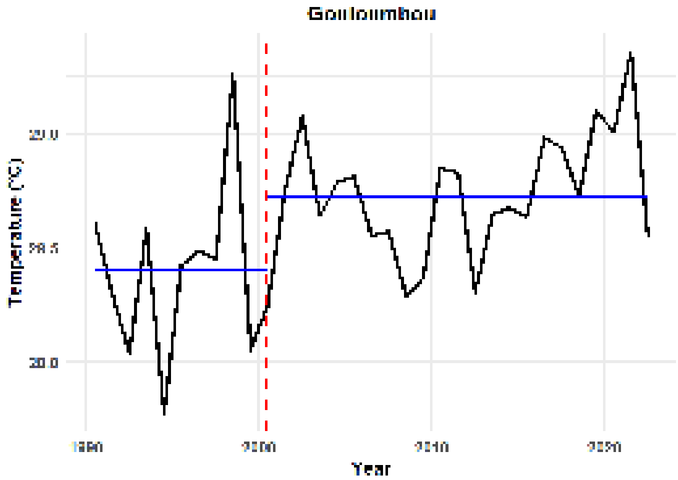


*Figure 13: Breakpoint Analysis of Temperature*

### 4.4 SPEI Indices

The SPEI was constructed at 12-month and 24-month scales (Figure 13), which are useful in assessing hydrological drought and surface water availability (Li et al., 2015). Several authors (Manatsa et al., 2008; Vicente-Serrano et al., 2012; Tirivarombo et al., 2018; Faye, 2022) confirm the effectiveness of SPEI in evaluating drought impacts across different climates. A notable dry phase occurred in the early 1990s and 2000s, indicated by negative SPEI values, with a breakpoint detected in 2008, marking the onset of rainfall recovery and a shift to wetter conditions. Modified MK trend analysis revealed significant increasing trends towards wetter conditions for SPEI-12 and SPEI-24, with p-values of $4.77\times10^{-6}$ and $3.01\times10^{-5}$, respectively. Despite the recent wet trend, fluctuations and periodic dry spells highlight ongoing variability, consistent with observations across the Sahel and West Africa (Dong and Sutton, 2015; Sanogo et al., 2015; Nicholson et al., 2018; Chagnaud et al., 2022).

The identification of breakpoints, especially the pronounced shift observed around 2008, warrants close examination. A key contributing factor could be large-scale climate variability, notably the El Niño–Southern Oscillation (ENSO), known to influence rainfall distribution across West Africa (Nicholson, 2013). The alternating warm (El Niño) and cool (La Niña) phases affect atmospheric moisture transport and the onset and strength of the West African monsoon, potentially leading to extended periods of drought or heavy rainfall. Supporting evidence is provided by (Nouaceur and Murarescu, 2020), which highlighted a second wave of rainfall recovery starting around 2008 in several Sahelian countries such as Senegal and Burkina Faso. This regional coherence strengthens the argument that 2008 marks a significant climatic transition toward wetter conditions in the study region. The observed wetting trend after 2008 corresponds with a broader recovery from the severe droughts of the 1970s and 1980s, a change often linked to increased greenhouse gas emissions and declining aerosol levels, which have reshaped atmospheric circulation and enhanced monsoon activity (Dong and Sutton, 2015; Biasutti, 2019).

Besides climate-related factors, changes in land use and land cover (LULC) may also have significantly influenced hydrological patterns. For instance, (Kayitesi et al., 2024) reported substantial LULC changes, such as deforestation and agricultural expansion, largely driven by socio-political upheavals and population displacements in the African Great Lakes area. In the Niger Basin, extensive vegetation clearance has degraded soil structure and reduced infiltration, promoting surface runoff (Hortonian flow), and contributing to gully and pond formation (Leblanc et al., 2008). Conversely, policy reforms promoting reforestation and stricter control over slash-and-burn practices have supported vegetation recovery and forest regrowth in some areas since 2008 (FAO, 2011; Lambin et al., 2001). These developments likely improved soil water retention and groundwater recharge, reinforcing the observed wetting trend. Furthermore, expanding croplands and shifts in vegetation cover have been linked to enhanced latent heat flux and moisture recycling, possibly intensifying summer rainfall and creating a feedback mechanism between vegetation and precipitation in the arid Sahel (Lee et al., 2015). Nonetheless, despite increased annual rainfall, recent years have seen a rise in rainfall variability and intensity, commonly known as the Sahelian paradox, marked by more frequent flooding due to intensified convective storms and rainfall clustering later in the season (Biasutti, 2019; Taylor et al., 2017).

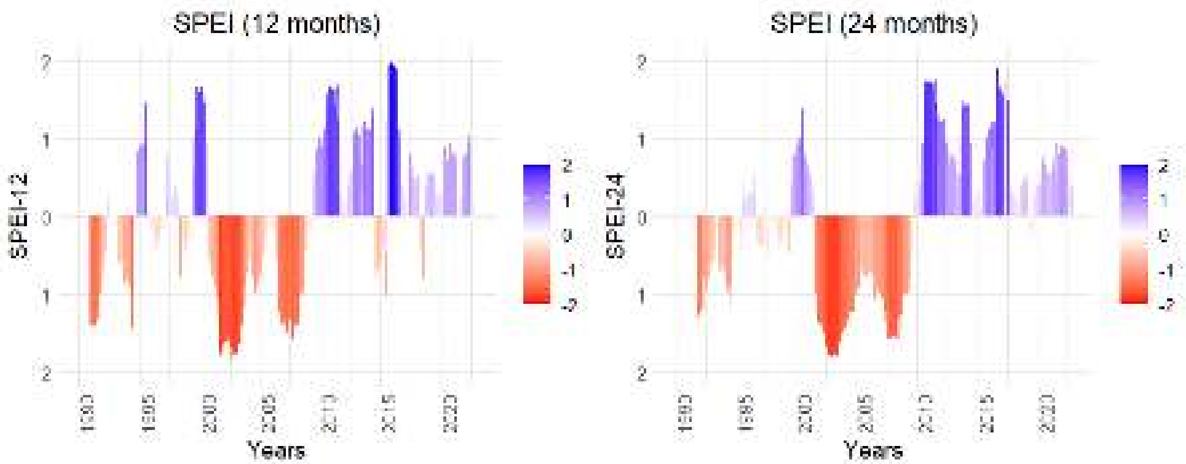


*Figure 14: Temporal Variation of SPI (left) and SPEI (right)*

### 4.5 Standardized Streamflow Index at the Simenti Station

The Standardized Flow Index (SFI) for Simenti (Figure 15), illustrates the deviations from average flow conditions from 1990 to 2022. Negative values (red bars) indicate below-average flow, while positive values (blue bars) represent above-average flow. The period from 1990 to 2010 is dominated by negative anomalies apart from the years 1994, 1999, 2003, and 2004. After 2010, a shift occurs with a predominance of positive anomalies, indicating a trend toward wetter conditions. The years after 2015 show consistently higher positive SFI values, with 2020 and 2022 standing out as particularly wet years, reinforcing the observation of increasing streamflow and suggesting a significant change in the hydrological regime of the region.

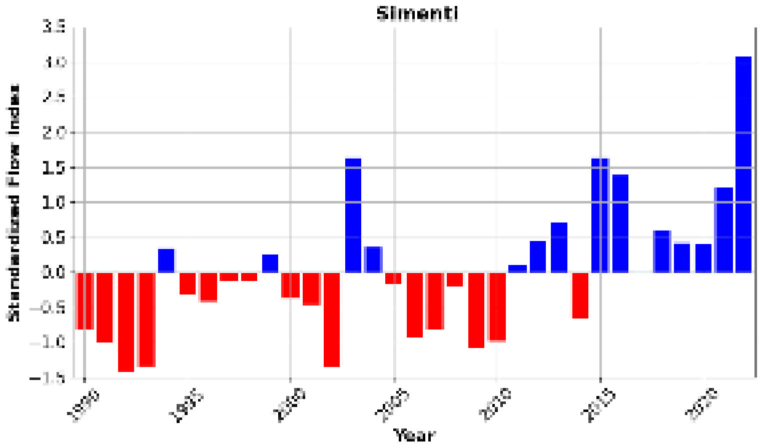


*Figure 15: Standardized Streamflow Index at the Simenti Station*

### 4.6 Discharge Trends at the Simenti Station

The discharge trend at Simenti Station from 1990 to 2022 (Figure 16) shows a gradual increase in river flow over the years. Before 2010, discharge levels fluctuate between 100 m³/s and 300 m³/s, with some moderate peaks and troughs, indicating relatively stable flow conditions. However, after 2010, the discharge exhibits a noticeable upward trend, with more frequent and higher peaks, particularly in the years following 2015. The highest discharge levels exceed 400 m³/s towards the end of the observed period, suggesting intensified hydrological activity, possibly driven by increased rainfall, land-use changes, or climate variability.

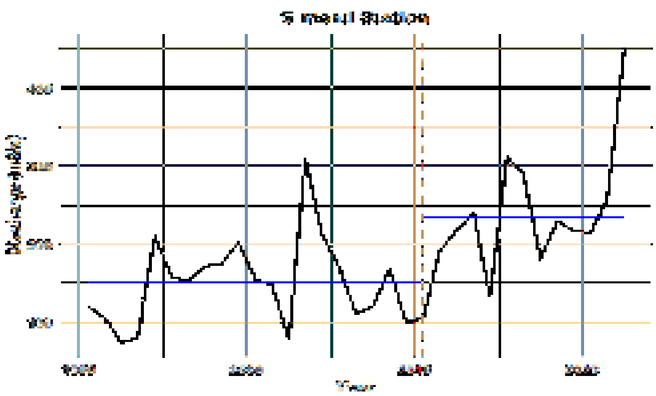

*Figure 16: Trend and Breakpoint Analysis of Discharge at the Simenti Station*

### 4.7 Discussion

The modified Mann–Kendall trend test for annual precipitation (1990-2022) revealed a significant increasing trend with a breakpoint in 2008, marking a shift from predominantly dry conditions before 2008 to wetter conditions afterward. Similarly, the trend test for mean annual temperature showed significant increases with a breakpoint in 2000, while the mean annual discharge at the Simenti station indicated increasing trends with a breakpoint in 2010, highlighting a transition to wetter conditions in the Gambia River Basin in recent years. Similar increasing trends of precipitation, temperature, and discharge have been documented in other river basins in West Africa by numerous researchers, such as Traoré (2014), Barry et al. (2017), Abungba et al. (2020), Adeyeri et al. (2020), Obahoundje et al. (2022), Ndiaye et al. (2023) in the Gambia, Mono, Black Volta, Komadugu-Yobe, Bandama, Sassandra, and Senegal River Basins. In addition, Barry et al. (2018), Biasutti (2019), Bichet and Diedhiou (2018), Loua et al. (2020) and Yanogo and Yaméogo (2023) documented similar trends in both the Sahel and Guinean Coasts. Moreover, the IPCC (2023) report along with the studies of Sylla et al. (2016), Dosio (2017), Emmanuel et al. (2019) and Almazroui et al. (2020) who have utilized either Global Climate Models (GCMs) or Regional Climate Models (RCMs) has yielded consistent findings regarding the increase of both annual precipitation and temperature across West Africa.

The observed spatial contrast in precipitation trends across the basin reflects the interaction between large-scale atmospheric dynamics, regional controls, and multi-decadal climate variability. In the southern part of the basin, particularly over the Guinean highlands around Labé, rainfall is primarily controlled by oceanic moisture influx, orographic lifting over the Fouta Djallon massif, and the early and prolonged presence of the Intertropical Front (ITF) (Kante et al., 2020; Djossou et al., 2024). Moist south-westerly monsoon flows transport moisture from the Atlantic Ocean and converge over elevated terrains, enhancing convection and rainfall (Kante et al., 2020). In addition, rainfall along the Guinea Coast exhibits a bimodal regime modulated by the West African Monsoon, with a distinct intra-seasonal dry phase known as the Little Dry Season (LDS), typically occurring in August and associated with a temporary southward shift of the Intertropical Discontinuity and reduced rainfall intensity (Aryee et al., 2025). This sub-seasonal variability reflects strong coupling between oceanic and atmospheric processes, where sea surface temperature gradients, moisture availability, and cloud dynamics play critical roles in shaping rainfall distribution (Aryee et al., 2025).

However, rainfall in Guinea is characterized by strong interannual variability driven by large-scale ocean-atmosphere oscillations such as the Atlantic Multidecadal Oscillation and ENSO, which modulate rainfall distribution and intensity (Kante et al., 2019). Empirical evidence from Upper Guinea further confirms that precipitation exhibits high variability with no statistically significant long-term trend, despite alternating wet and dry periods (Diallo et al., 2026). Historical evidence shows a marked rainfall deficit during the 1980s followed by partial recovery since the 1990s, consistent with Sahel-wide climate variability (Kante et al., 2019). At the same time, long-term regional analyses indicate an overall decline in rainfall across West Africa since the mid-20th century, with significant regime shifts occurring around the late 1960s associated with major drought episodes (Tano et al., 2023). This combination of long-term decline, partial recovery, and strong interannual variability contributes to weak or non-significant rainfall trends in Guinea.

In contrast, temperature trends show a clear and consistent increase. Evidence from Upper Guinea indicates a significant warming trend of approximately +0.03°C per year for both minimum and maximum temperatures, with stronger and more statistically robust signals than precipitation (Diallo et al., 2026). This warming occurs alongside only weak negative correlations between temperature and rainfall, suggesting a partial decoupling between thermal and hydrological processes at the regional scale (Diallo et al., 2026). Physically, rising temperatures increase evapotranspiration and atmospheric instability, yet these effects do not translate into consistent increases in rainfall due to the dominant influence of large-scale circulation systems. Furthermore, recent projections suggest increasing rainfall variability, with more frequent light rainfall events and spatially heterogeneous changes in rainfall intensity under climate change scenarios, reinforcing uncertainty in trend detection (Aryee et al., 2025). In addition, rainfall in this region is dominated by convective systems and thunderstorms, which introduce strong temporal variability and weaken detectable linear trends (Kante et al., 2019). Recent climate change evidence further indicates a shift toward fewer rainy days but more intense rainfall events, alongside localized drying in mountainous regions, reinforcing the spatial inconsistency of precipitation trends (Vyshkvarkova et al., 2025).

In contrast, the northern part of the basin, located in Senegal (Tambacounda and Kedougou), lies within the Sudano-Sahelian transition zone where rainfall is more directly controlled by the latitudinal migration of the ITF and the strength of the West African Monsoon system (Djossou et al., 2024). Rainfall onset, duration, and intensity in this region depend strongly on monsoon dynamics and moisture transport from the Gulf of Guinea. Following prolonged drought conditions during the late 20th century, the Sahel has experienced partial rainfall recovery since the early 2000s, linked to improved monsoon circulation and increased atmospheric moisture availability (Kante et al., 2019; Tano et al., 2023; Vyshkvarkova et al., 2025). Because this region is relatively dry, small increases in rainfall produce clearer and more statistically significant positive trends. This explains the stronger and more consistent positive precipitation signals observed in the northern basin compared to the more variable southern regions.

The Overall spatial pattern reflects a transition from a humid, ocean-influenced and topographically controlled rainfall regime in the south to a more climate-sensitive, monsoon-driven system in the north. While the southern region exhibits high variability due to convective processes, ocean–atmosphere interactions, and multi-decadal climate oscillations, it is also experiencing a clear warming trend without a corresponding significant increase in rainfall, indicating a growing imbalance between thermal and hydrological processes. In contrast, the northern region shows clearer rainfall trends linked to monsoon recovery and large-scale atmospheric circulation changes. These findings highlight the importance of integrating long-term climate trends, sub-seasonal dynamics, and temperature–precipitation interactions when interpreting precipitation variability across the basin.

Some authors, such as Descroix et al. (2020) have attributed these changes in discharge to the rainfall recovery in the Sahel. The authors documented that natural reservoirs that had emptied to sustain streamflow during the major drought are slowly being replenished and annual discharges continue to slowly increase, nearly reaching a long-term average. It can be observed that the streamflow has only begun to recover two years after the precipitation recovery in the region. This is because a return to more favourable climatic conditions does not immediately result in a return to the previous hydro system. Bricquet et al. (1997), further explained that even if there is a noticeable recovery in rainfall, the increase in discharges will not commence immediately. This delay is attributed to the required replenishment of various natural storage systems such as surface and sub-surface reservoirs. Some authors such as Amogu et al. (2010), Mahe et al. (2013) and Descroix et al., (2018) attribute the return of Sahelian rivers to wetter conditions to the land degradation, reporting that even though the great droughts have been followed by a general regreening, the efficiency of water infiltration in soils has decreased and is associated with the expansion of cropped areas, alongside the deterioration of vegetation and erosion of topsoil in shallow soils. The resulting consequences on water resource availability are a decline of streamflow duration in smaller rivers and a shortening of flood durations in larger rivers. Consequently, this new increase in streamflow poses greater challenges for utilization of the resource and gives rise to issues related to flood disasters.

### 4.8 Conclusion

The analysis of hydroclimatic data from 1990 to 2022 in the Gouloumbou region reveals significant shifts in precipitation, temperature, and discharge patterns. A notable change occurred around 2008, with a shift toward wetter conditions, as reflected in the Standardized Precipitation Index (SPI) and the Standardized Flow Index (SFI), which show increased rainfall and streamflow post-2008. Trend analyses confirm significant increases in precipitation and temperature, with a clear upward temperature trend since 2000, suggesting potential impacts from regional or global climate change. Despite these wet trends, variability remains, with periods of drought and fluctuating river flow, highlighting the dynamic nature of the region's climate and hydrological systems. The findings emphasize the need for adaptive water resource management strategies to cope with ongoing environmental variability and potential future climate changes.

## Chapter 5: Land Use and Land Cover Mapping and Change Analysis

### 5.1 Spatial and Temporal Evolution of Land Use and Land Cover

#### 5.1.1 Spatial Evolution of Land Use and Land Cover

From the spatial analyses (Figure 17), a densification of vegetation is observed from the north to the south of the basin, transitioning from Senegalese territory to that of Guinea-Conakry. The northern part of the basin is dominated by savanna, while the southern part is characterized by forest. In the north and northwest, bowe and steppe are predominant, whereas in the southern part, they are scattered across the landscape. Agricultural areas and bare soils are more common in the northern part of the basin. Areas affected by fires are also more present in the northern part and are notably significant in images from 1988 to 2002. Water surfaces primarily correspond to the hydrographic network and ponds, which follow their natural course and are mainly located in the central and southern parts of the basin.

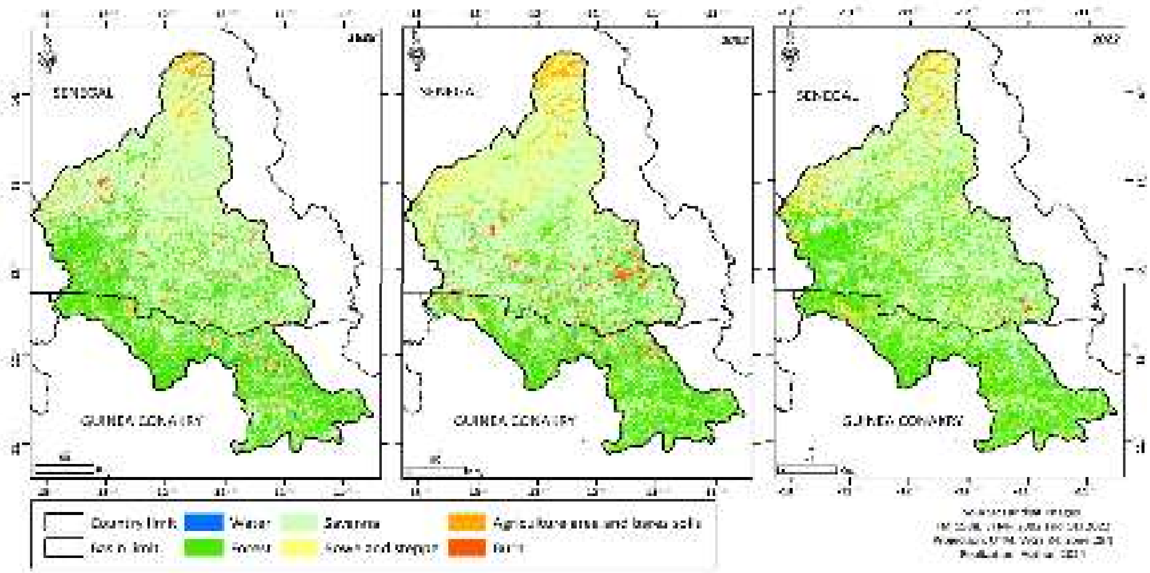


*Figure 17: State of Land Use and Land Cover in 1988, 2002, and 2022 in the CGRB*

#### 5.1.2 Area Statistics (in Hectares) for the Year 1988, 2002, and 2022

The statistical analyses of the data (Table 6) show that overall, forest experienced an increase from 1,374,975 ha (32.36%) to 1,541,035 ha (36.27%) between 1988 and 2022, while savanna saw a decline from 2,400,358 ha (56.49%) to 2,019,953 ha (47.54%). At the basin scale, we observe a vegetation densification following a degradation phase noted between 1988 and 2002. The evolution of climatic conditions (rainfall and hydrology) and bush fires are the main factors explaining the vegetation dynamics in the basin. The former results in an increase or decrease in vegetation density depending on whether conditions are favourable or not, while the second leads to a decrease in vegetation density with the transition from forest to savanna. This densification is also accompanied by anthropogenisation in some areas, with an increase in agricultural lands and bare soils from 117,717 ha (2.77%) in 1988 to 130,289 ha (3.07%) in 2022. Additionally, water surfaces experienced a slight decline between 1988 and 2002 from

26,807 ha (0.63%) to 25,337 ha (0.6%), and a more significant decline between 2002 and 2022 from 25,337 ha (0.6%) to 11,862 ha (0.28%).

*Table 7: Land Use and Land Cover by Class in the CGRB, Showing Area (ha) and Percentage (%) in 1988, 2002, and 2022*

| **Land cover** | **1988** | | **2002** | | **2022** | |
|---|---|---|---|---|---|---|
| | Ha | % | Ha | % | Ha | % |
| **Water** | 26 807 | 0.63 | 25 337 | 0.6 | 11 862 | 0.28 |
| **Forest** | 1 374 975 | 32.36 | 1 092 177 | 25.7 | 1 541 035 | 36.27 |
| **Savanna** | 2 400 358 | 56.49 | 2 292 801 | 53.96 | 2 019 953 | 47.54 |
| **Bowe and steppe** | 243 284 | 5.73 | 610 811 | 14.37 | 536 513 | 12.63 |
| **Agriculture area and bares soils** | 117 717 | 2.77 | 79 453 | 1.87 | 130 289 | 3.07 |
| **Burn** | 86 192 | 2.03 | 148 753 | 3.5 | 9 680 | 0.23 |
| **Total** | **4 249 333** | **100** | **4 249 333** | **100** | **4 249 333** | **100** |

Figure 18 summarises the overall percentage change in each land use for the study period from 1988 to 2022. Burn areas reduced significantly by -88.77%, followed by water (-55.75%) and lastly savanna by -15.85%. The Bowe and steppe class, on the other, increased significantly by 120.08 %, followed by forest and agricultural & bare soil areas which increased slightly by 12.08 and 10.68%, respectively.

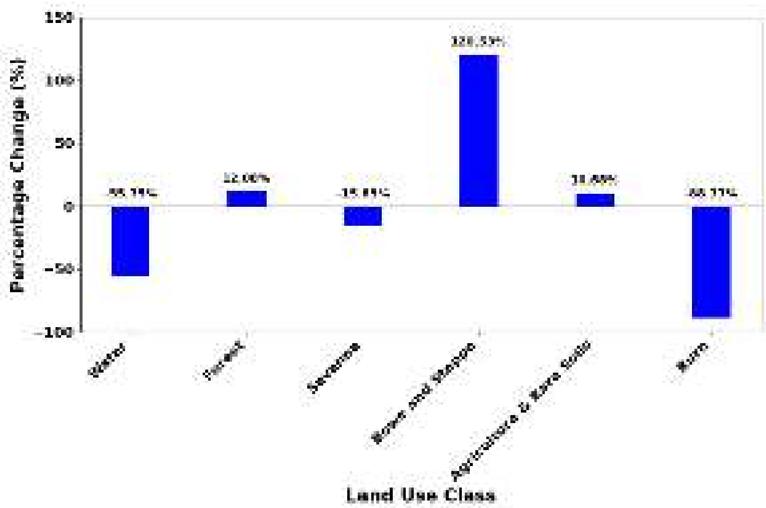


*Figure 18: Overall Change (%) for each Land Use and Land Cover Class from 1988 to 2022*

### 5.1.3 Changes in Land Use and Land Cover, 1988 to 2002

Figure 19 shows the land cover change map from 1988 to 2002. it depicts moderate land cover changes over 14 years. During this period, dense forests were relatively well-preserved, particularly in the southern and central regions of the basin. Savanna areas are observed to be maintained mostly in the northern and central basin areas. Savanna areas have expanded especially in the extreme west of the basin. Additionally, cropland areas expanded moderately, primarily in the southern regions and central regions. Bowe & steppe areas progressed significantly in the north and Northwest of the basin.

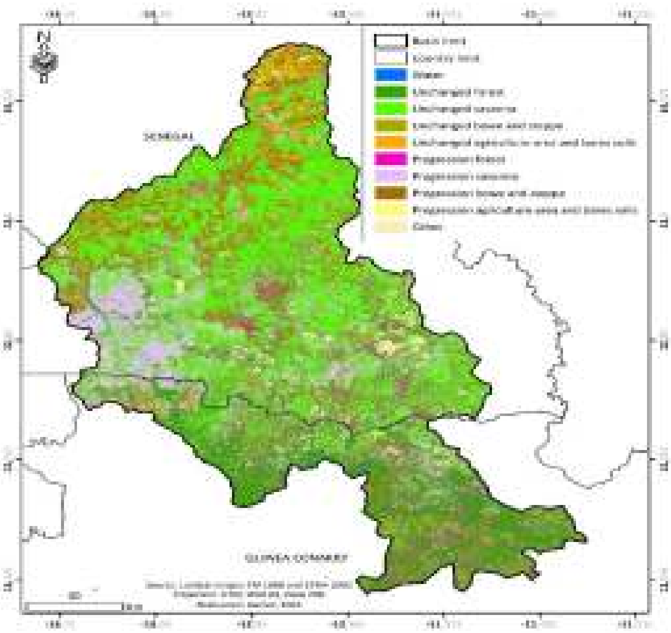


*Figure 19: Changes in Land Use and Land Cover 1988-2002*

The statistical representation of change from 1988-2002 is presented in Table 7. The land cover change matrix for the period 1988 to 2002 reveals significant transformations across various land use types. One of the most notable trends is the substantial reduction in forest cover. Although 770,864.2 hectares of forest remained stable, approximately 597,416.6 hectares were lost, with the majority of the lost area, 468,283.2 hectares being converted to savanna, reflecting extensive degradation. Additionally, 51,551.8 hectares of forest transitioned into bowe and steppe, while 68,312.5 hectares were lost to burn areas, indicating the impact of fire or slash-and-burn agricultural practices.

Savanna, on the other hand, emerged as the dominant land cover type, with a total area of 2,398,681.5 hectares by 2002. This expansion was driven by significant gains from forest loss, with 290,391.4 hectares transitioning from forest to savanna, and an additional 408,858.9 hectares gained from bowe and steppe. Despite losing 797,655.9 hectares to other land uses, savanna continued to expand, reflecting a shift towards more open landscapes. Similarly, bowe and steppe saw substantial changes, with 125,070.2 hectares transitioning into savanna, highlighting an increase in vegetation cover over previously degraded areas.

Agricultural and bare soil areas also expanded significantly, gaining 44,441.2 hectares from bowe and steppe and 33,140.4 hectares from savanna, indicating increased land conversion for cultivation. This expansion underscores the growing human impact on the landscape, likely driven by population growth and the need for more agricultural land. However, agriculture and bare soils lost 81,009.9 hectares to other classes, primarily due to transitions to natural vegetation and burn areas.

Water bodies also experienced a notable reduction, with 11,808.7 hectares transitioning into other land cover types, including forest (7,491.5 hectares) and savanna (2,412.5 hectares). This decline suggests possible drought conditions or changes in water management during the study period. Lastly, burn areas played a significant role in shaping the landscape, with 54,345.2 hectares of savanna and 10,031.0 hectares of forest converted into burn areas, reflecting a dynamic fire regime or human-induced burning. Overall, the period from 1988 to 2002 was characterized by extensive deforestation, significant savanna expansion, and increased agricultural land use.

*Table 8: Land Use Change Matrix in the Continental Gambia River Basin between 1988 and 2002*

| Classes | Water | Forest | Savanna | Bowe and steppe | Agriculture area and bares soils | Burn | Total | Regression |
|---|---|---|---|---|---|---|---|---|
| Water | 17,903.5 | 7,491.5 | 2,412.5 | 253.9 | 127 | 1,523.7 | 29,712.1 | 11,808.7 |
| Forest | 7,872.4 | 770,864.2 | 468,283.2 | 51,551.8 | 1.396.7 | 68,312.5 | 1,368,280.7 | 597,416.6 |
| Savanna | 1,142.8 | 290,391.4 | 1,601,025.6 | 408,858.9 | 25,141 | 72,121.7 | 2,398,681.5 | 797,655.9 |
| Bowe and steppe | 127 | 10,665.9 | 125,070.2 | 94,723.2 | 11,681.7 | 3,936.2 | 246,204.2 | 151,481.0 |
| Agriculture area and bares soils | 0 | 2,539.5 | 33,140.4 | 44,441.2 | 40,124 | 888.8 | 121,134.0 | 81,009.9 |
| Burn | 127.0 | 10,031 | 54,345.2 | 10,792,9 | 380.9 | 10,158 | 85,835.0 | 75,677.0 |
| Total | 27,172.6 | 1,091,983.5 | 2,284,277.1 | 610,621.9 | 78,851.4 | 156,940.9 | 4,249,847.5 | 1,715,049.0 |
| Progression | 9,269.2 | 321,119.3 | 683,251.5 | 515,898.7 | 38,727.3 | 146,782.9 | 1,715,049.0 | |

### 5.1.4 Changes in Land Use and Land Cover, 2002 to 2022

Figure 20 highlights land cover changes over 20 years, from 2002 to 2022. This period shows a significant retention of forest areas in the centre of the basin, especially the west-central area. Savanna areas that remained unchanged are observed throughout the basin but are observed to progress most in the north and east central of the basin. Agricultural area & bare soils remained mostly unchanged in the north and have progressed in the same areas as well. Bowe & Steppe areas remained unchanged particularly in the north and are observed to progress all over the basin.

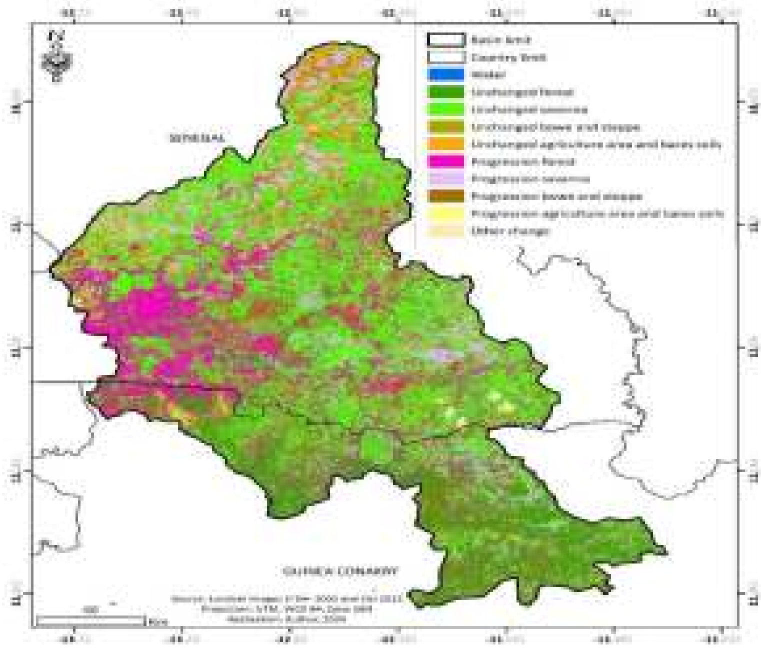


*Figure 20: Changes in Land Use and Land Cover Classes between 2002 and 2022*

The land cover change matrix for the period 2002 to 2022 (Table 8) highlights significant transitions across various land cover types, driven by both natural and human factors. One of the most striking trends is the continued reduction in water bodies, with only 8,507.3 hectares remaining stable. A notable 14,348.2 hectares of water were converted into forest, and 3,936.2 hectares transitioned into savanna, suggesting changes in hydrological conditions, possibly due to drought or human water extraction. Overall, water bodies regressed by 18,665.3 hectares, indicating a significant decline over this period. Forest cover exhibited a mixed trend, with 811,623.1 hectares remaining intact, reflecting a relatively high degree of stability. However, forest losses were substantial, with 211,159.1 hectares transitioning into savanna, and 60,820.9 hectares converting into bowe and steppe, indicating widespread deforestation and forest degradation. Additionally, 64,122.3 hectares were lost to burn areas. In total, forest cover regressed by 280,360.4 hectares, continuing the deforestation trend observed in previous years. Savanna emerged as the most dynamic land cover type, with 1,393,548.7 hectares remaining stable and substantial gains from forest (580,275.0 hectares) and bowe and steppe (261,441.2 hectares). These gains reflect the expansion of more open landscapes due to deforestation and the degradation of previously forested and semi-arid areas. Despite these gains, savanna experienced a regression of 890,728.4 hectares, primarily due to conversion to forest (580,275.0 hectares), bowe & steppe (261,441.2 hectares) and agricultural & bare soil areas (41,520.8 hectares). Bowe and steppe, typically associated with degraded land, showed significant changes as well. While 181,701.0 hectares remained stable, 428,921.0 hectares were lost, mainly transitioning into savanna (303,215.9 hectares), forest (82,914.6 hectares) and agricultural land (42,663.5 hectares), reflecting ongoing land conversion. Agricultural areas and bare soils expanded considerably, with 44,060.3 hectares remaining stable and 22,093.6 hectares lost to bowe and steppe. Another 11,173.8 hectares were lost to savanna. Despite the considerable area maintained, agriculture and bare soils lost 34,791.1 hectares in total during the period, indicating some areas were reclaimed by natural vegetation or lost to fire. Burn areas, characterized by their dynamic nature, saw only 127.0 hectares remain stable. Nearly all burn areas (156,813.9 hectares) transitioned into other land cover types, emphasizing their transient nature. Overall, the period from 2002 to 2022 was marked by extensive land cover changes, with savanna expansion, deforestation, and agricultural growth as the dominant trends.

*Table 9: Land Use/Land Cover Change Matrix (in ha) in the Continental Gambia River Basin between 2002 and 2022*

| Classes | Water | Forest | Savanna | Bowe and steppe | Agriculture area and bares soils | Burn | Total | Regression |
|---|---|---|---|---|---|---|---|---|
| Water | 8,507.3 | 14,348.2 | 3,936.2 | 380.9 | 0 | 0 | 27,172.6 | 18,665.3 |
| Forest | 761.8 | 811,623.1 | 211,159.1 | 60,820.9 | 4 825.0 | 2,793.4 | 1,091,983.5 | 280,360.4 |
| Savanna | 761.8 | 580,275 | 1,393,548.7 | 261,441.2 | 41,520.8 | 6,729.7 | 2,284,277.1 | 890,728.4 |
| Bowe and steppe | 0 | 82,914.6 | 303,215.9 | 181,701 | 42,663.5 | 127.0 | 610,621.9 | 428,921.0 |
| Agriculture area and bares soils | 0 | 1,523.7 | 11,173.8 | 22,093.6 | 44,060.3 | 0 | 78,851.4 | 34,791.1 |
| Burn | 253.9 | 64,122.3 | 81,898.8 | 8,888.2 | 1,650.7 | 127 | 156,940.9 | 156,813.9 |
| Total | 10,285.0 | 1,554,806.8 | 2,004,932.5 | 535,325.9 | 134,720.3 | 9,777.1 | 4,249,847.5 | 1,810,280.1 |
| Progression | 1,777.6 | 743,183.7 | 611,383.8 | 353,624.9 | 90,660.0 | 9,650.1 | 1,810,280.1 | |

### 5.1.5 Changes in Land Use and Land Cover, 1988 to 2022

Figure 21 shows the spatial map of change between 1988 and 2022. Forest areas in the south and southwest of the basin are observed to remain unchanged while they are observed to mainly increase on the upper west of the basin. Unchanged savanna areas are observed throughout the study area but are mostly concentrated in the north and central part of the basin. They are observed to have progressed throughout the basin. Progressions in bowe & steppe areas were mostly observed in the central basin area, in the extreme north and some parts of the south. An increase in the area of agricultural land & bare soils is observed mainly along the main watercourse and areas that remain unchanged are also mostly in the same locations.

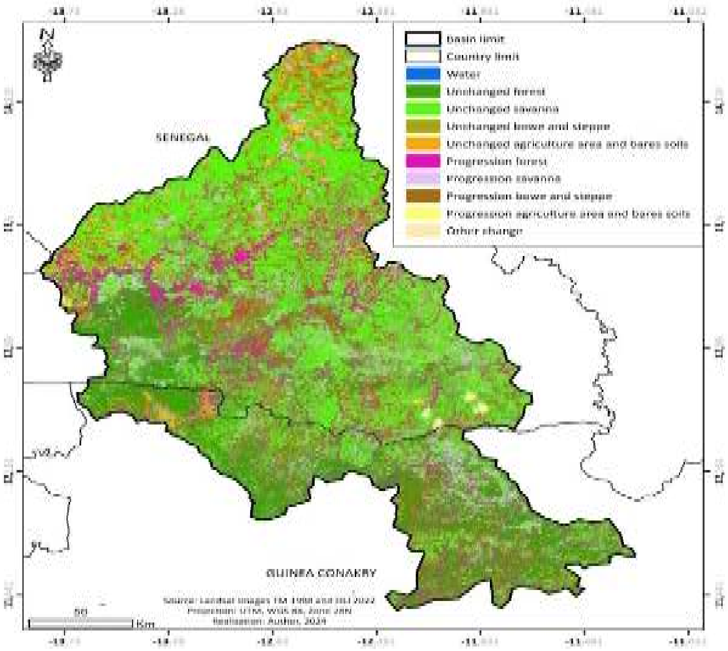


*Figure 21: Land Use and Land Cover Change Map between 1988 and 2022*

The land cover change matrix for the period 1988 to 2022 highlights significant transformations across various ecosystems, driven by both natural processes and human activities. Water bodies experienced a substantial decline, with only 9,142.2 hectares remaining stable and a regression of 20,569.9 hectares, largely transitioning to forest (15,998.8 hectares) and savanna (4,444.1 hectares). Forests, while maintaining 1,029,765.9 hectares, suffered a regression of 338,514.9 hectares, mainly converting to savanna (249,505.5 hectares) and bowe and steppe (75,169.1 hectares), indicating deforestation and land degradation. Savanna emerged as the most extensive and dynamic land cover, with 1,539,696.8 hectares remaining stable and significant gains from forests (249,505.5 hectares) and bowe and steppe (122,276.8 hectares), yet it also faced a total regression of 858,984.7 hectares. Bowe and steppe saw a net regression of 169,130.5 hectares, primarily converting to savanna (122,276.8 hectares) and agricultural areas (20,442.9 hectares), reflecting ongoing land degradation. Agricultural lands and bare soils had 47,488.6 hectares that remained unchanged but most of its areas were lost to savanna (28,061.4 hectares) and bowe & steppe (37,457.6 hectares). Burn areas saw most of their extent transition into savanna (60,947.9 hectares) and forest (17,522.5 hectares), emphasizing post-fire recovery, but lost almost all of their original coverage. Overall, the region experienced a decrease in water bodies, savanna, and burn areas. On the other hand, forest, bowe & steppe, and Agriculture & bare soil areas increased.

*Table 10: Land Use/Land Cover Change Matrix (in ha) in the Continental Gambia River Basin between 1988 and 2022*

| Classes | Water | Forest | Savanna | Bowe and steppe | Agriculture area and bares soils | Burn | Total | Regression |
|---|---|---|---|---|---|---|---|---|
| Water | 9 142,2 | 15 998,8 | 4 444,1 | 0 | 127 | 0 | 29,712.1 | 20,569.9 |
| Forest | 888,8 | 1 029 765,9 | 249 505,5 | 75 169,1 | 9 904,0 | 3 047,4 | 1,368,280.7 | 338,514.9 |
| Savanna | 127 | 457 363,3 | 1 539 696,8 | 339 784,6 | 55 488 | 6 221,8 | 2,398,681.5 | 858,984.7 |
| Bowe and steppe | 0 | 26 156,8 | 122 276,8 | 77 073,7 | 20 442,9 | 253,9 | 246,204.2 | 169,130.5 |
| Agriculture area and bares soils | 0 | 7 999,4 | 28 061,4 | 37 457,6 | 47 488,6 | 127 | 121,134.0 | 73,645.4 |
| Burn | 127 | 17 522,5 | 60 947,9 | 5 840,8 | 1 269,7 | 127 | 85,835.0 | 85,708.0 |
| | | | | | | | | |
| Total | 10,285.0 | 1,554,806.8 | 2,004,932.5 | 535,325.9 | 134,720.3 | 9,777.1 | 4,249,847.5 | 1,546,553.4 |
| Progression | 1,142.8 | 525,040.9 | 465,235.8 | 458,252.2 | 87,231.7 | 9,650.1 | 1,546,553.4 | |

### 5.2 Influence of Precipitation on Land Use Transitions

To evaluate the role of precipitation in shaping land cover dynamics, correlation analyses were conducted between annual precipitation and each land cover transition for the periods 1988–2002 and 2002–2022 (Table 10). It should be noted here that, due to the relatively small sample sizes for some of the land use conversion periods, correlation coefficients are interpreted with caution, and only statistically significant correlations ($p < 0.05$) are considered in the discussion.

*Table 11: Correlation between Land Use/Land Cover Conversions and Precipitation*

| Land Conversion | Change Year | Correlation (r) | P-Value |
|---|---|---|---|
| **Agricultural areas & Bare soil to Bowe & Steppe** | 2002–1988 | 0.268 | 0.034 |
| **Forest to Bowe & Steppe** | 2002–1988 | 0.225 | 0.007 |
| **Forest to Water** | 2002–1988 | -0.633 | 0.001 |
| **Savanna to Bowe & Steppe** | 2022–2002 | -0.073 | 0.034 |

| | | | |
|---|---|---|---|
| **Savanna to Forest** | 2022–2002 | 0.058 | 0.048 |

As previously described, long-term precipitation trends across the CGRB between 1990 and 2022 exhibit a distinct north–south gradient, with increasing rainfall in the northern regions and declining trends toward the south. While this spatial pattern reflects broad climatic shifts over the 33-year period, it is important to note that precipitation conditions during sub-periods such as 1988–2002 may differ from these long-term trends, and regional variability must be considered when interpreting land cover changes.

During the 1988–2002 period, the conversion of agricultural areas and bare soil to bowe and steppe exhibited a weak positive correlation with precipitation ($r = 0.268$, $p = 0.034$), suggesting that wetter conditions have favoured the spread of these land types. Similarly, the transition from forests to bowe and steppe also showed a weak positive correlation ($r = 0.225$, $p = 0.007$). This pattern is unexpected, as increasing precipitation would typically support forest persistence or regrowth rather than degradation into open, sparsely vegetated landscapes of bowe and steppe. This unexpected pattern reflects the overriding role of anthropogenic pressures, such as deforestation, unsustainable land use, frequent burning, and overgrazing, which can alter soil conditions and vegetation dynamics despite favourable climatic conditions (Dieng et al., 2023). In these contexts, the presence of favourable rainfall is insufficient to reverse or resist degradation processes once they have been set in motion. In other words, anthropogenic pressures may decouple ecological transitions from climatic conditions, leading to land cover changes that would not normally be expected under wetter scenarios.

A contrasting trend is observed in the conversion of forests to water, which showed a strong negative correlation with precipitation ($r = -0.633$, $p = 0.001$), suggesting that this transition was more frequent under drier conditions. While reduced precipitation would typically lead to lower surface water availability, studies have shown that human activities, such as deforestation and agricultural expansion, can significantly alter local hydrological conditions, contributing to water accumulation in previously forested areas (Fitzpatrick and Knox, 2000; Schiesari et al., 2020).

In the 2002–2022 period, fewer significant correlations were observed, but notable trends include the weak negative correlation between the conversion of savanna to bowe and steppe and precipitation ($r = -0.073$, $p = 0.034$), suggesting that this transition was more pronounced in drier conditions. Additionally, the conversion of savanna to forest displayed a weak positive correlation ($r = 0.058$, $p = 0.048$), implying that increased precipitation supports forest regrowth in some savanna-dominated areas.

Overall, these results underscore that while precipitation trends do influence land cover change, they do not act in isolation. The interaction between climate variability and human land use decisions, such as farming practices, deforestation, and land abandonment, shapes the landscape in ways that sometimes override the expected climatic responses.

### 5.3 Local Perceptions of Land Use and Hydrological Changes

To complement the satellite-based land use/land cover analyses, structured interviews and questionnaires were conducted with local farmers, herders, and community members. Respondents provided observations on trends in land cover, climate, and water availabilityover recent decades, offering qualitative validation of the observed changes.

#### 5.3.1 Perceptions of Climatic Trends

Respondents identified significant changes in climate trends compared to the past as presented in Figure 22. A decrease in rainfall was the most cited (90%), followed by a delay in the onset of the rainy season, a reduction in the number of rainy days, and an early cessation of rainfall, cited by 56.55, 53.45, and 46.9%, all of which indicate shifts in precipitation patterns. Rising temperatures and stronger winds were also frequently mentioned, cited by 36.99 and 29.66%, suggesting increasing heat stress and potential impacts on agriculture and water availability. Some respondents reported increased evaporation (13.79%), while only a few observed a drop in temperatures (7.93%) or a decrease in evaporation (2.76%). Very few mentioned increased rainfall (2.07%) or an extension of the rainy season (0.34%), highlighting a general perception of worsening drought conditions. These perceptions contrast with the precipitation trend analysis, which indicates an overall increase in rainfall post-2008. However, the variability in rainfall patterns and the occurrence of extreme dry years before 2008 may explain why respondents perceive a decline. Additionally, the combination of rising temperatures and shifting rainfall timing could exacerbate water stress, reinforcing the local perception of worsening climatic conditions.

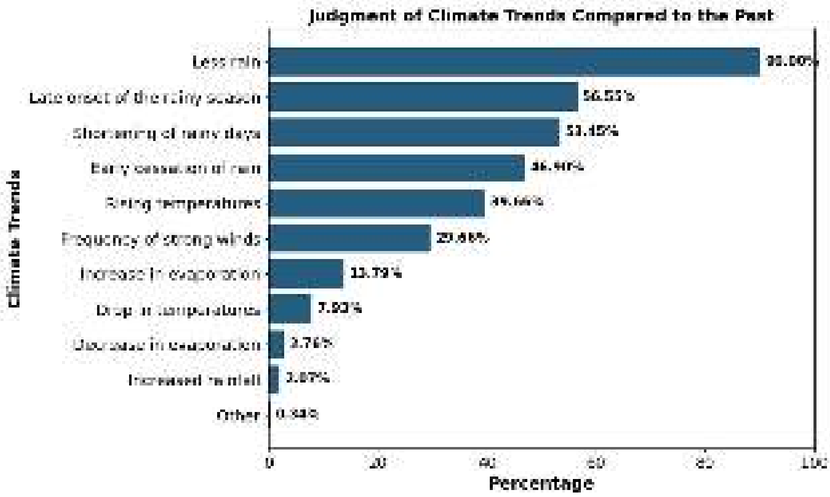


*Figure 22: Perception of Respondents on Climatic Trends in the Surveyed Region*

#### 5.3.2 Perceived Hydrological Impacts

The reported effects of climate change on hydrological conditions are presented in Figure 23, which highlights widespread water shortages. The most frequently mentioned impact is the early drying up of watercourses (3.1%), followed by the early drying of wells (58.28%). Many respondents also noted a decline in groundwater levels (39.31%) and decreased flow in rivers and streams (1.38%), while a smaller number highlighted reduced infiltration (11.72%). Very few respondents reported an increase in groundwater levels or streamflow (1.38%). This contrasts with the results of the Standardized Flow Index (SFI), which indicates a shift toward wetter conditions in recent years. The discrepancy between observed trends and local perceptions may be influenced by seasonal variations, groundwater depletion, or changes in water accessibility, rather than overall discharge trends. Additionally, two respondents mentioned effects on agricultural yields and fish availability, further emphasizing the local consequences of hydrological changes.

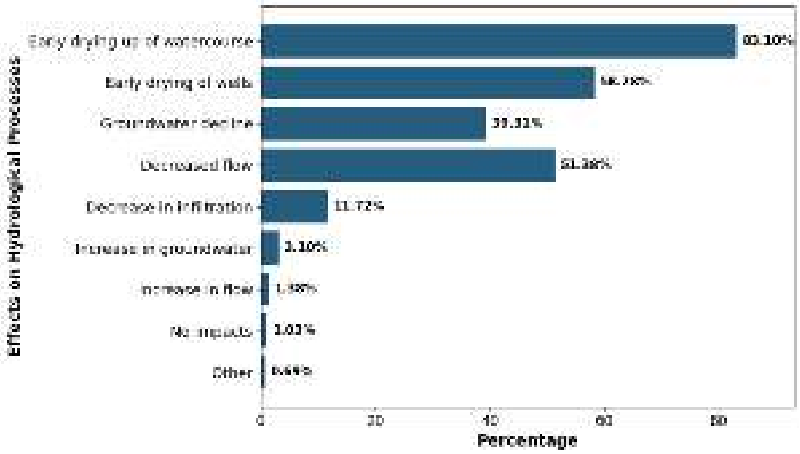


*Figure 23: Perceived Effects of Climate Change on Hydrological Conditions*

### 5.3.3 Perceived Land Use Trends

The respondents' observations on land use evolution highlight several key trends as presented in figure 24. The most commonly noted change is the expansion of built-up areas and a decline in vegetation cover, cited by 62.41 and 53.79%. Many respondents reported a decrease in water surfaces (46.21%), which is consistent with the reduction in water areas observed in the land cover data. Furthermore, some respondents noted a reduction in agricultural areas (46.9%), but a notable portion also observed an increase in agricultural land (37.59%) as shown in the remote sensing data. The number of respondents who reported an increase in vegetation surfaces or water areas were 6.55 and 3.79 % respectively. Finally, there was very little mention of the regression of built-up areas (3.45%).

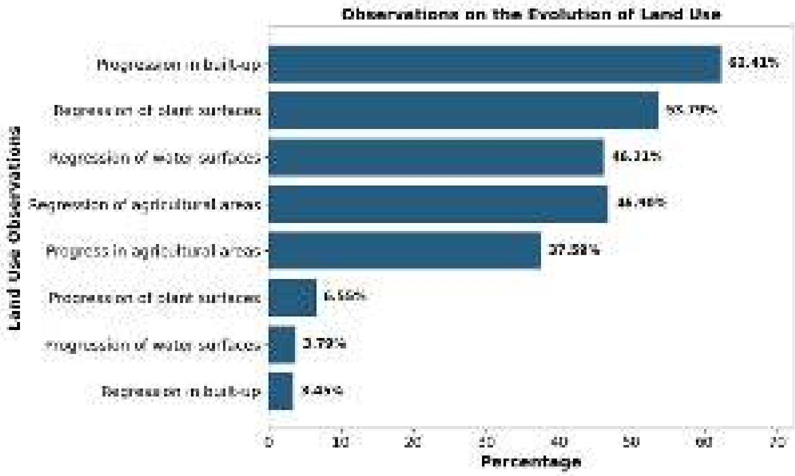


*Figure 24: Perception of Respondents on the Trends of Land Use*

### 5.3.4 Perceived Effects of Land Use Changes on Hydrology

The reported effects of land use changes on hydrological conditions include the early drying of watercourses (68.28%) and wells (57.59%), which were the most commonly observed impacts (figure 25). There were also reports of decreased flow (52.07%) in rivers and streams, along with a decline in groundwater levels (37.24%). Some respondents noted a decrease in infiltration (18.28%), while only a few observed an increase in groundwater levels, river flow, or infiltration as cited by 11.72, 5.52, and 0.69%, respectively. A small number of respondents reported no impacts (0.69%). Very few mentioned other effects such as a decrease in rainfall or lack of growing space.

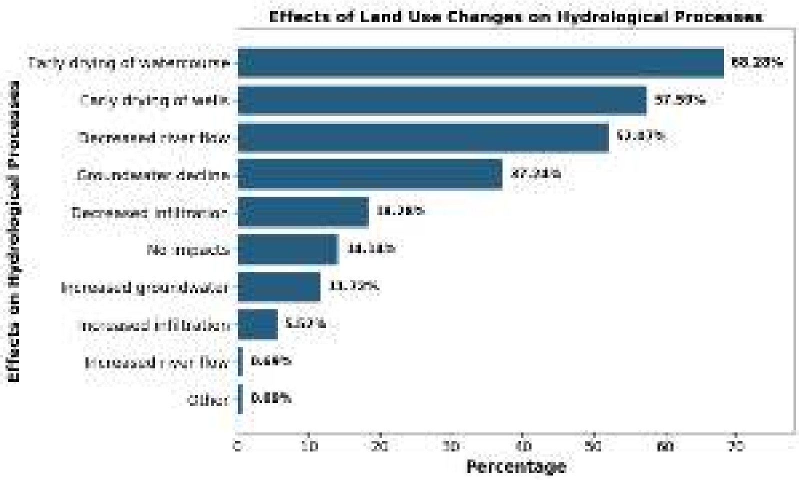


*Figure 25: Perception of Respondents on the Effects of Land Use on Hydrological Conditions*

## 5.4 Discussion

Between 1988 and 2022, land cover changes in the CGRB were shaped by both climate variability and human activity. The decline in forest and savanna cover between 1988 and 2002 coincided with a relatively dry period, as reflected in discharge trends at Simenti station. These drier conditions likely intensified livelihood pressures, prompting communities to expand agricultural lands and increase charcoal production, contributing to deforestation. Several authors, including Gueye (2000) and Tappan et al. (2000), have documented how Senegal's wooded savannas, particularly in the southern and southwestern regions (Tambacounda and Kolda), overlapping with the northern CGRB, have been heavily exploited for wood logging, charcoal production, and slash-and-burn practices. These activities are largely driven by the persistent demand for charcoal in urban centres such as Dakar, Kaolack, Thiès, Diourbel, and Saint-Louis. Logging is often conducted by cooperatives or organized groups, many of whose members are not from the extraction zones and rely on foreign labour (notably Sourgha Guineans). This exploitation is further exacerbated by the lack of adherence to cutting standards and the failure to protect harvested areas, which are commonly converted into croplands by local populations. This mirrors broader West African patterns, where past droughts in the Sahel have led to land conversion, forest loss, and competition over resources (Ahmed et al., 2021; Doso Jnr, 2014; Njoki, 2023). Supporting this, (Barnieh et al., 2020) observed that post-drought years saw a greater loss of water bodies than the drought years themselves, suggesting lingering climatic effects on land cover.

Conversely, the post-2008 increase in precipitation, indicated by changes in SPEI and discharge data, corresponds with a significant rise in forest cover between 2002 and 2022. This shift may reflect improved conditions for vegetation regrowth, supported by a weak positive correlation between savanna-to-forest transitions and rainfall (Table 10) and by research linking forest recovery to increased precipitation (Abera et al., 2018; Boland, 2014; Zhou et al., 2021). The forest gain, however, is likely due to multiple interacting factors. Wetter conditions may have enhanced soil moisture and reduced fire frequency, supporting natural regeneration. This may have been reinforced by reforestation efforts, both governmental and community-led, in response to land degradation. Additionally, forest recovery may have resulted from agricultural land abandonment, linked to migration or falling profitability. However, isolating the individual contributions of climate, policy, and human agency requires more detailed field studies and socio-economic data.

The marked reduction in burned areas, from 3.5% in 2002 to 0.23% in 2022, points to changing fire dynamics. This may reflect wetter conditions that reduce fire spread or shifts in fire use practices, including fire suppression or land conversion. In Senegal, fire regimes are predominantly shaped by human activities, especially in savanna and farming zones, where fire is used for field clearing and grazing management. Fire peaks during the dry season, particularly in February and March, driven by dry vegetation, Harmattan winds, and agro-pastoral activities (Republique du Senegal*, 2022*; Mbow et al., 2000; Nielsen et al., 2003; Samb et al., 2025). Most fires are intentionally lit, with lightning playing a negligible role. These human-driven fire regimes influence vegetation cover and land degradation, and understanding them is essential for effective fire and land management strategies.

Agricultural expansion, strongly promoted by food security policies, has also reshaped land use. Programs like GOANA and PRACAS in Senegal drove major increases in cultivated areas, over 40% in rainfed cropland post-2008. Policy reforms encouraged private land investments, leading to large-scale acquisitions (844,796 ha in 40 deals), often at the expense of traditional land uses (CNRF, 2016). These efforts were backed by legal frameworks like the LOASP and national land strategies, aiming to modernize agriculture and attract investors. However, this transformation has concentrated in fertile zones, worsening deforestation and land pressure. Between 2000 and 2010, around 405,000 ha of forest were lost, with 15 million $m^3$ of biomass depletion, largely due to land clearing, charcoal production, and weak governance. The decentralization of land management to local councils often lacked institutional capacity, resulting in informal land sales and poor conservation outcomes. Although satellite data confirm cropland expansion, local accounts report declining agricultural productivity, underscoring the gap between land use intensity and livelihood improvement.

Beyond farming, livestock grazing places intense pressure on ecosystems. Over 90% of animals depend on natural pastures, yet forage availability remains low, especially in arid zones, making pastoral systems highly sensitive to climate fluctuations (Abdoulaye Dieng and Faso, 2022). Forage deficits reported from 2009 to 2018 highlight chronic pressure, which, along with agriculture, has reduced grazing land and led to conflicts between herders and farmers. Overgrazing has further degraded vegetation and soil quality, undermining ecological resilience.

Despite these pressures, recent developments suggest some forest recovery. Reforestation programs, notably the Great Green Wall (GGW), have restored over 57,000 ha in Senegal between 2008 and 2021, with millions of seedlings planted and community involvement bolstered (Macia et al., 2023). In addition to state-led initiatives, private plantations (e.g., gum arabic) and farmer-led regreening efforts have significantly contributed to land restoration (Sarr et al., 2022). Approaches like Farmer-Managed Natural Regeneration (FMNR) promote the regrowth of native tree species through selective protection and pruning. These practices improve tree cover, soil fertility, and climate resilience, offering sustainable alternatives to conventional reforestation (Winterbottom Robert et al., 2020; Sarr et al., 2022; Karambiri et al., 2023).

Cropland expansion in the study area from 1988 to 2022 also reflects regional migration patterns. Influxes of Wolof and Serer farmers from Senegal's northwest, seeking fertile land, drove widespread conversion of wooded savannas into farmland. Animal traction and the cultivation of cash crops like cotton and peanuts accelerated this transformation, often at the expense of forests and grazing areas (Fanchette, 1999; Tappan et al., 2004; Solly et al., 2020). Charcoal demand from urban centres such as Dakar and Kaolack further fuelled deforestation in southern zones (Gueye, 2000; Tappan et al., 2000). Other contributing factors include bushfires, overhunting, and shifting cultivation, which are associated with increased bare soils, cropland, and burned areas. The expansion of bowe and steppe suggests advancing land degradation, likely driven by overgrazing, erosion, and nutrient depletion (Doso Jnr, 2014).

Socio-economic drivers, migration, urbanization, and decentralization, also shaped land dynamics. Rural–urban migration due to limited land access and livelihood options has led to both land abandonment and new cultivation areas, particularly in southeastern Senegal (Hummel, 2016; Cabral and Costa, 2017). Return migrants and remittances have enabled investment in cash crops and agroforestry (Kaag et al., 2019). Conflict in Casamance reduced land pressure in some zones, allowing forest regeneration, while intensifying land use elsewhere (Cabral and Costa, 2017). Although decentralization since 2000 aimed to boost rural development through infrastructure and inputs, weak oversight has often resulted in unchecked land conversion (Faye et al., 2024). Growing urban populations have further increased charcoal demand and land degradation near towns (Wood et al., 2004; Brandt et al., 2014).

Human activities have not only altered land cover, but also affected hydrology in the CGRB. Expansion of cropland and bare land, particularly in the north, may have reduced infiltration and increased surface runoff, raising the risk of flash floods. While rising precipitation likely contributed to greater streamflow, degraded landscapes (marked by bowe and steppe) may have amplified runoff efficiency. This is evident in the increased variability and positive discharge anomalies at Simenti after 2010. While higher discharge can improve water availability, it also increases flood risk. In recent decades, West Africa has faced devastating floods affecting millions (Baddianaah, 2023). This calls for urgent assessments of extreme events to guide disaster risk reduction and water management strategies.

Local perceptions provide qualitative support for the observed land use and hydrological trends. Respondents reported declines in rainfall, delayed rainy seasons, and reductions in water availability from wells and rivers, which align with the mapped decreases in water bodies and transitions from forest to savanna or bowe and steppe. Some respondents noted worsening droughts despite the post-2008 wetter conditions detected in climate records, reflecting high inter-annual variability, localized water scarcity, and the influence of memorable extreme events on perception. Observed expansions of agricultural and built-up areas, alongside declines in vegetation cover, were also confirmed by community members, corroborating the remote sensing data. Together, these insights bridge scientific analyses and local experiences, demonstrating how socio-ecological knowledge can validate and enrich quantitative findings.

In conclusion, land and water management in the CGRB must prioritize sustainable, integrated approaches. Balancing agricultural development with ecological conservation is vital, especially as savanna and steppe ecosystems face increasing degradation. Community-based strategies like FMNR offer promising, cost-effective pathways for restoring land and boosting soil health. At the same time, the growing hydrological variability necessitates watershed-based flood control, protecting riparian zones, enhancing drainage, and reducing erosion. As land use changes continue to impact water availability and disaster exposure, management policies must support climate resilience, environmental sustainability, and improved rural livelihoods.

The above land use analysis results suggest several potential effects on streamflow within the CGRB. The densification of vegetation from north to south, with the northern part dominated by savanna and the southern part by forest, can affect streamflow by enhancing evapotranspiration and increasing groundwater recharge in forested areas, thus reducing surface runoff. The expansion of agricultural areas and bare soils, particularly in the northern part, can lead to higher surface runoff and potential flash floods due to reduced vegetation cover.

Burn areas, especially in the north, can temporarily increase surface runoff and streamflow and consequently could cause floods (Efiong, 2011), though this effect may be mitigated over time as these areas convert back to savanna or forest. The reduction in water bodies from 1988 to 2022 indicates decreased surface water storage, potentially reducing streamflow during dry periods as water bodies transform into forest and savanna areas. Significant land use transitions, such as the conversion of savanna to bowe and steppe or forest, indicate changes in land cover that can affect hydrological processes. Increased vegetation cover is widely agreed to reduce average streamflow due to higher canopy interception and plant transpiration, while decreased vegetation cover can result in increased streamflow (Bosch and Hewlett, 1982; Xu et al., 2021).

### 5.5 Conclusion

Land use analysis over the study period (1988-2022) revealed substantial vegetation densification, particularly in the southern part of the basin, while the northern regions experienced a decline in savanna and an increase in agricultural lands and bare soils. This densification can be attributed to improved climatic conditions and the reduction of bushfires, although anthropogenic activities also played a role. The increase in forest cover and the simultaneous decline in savanna highlight a shift towards more densely vegetated landscapes, influenced by both natural and human-induced factors. The observed trends and changes reflect broader regional patterns of climate recovery in the Sahel, with significant implications for water resources management and land use planning in the basin. Incorporating standardized drought indices and trend analyses offers a strong foundation for tracking and responding to the ongoing changes in the basin.

**The main results presented in Chapters 4 and 5 have been published in Kah, M.; Faye, C.; Mbaye, M.L.; Yalo, N.; Gunnar, L. (2025). Hydroclimatic Trends and Land Use Changes in the Continental Part of the Gambia River Basin: Implications for Water Resources. Water, 17, 2075. https://doi.org/10.3390/w17142075.**

# Chapter 6: Local Perceptions on Water Use, Socio-Economic Activities, and Water Management

While previous chapters focused on satellite-derived land use changes and hydroclimatic trends, this chapter examines how these changes are perceived, experienced, and managed by local communities within the CGRB. Drawing on structured interviews and questionnaires, it highlights the socio-economic dimensions of water use, governance, and adaptation strategies, thereby bridging scientific evidence with local realities.

The sustainability of river basin ecosystems and socioeconomic development is fundamentally linked to water security. Recent evidence indicates that climate change and human activities are significantly influencing hydrological cycles worldwide (Sharifi et al., 2021). Climate change is expected to bring warmer atmospheric temperatures and more intense hydrological cycles, resulting in altered precipitation and evaporation patterns. Simultaneously, human activities are modifying the spatial and temporal distribution of water resources (Jin et al., 2024; Wu et al., 2024).

To address these challenges, it is essential to understand the socio-economic drivers behind land use and climate variability. These factors can disrupt hydrological processes and impact streamflow through altered land use practices, reservoir management, and direct water extraction (Xu et al., 2014). Effective management of water resources and hydrological regimes on a broad scale is crucial, particularly given the pressures from population growth and changing land and water policies (Mishra and Singh, 2010). As the demand for food, clothing, and improved living conditions rises, the reliance on water resources intensifies.

Local communities, such as those along the Gambia River, are often the first to experience the impacts of climate change due to their close relationship with their environment. Their traditional knowledge and practices play a vital role in enhancing ecosystem resilience and provide valuable strategies for adaptation and mitigation. River basins are essential for healthy ecosystems and are pivotal in assessing water resources and addressing water security challenges (Xu et al., 2022). Economic activities primarily affect water resources through extraction, and high levels of water withdrawal, especially for consumptive use, can significantly reduce river runoff and may even lead to the complete depletion of rivers. Irrigation, a major human activity influencing watersheds (Wu et al., 2024), not only lowers average river flow but also alters flow patterns, decreasing streamflow during the growing season while increasing it at other times. As climate conditions evolve, agricultural water requirements also change (Kirby et al., 2017).

Given the critical role of the CGRB in sustaining water resources and promoting socioeconomic development, it is vital to understand how various human activities influence hydrological processes and water availability. By integrating local perceptions through structured interviews and questionnaires, this chapter explores the interactions between climate variability, land use changes, and socio-economic activities (such as agriculture and fishing) on water resources, providing a more holistic understanding of water management challenges and community adaptation strategies.

### 6.1 Demographics

The distribution of the survey responses in each municipality is represented in figure 26. The results indicate that Missirah was the most represented municipality consisting of 56.21% of respondents followed by Dialocoto (27.59%) and Nette Boulou (16.21%). This distribution reflects the differences in population size in the municipalities.

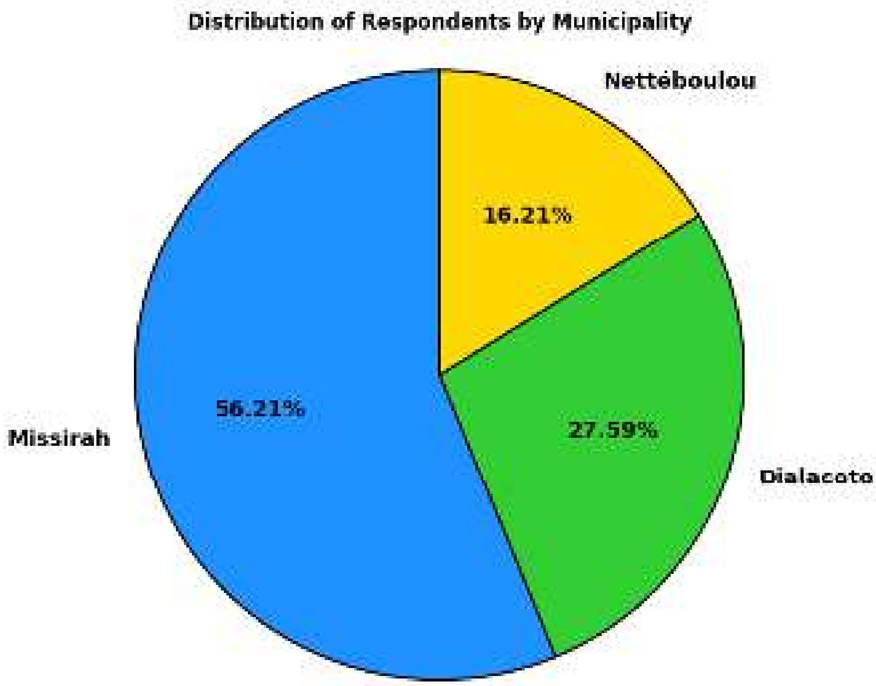


*Figure 26: Distribution of Survey Responses in Each Municipality*

Figure 27 represents the frequency of respondents from various villages. The villages with the highest percentage of respondents are Ouassadou Depot (16.55%), Gouloumbou (15.17%), and Koar III (13.45%). These three villages have the largest share of respondents, contributing to over 40% of the total responses. Other villages such as Sankagne I (11.03%), Bantantinti (8.97%), and Nguene Sérère (8.28%) also have a notable presence, but with smaller shares compared to the top three. Several villages have fewer respondents, including Damantan II, which has the least with only 0.69% of responses.

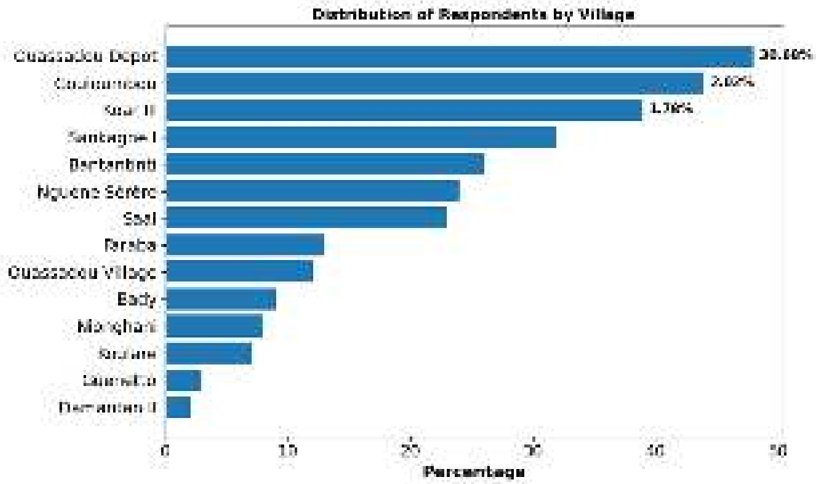


*Figure 27: Distribution of Survey Responses in Each Village*

Figure 28 represents the perception of respondents on the evolution of the population in the study region. The majority of respondents (88.97%) perceive the population as increasing, a smaller portion believes the population has dropped (5,86%), while an even smaller group considers the population to be stable (5.17%).

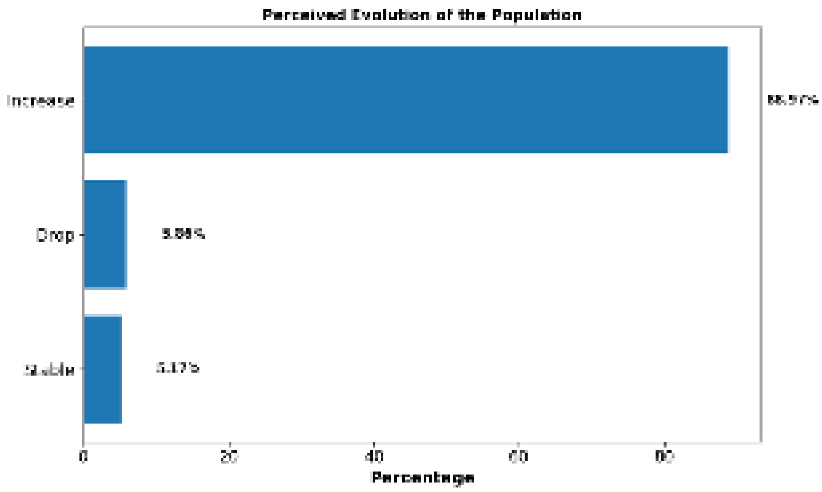


*Figure 28: Respondents' Perception on Population Evolution*

The most commonly identified factor behind population growth is a high birth rate (56.55%), followed by a decline in socio-economic activities (30.34%) and migration (13.1%), figure 29.

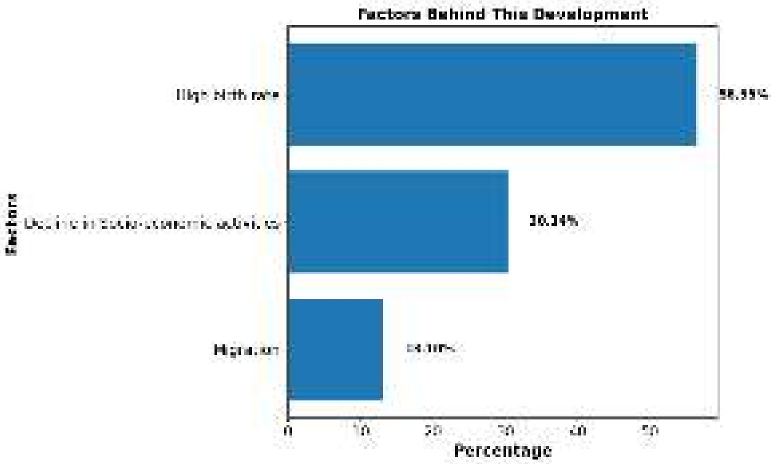


*Figure 29: Respondents' Perception of Factors Behind Population Trends*

The ethnic groups (figure 30) in the region are predominantly Peulh consisting of 56.21% of respondents, which make up the largest group. Other significant ethnic groups include Serere (13.10%), Soninke (9.31%), and Manding (9.66%), followed by smaller groups like Diakhanke (6.55%) and Bambara (3.1%). Additional ethnicities mentioned include Moor, Diola, Bassari, Koniagui, and Tandanké which make up 2.07% of the respondents. The demographic history of the region is intricately intertwined with successive paleo-migratory movements following the decline of the Ghana and Mali empires, which witnessed the settlement of various ethnic groups such as the Manding, Soninke, Diakhanke, and Bambara. Additionally, the extensive droughts of the 1970s led to significant migration of populations from arid regions to the more agriculturally viable southern parts of the country, characterized by better rainfall and soil conditions (Ndione, 2018). Serere are reported to have migrated southwest in search of richer fishing grounds and more fertile lands for agriculture, while Fulani pastoralists expanded their transhumance areas towards the southern and eastern regions (Badji, 2018; ANSD, 2019).

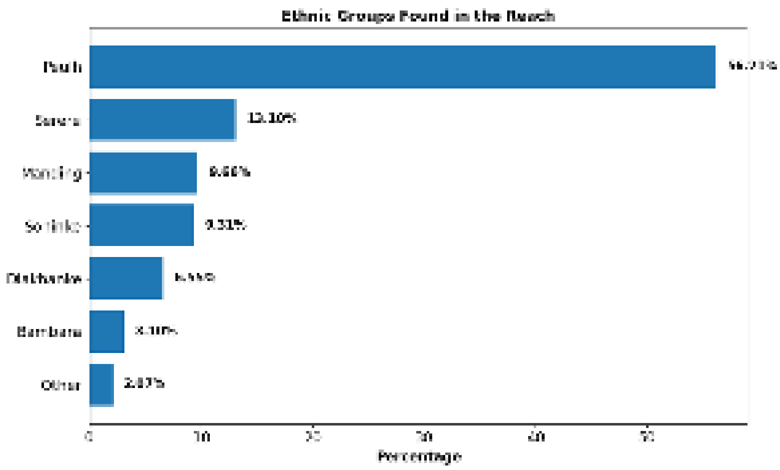


*Figure 30: Major Ethnic Groups Found in the Surveyed Region*

Figure 31 presents the main sources of water supply in the region. Wells are the most commonly used reported by 84.82%, followed by boreholes (61.03%) and watercourses

(49.31%). Temporary ponds (15.52%) are also a source of water, though they are less commonly relied upon. A minority of respondents, reported the absence of wells in their neighborhood. The survey responses generally indicate that groundwater is favoured over surface water which makes overexploitation nearly "invisible" to the naked eye, underscoring the urgent need for effective monitoring and conservation measures to safeguard water resources.

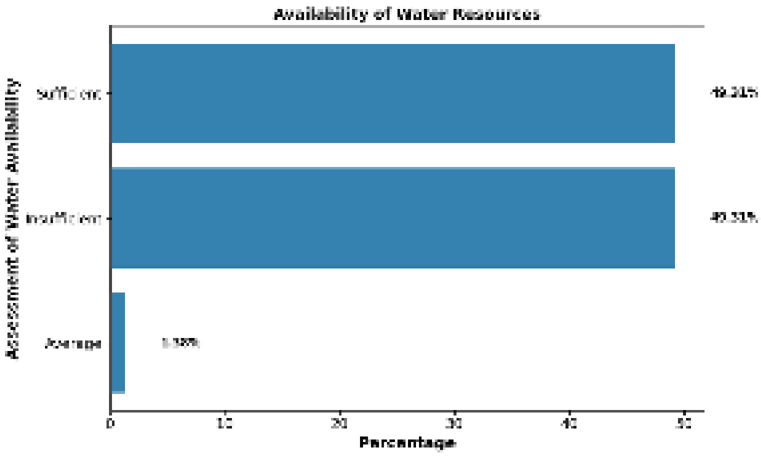


*Figure 31: The Main Places of Water Supply in the Surveyed Region*

The assessment of water resource availability is divided equally, with half of the respondents considering the water resources sufficient (49.31%) and the other half finding them insufficient (49.31%). Only a small proportion of respondents rated the availability as average (1.38%). This information is presented in Figure 32.

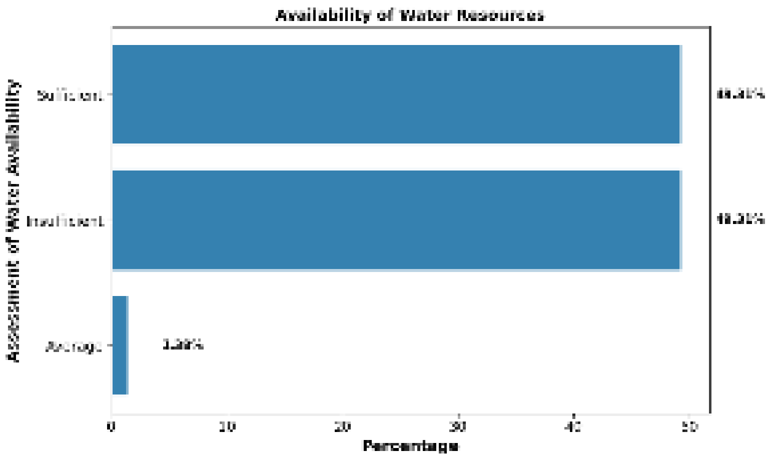


*Figure 32: Respondents' Perception on Water Resource Availability*

Surface water (figure 33) in the study area is primarily used for crop farming (81.03%), livestock farming (74.83%), and fishing (74.83%), with a significant number of respondents also using it for domestic chores (50.69%). Drinking water (36.21%) is another key use, though less common. A small portion of respondents mentioned hobbies (13.79%) as a use, and very few cited other purposes. We can assume from the data that total water use in the region is mostly due to farming activities. Groundwater, similar to surface water is also used for multiple purposes by respondents (Figure 33). The predominant uses of groundwater in the region include crop & livestock farming indicated by 81.03 and 74.83% of respondents respectively, domestic purposes (50.69%) and drinking (36.21%).

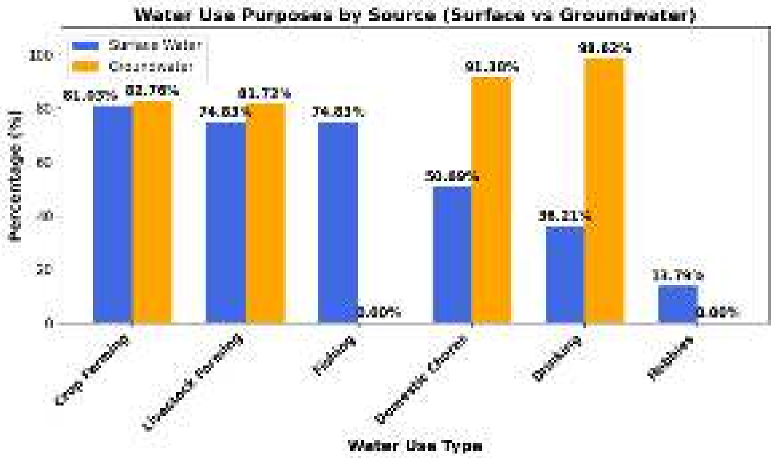


*Figure 33: Surface and Groundwater Use in the Surveyed Region*

**6.2 Socioeconomic Activities**

Figure 34 presents the socioeconomic activities the respondents in the study area engage in. Crop farming is the most common socio-economic activity engaged in by 81.03% of respondents, followed closely by livestock farming (74.83%) and fishing (74.83%), both of which are widely practiced. Trade (66.55%) also plays a significant role and lumbering, while less prevalent, remains an important activity for a portion of the population as it is practiced by 21.38%. A small number of respondents consisting of 2.76% engage in other economic activities such as exploitation of river sand, gold panning, involvement in mechanics and masonry and artistic endeavours.

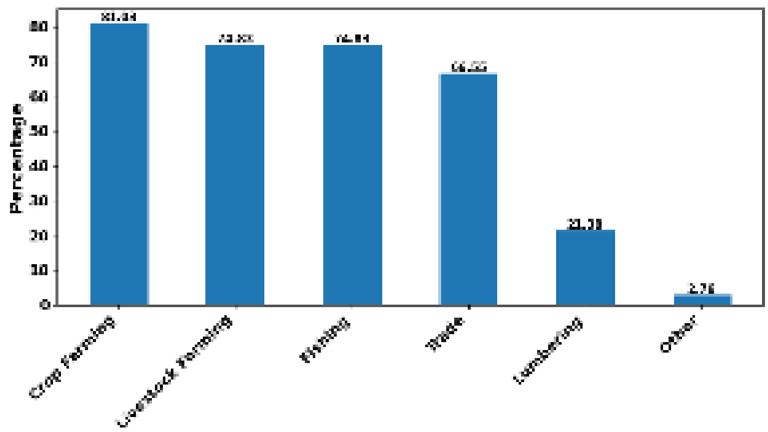


*Figure 34: The Main Socio-economic Activities in the Surveyed Region*

### 6.2.1 Agriculture

#### 6.2.1.1 Crop Farming

The survey results show that all respondents practice rainfed agriculture, making it the most prevalent agricultural method, figure 35. Market gardening is also widely practiced, involving 81.38% of respondents. Flood recession agriculture (which involves planting crops during the dry season on land that was previously flooded during the rainy season) is practiced 16.9% of respondents, while some respondents engage in other forms of agricultural practices.

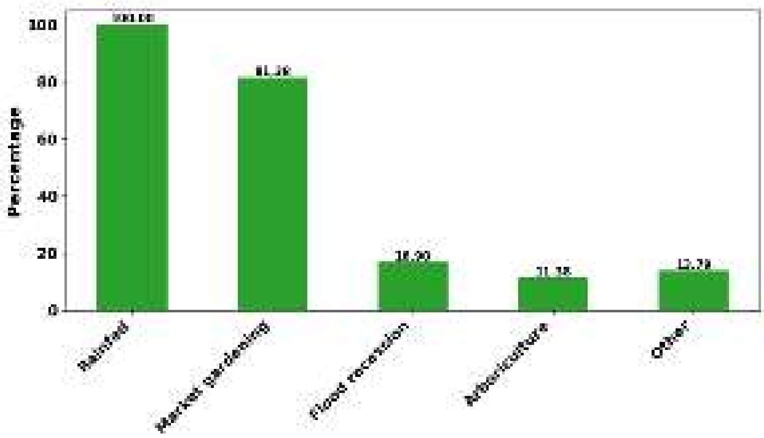


*Figure 35: Agricultural Cropping Methods Practiced*

Figure 36 presents the crops types cultivated in the study area. The most frequently mentioned crops cultivated by respondents are maize (94.48%), groundnuts (86.21%), and millet (76.55%). Other crops such as okra, pepper, rice, cotton, and tomatoes are also produced by 53.4, 50.69,38.97,20.69 and 19.31% of respondents respectively. Additionally, there are various combinations of crops mentioned, indicating that many respondents engage in mixed cropping practices. The “other" category includes crops like cowpea, beans, fonio, onions, bitter tomatoes, eggplant, sorghum, cassava, and hibiscus flower (locally known as bissap). These crops have different water requirements depending on their specific characteristics and growth stages. Some, like sorghum, millet and cassava, are more drought-tolerant, while others, like okra, pepper, tomatoes, lettuce and onion require consistent moisture supply especially during flowering and fruiting stages. Other crops like bananas and rice are water intensive crops requiring adequate irrigation for optimal yield and fruit quality. Additionally crops that are to be harvested fresh like lettuce and cabbage require constant water supply until harvest, while dry harvested crops such as cotton and maize experience reduced water needs as they dry out, requiring minimal irrigation or none during this stage (FAO, 1986). Understanding the water requirements of the different crops is therefore vital for effective agricultural planning, as it allows farmers to make informed decisions about crop selection, irrigation practices, and overall water management especially in regions where water availability can vary significantly throughout the year. This knowledge is important in guiding agricultural planning and optimizing water use efficiency in crop production as agriculture and food production are the largest water consumers (Zahoor et al., 2019). The presence of these crops underscores the adaptability and resilience of farmers, who utilize a range of crops tailored to local conditions and preferences. By diversifying their agricultural activities, farmers can mitigate risks associated with climate variability and market fluctuations, ultimately enhancing the overall resilience of the agricultural sector.

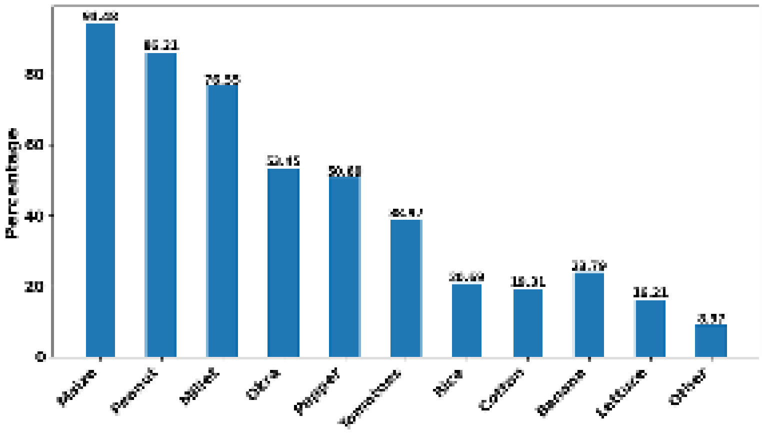


*Figure 36: The Agricultural Crops Grown by Respondents*

Figure 37 presents the types of tools used for agricultural production in the region. Traditional tools are the most frequently mentioned (90.69%), indicating their continued importance in farming. Motor pumps (58.62%) and mechanized (37.59%) equipment are also widely used, suggesting a shift towards more modern technologies in some areas. Solar pumps (20.34%), while less common, still play a role, likely reflecting the growing interest in sustainable and renewable energy sources. A small number of respondents also mentioned "other" tools, which include the use of animal traction machines. The variety of tools reported reflect a blend of traditional methods and modern technologies to meet diverse agricultural needs, challenges and increased productivity.

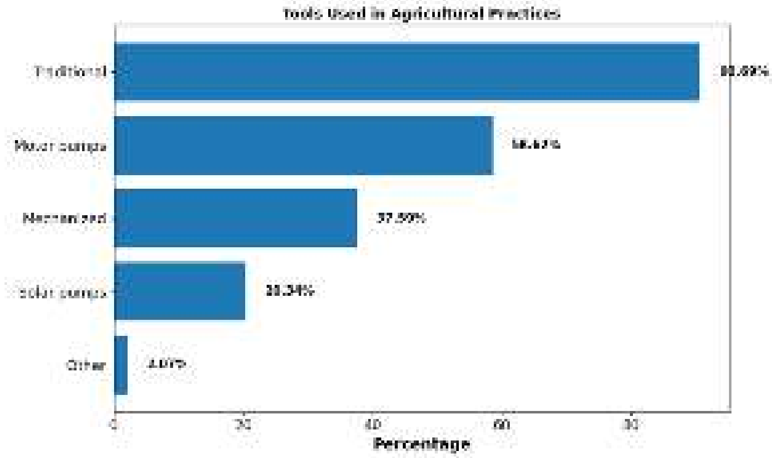


*Figure 37: Tools Used in Agricultural Crop Production in the Surveyed Region*

The most commonly used fertilizers for agricultural production are presented in figure 38. Manure was the most cited fertilizer, cited by 80.34% of respondents. Chemical products are also widely used, as indicated by 78.28% indicating that both traditional and modern farming practices coexist. Despite the prominence of these inputs, manure is slightly more favoured than chemical products, reflecting a preference for organic or locally sourced fertilizers. However, the overlap in usage between manure and chemical products suggests that farmers often utilize a combination of both, depending on availability, cost, and the specific needs of their crops. Since the choice of fertilizers can have environmental implications, such as nutrient runoff and soil degradation, understanding farmers' fertilizer preferences allows for the assessment of potential environmental impacts and the development of sustainable agricultural practices for farmers by authorities.

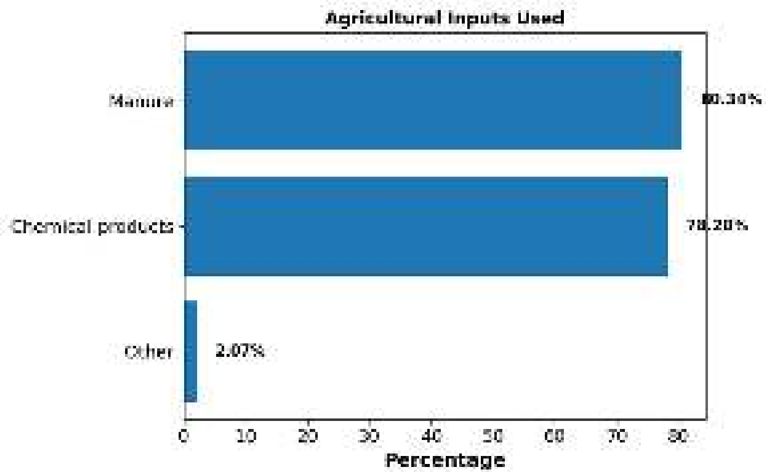


*Figure 38: Fertilizer Types Used in Agricultural Crop Production*

The respondents' perception on the trends of the farming activities is presented in figure 39. The majority of respondents (55.52%) perceive a decline in crop farming activity, indicating concerns about decreasing productivity or other challenges affecting agriculture. A considerable number (37.93%), however, view the activity as expanding, suggesting improvements or opportunities in certain areas. A smaller group (6.55%) believes there has been no noticeable change, reflecting stability in their farming practices.

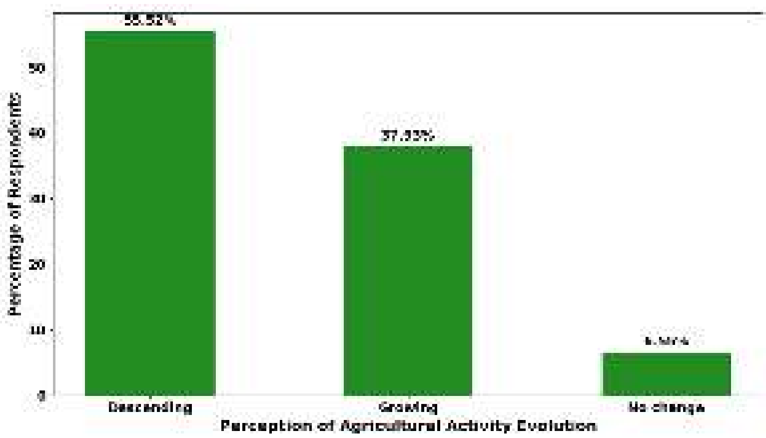


*Figure 39: Respondents' Perception on the Evolution of Crop Farming Activities*

Respondents' perception on the factors influencing the evolution of crop farming activities is presented in figure 40. Limited financial and material resources, cited by 43.1%, along with a reduction in water availability cited by 43.79%, were mentioned as key challenges. Population dynamics also play a role, with some linking changes in farming activities to population growth (22.76), while others associate it with rural exodus or population decline (22.07%). The modernization of agricultural practices was recognized as a contributing factor by 19.66% of respondents, indicating shifts in farming methods. Additionally, a smaller number of respondents noted an increase in water resources (2.76%) or other unspecified factors as influences on agricultural trends. Other factors mentioned include a decline in youth participation in agriculture, the emergence of alternative economic activities such as bakeries, and limited access to cultivable land due to privatization. Some respondents also highlighted the role of external support, aging farming equipment, and the lack of agricultural inputs. Environmental challenges, such as heavy rainfall, strong winds, and wandering livestock, were also cited as influencing farming activities. Moreover, broader development policies were recognized as shaping agricultural trends.

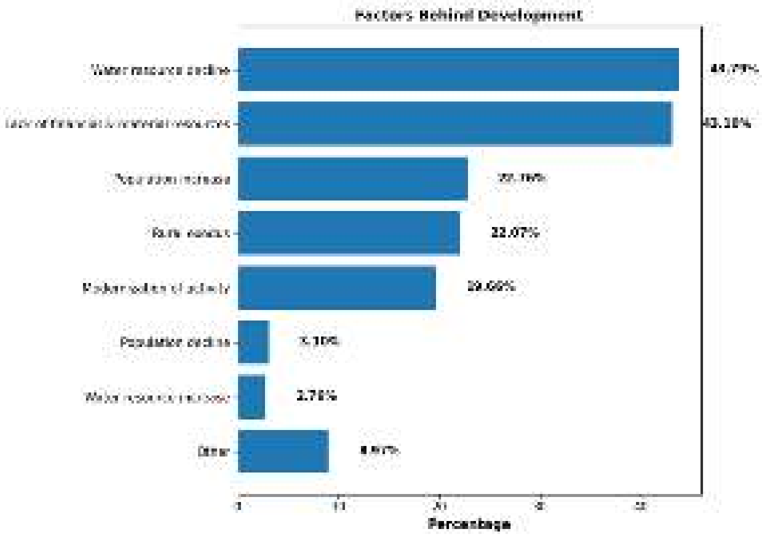


*Figure 40: Respondents' Perception on Factors Influencing the Trends of Agricultural Development*

#### 6.2.1.2 Livestock Farming

Figure 41 presents the various types of livestock farming are practiced in the region. Intensive farming, which involves high inputs and a confined environment to maximize the production of meat, milk, or eggs, is the most commonly observed as cited by 47.24% of respondents. Extensive farming, a low-input system where livestock graze over large outdoor areas, is also prevalent, cited by 36.9%. Semi-intensive farming, which combines aspects of both intensive and extensive methods with moderate inputs, is practiced to a lesser extent by 15.86%.

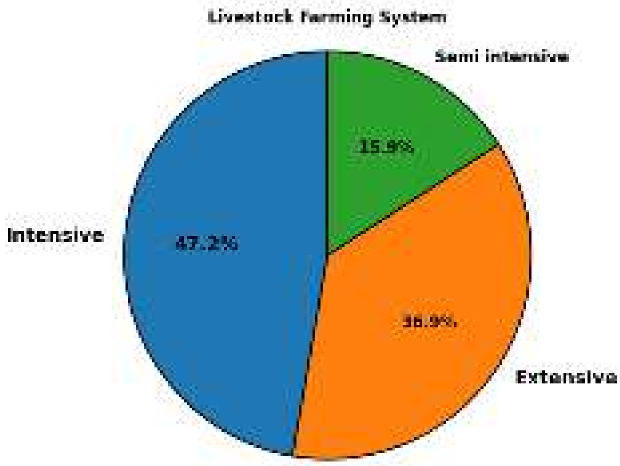


*Figure 41: Types of Livestock Farming Practiced*

The most commonly raised animals in the region, in order of importance are presented in figure 42. Sheep are the most frequently raised cited by 82.41%, followed closely by cattle reported by 77.24% and poultry by 76.21% respectively, indicating a strong focus on these livestock types. Goats are also a significant part of livestock farming, though they are less common than the top three cited by 66.21%. Donkeys and horses are raised less frequently, cited by 31.03 and 24.49% respectively, suggesting they are of secondary importance compared to other livestock categories.

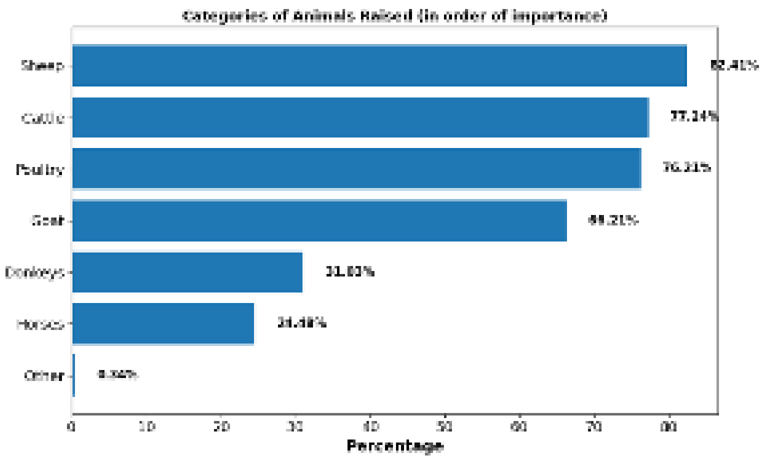


*Figure 42: Categories of Animals Raised (in Order of Importance)*

The primary watering points for livestock is presented in figure 43. Hand-dug wells were the most commonly cited mentioned by 76.9%, followed by the watercourses (66.9%) and borehole drinkers (56.55%).  Temporary ponds (32.76%) serve as another important source, although they are less prevalent. A small number of respondents mentioned "other" watering points, including taps and water troughs within households.

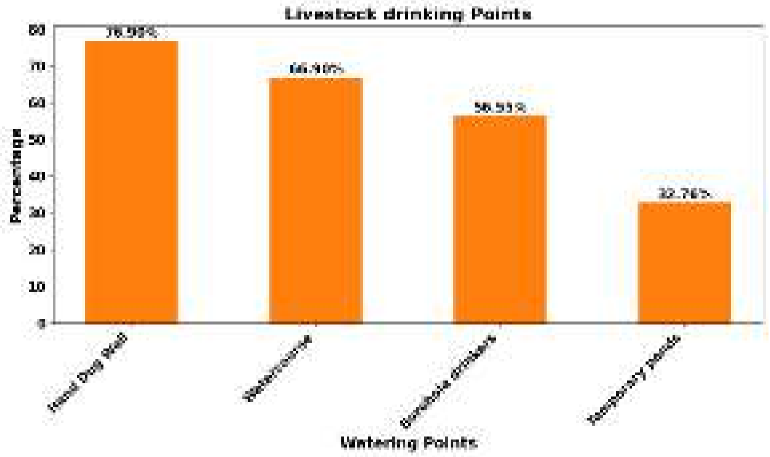


*Figure 43: The Main Sources of Drinking Water Points for Animals*

In comparison to Figure 33, this accentuates that both humans and animals in the surveyed region heavily rely on hand dug wells and the watercourse. Additionally, the higher use of temporary ponds for animals compared to the general water supply for humans suggests that these sources are more crucial as drinking water for animals than humans in the area. This is a potential area for further investigation into specific water needs and availability for livestock versus general water use for the population.

Perception of respondents on the trends of the livestock farming activities is presented in Figure 44. The majority of respondents, 67.47% view the evolution of animal rearing activity as declining. A smaller group, 21.8% considers it to be growing, while a few (10.73%) perceive no change in the activity.

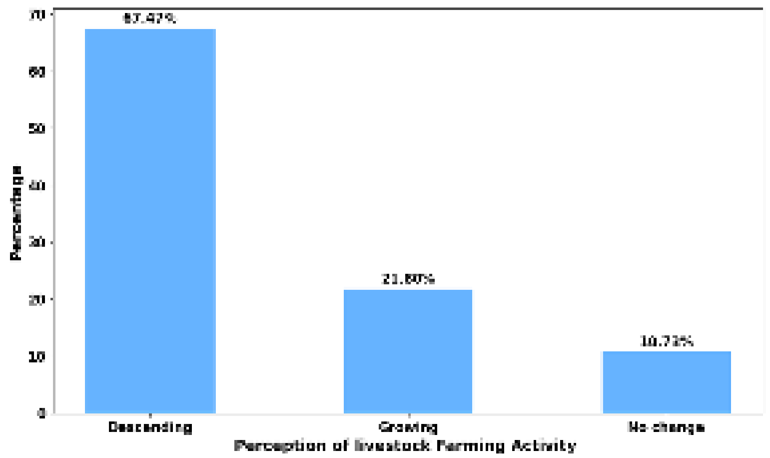


*Figure 44: Respondents' Perceived Trends in Agricultural Activities*

The factors behind the trends in livestock farming activities include a variety of challenges and conditions, as presented in Figure 45. Poverty and insufficient water are key contributors, cited by 42.41% and 41.03% of respondents respectively. Reduced forage availability, which impacts the livelihoods of those engaged in animal rearing, was cited by 26.55%. Bushfires also play a role in shaping the activity, cited by 24.48%, along with population growth, which may intensify the demand for livestock, cited by 16.9%. Other influencing factors include increased forage availability (9.66%) and sufficient water (5.52%). Additionally, a decline in population was cited by only 2.76% of respondents, suggesting its relatively lower impact on the development of animal rearing in the studied context.

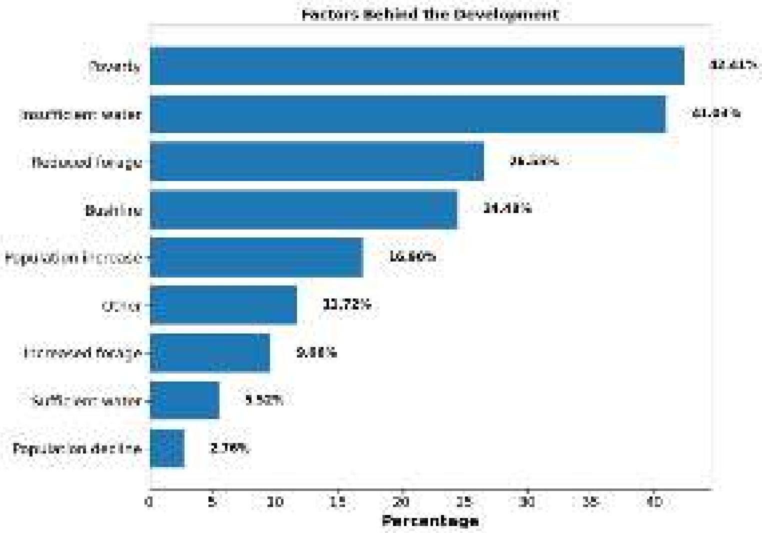


*Figure 45: Perception of Respondents on Factors Influencing the Development of Livestock Farming*

### 6.2.2 Fishing

Figure 46 presents the fishing practice periods by the respondents. The majority of respondents practice fishing throughout the entire year (76.55%), reflecting its vital role in sustaining livelihoods and providing nutrition for the local populace. A smaller number focus on fishing during the rainy season (16.9%), while fewer engage in fishing during the cold dry season (6.21%). Only 0.34% of respondents indicated fishing during the hot dry season. Research conducted by Belhabib et al., 2014 documented that fishing contributes significantly as a protein source, providing over 75% of the animal protein consumed by the local population in Senegal.  This reliance underscores the socio-economic importance of the fishing industry, not only as a source of income but also as a primary means of meeting nutritional needs in these communities.

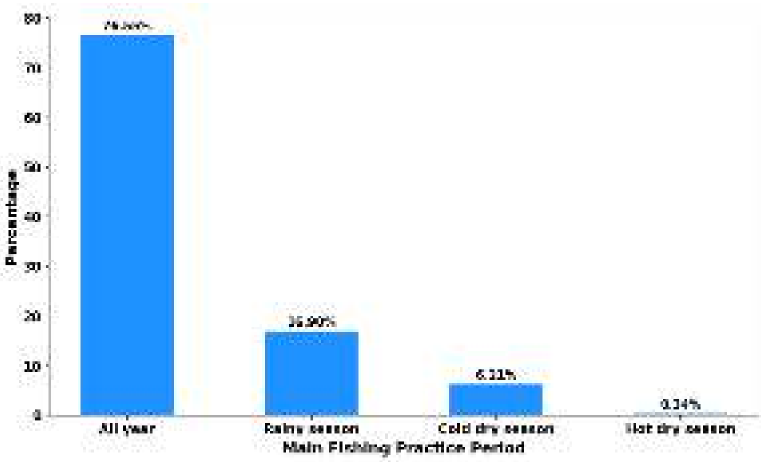


Figure 46*: The Main Fishing Practice Period in the Surveyed Region*

The most commonly practiced fishing technique is the use of fixed nets as reported by 94.48% as presented in figure 47. A small number of respondents practice fishing by digging holes (1.72%). Digging holes is mostly practiced when the stream reaches dry out or during periods of low water levels, which makes fish more accessible in the remaining water pools. Other methods, such as using fish hooks and trapping, are also mentioned but are less frequently used.

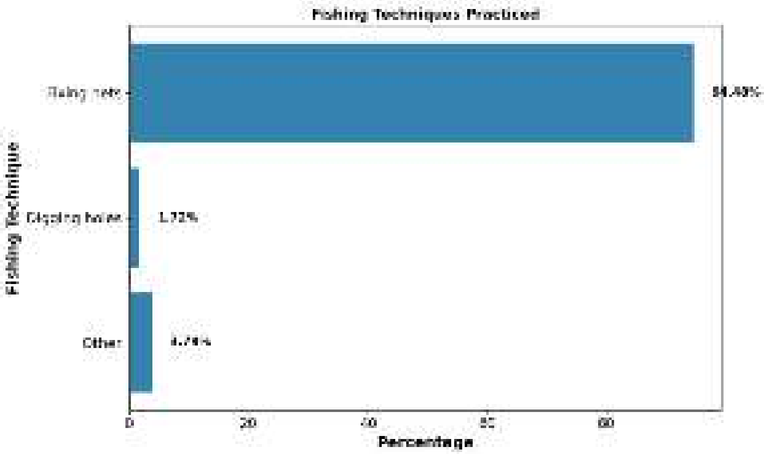


*Figure 47: Fishing Techniques Used in the Study Area*

The perspective of respondents with regards to the trends of the fishing activities is presented in figure 48. The majority of respondents (81.38%) believe that the fishing activity is declining, while a smaller proportion (13.79) feel that it has remained unchanged. A small number of respondents (4.83%) perceive that the activity is growing.

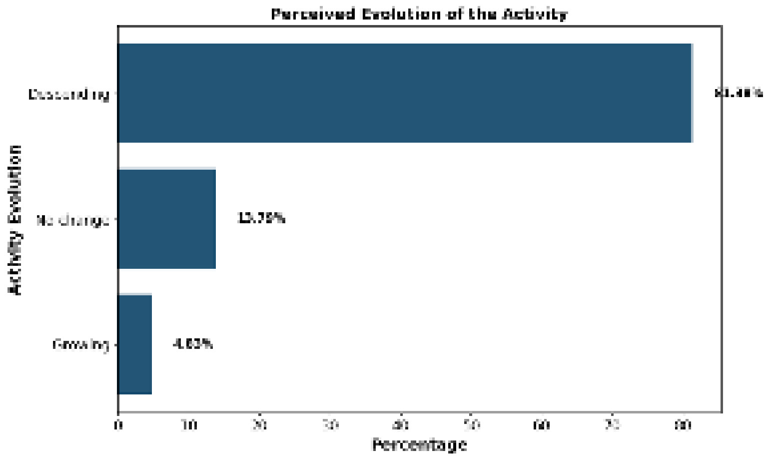


*Figure 48: Perceived Trends in Fishing Activity*

The factors contributing to the evolution of fishing practices are varied as presented in figure 49. The majority of respondents (91.03%) identified fish scarcity as a key factor influencing the development, highlighting the declining availability of fish as a significant concern. Other factors include the decrease in water resources, which was mentioned by 48.97% of the respondents, indicating that reduced water levels are also playing a role in the evolution of fishing activities. Poverty, population increase, and modernization were mentioned less frequently, by 15.86, 4.14 and 1.38 % of respondents suggesting that these factors may have a lesser, yet still notable, impact. A small number of respondents (0.69%) mentioned increased water resources, while others identified specific issues such as pollution, the presence of hippopotamuses, the arrival of Malians, overexploitation, and the use of non-recommended fishing nets as additional contributing factors. These diverse factors reflect both environmental and social influences on fishing practices in the region.

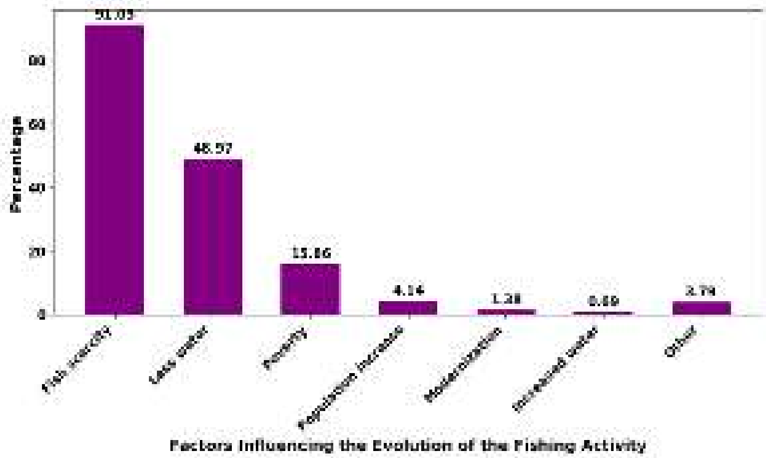


*Figure 49: Respondents' Perception of Factors Behind the Trends of the Fishing Activity*

### 6.2.3 Trade

Figure 50 highlights the different products marketed by respondents, with crops being the most commonly traded cited by 96.55% of respondents. Many respondents are also involved in the trade of animals (54.83%), while a smaller group (13.79%) markets other product which include forest products (e.g., timber and other forestry-related goods), artistic products, boutique items, and artisanal goods. We should note here that some respondents are engaged in trading more than one type of product.

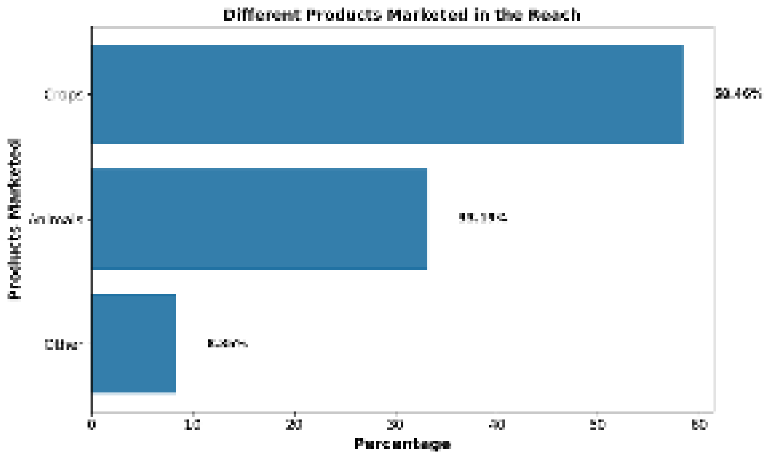


*Figure 50: Products Traded by Respondents*

The sale of goods takes place across multiple locations as presented in figure 51. Majority of respondents sell their products at local markets (68.62%) and weekly markets (63.45%) (locally known as loumas), such as those in Gouloumbou and Tamba, being the most frequently mentioned. Some traders also sell in major city markets (41.72%), including Dakar. In certain cases, buyers travel from urban areas to purchase goods directly. A few respondents (11.38%) indicated that they do not have access to a market, while others rely on intermediaries for selling their products.

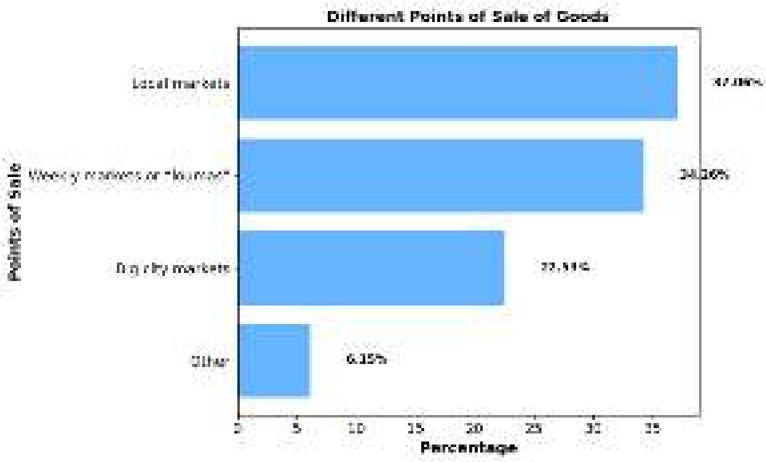


*Figure 51: The Different Sale Points in the Surveyed Region*

The responses indicate varying perceptions regarding the evolution of trade activity in the region as presented by figure 52. A significant number of respondents (46.21%) believe that trade is declining, while others see it as growing (27.93%). A notable portion of respondents perceive no significant change (25.86%) in trade activity.

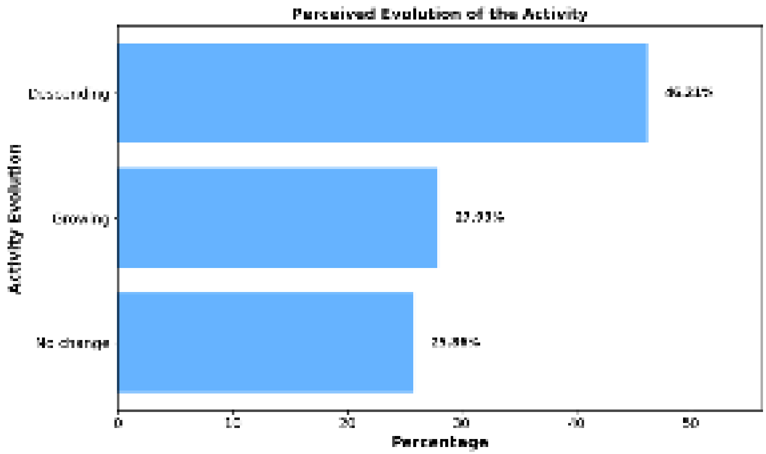


*Figure 52: Perception of Trends in Trading Activity*

Traders in the region face several constraints that impact their activities, as shown in Figure 33. Limited transportation options are a major challenge, cited by 58.62% of respondents, making it difficult to move goods efficiently. Storage issues further complicate trade, with 48.62% citing inadequate facilities that affect product preservation. A lack of sufficient markets (28.97%) also limits selling opportunities. Other challenges, cited by 11.38%, include financial constraints, high market competition, fluctuating prices, poor road conditions, and difficulties in accessing production sites. Traders also face issues such as weak market regulation, a limited customer base, low prices offered for goods, strict enforcement of regulations, and long distances to weekly markets ('loumas').

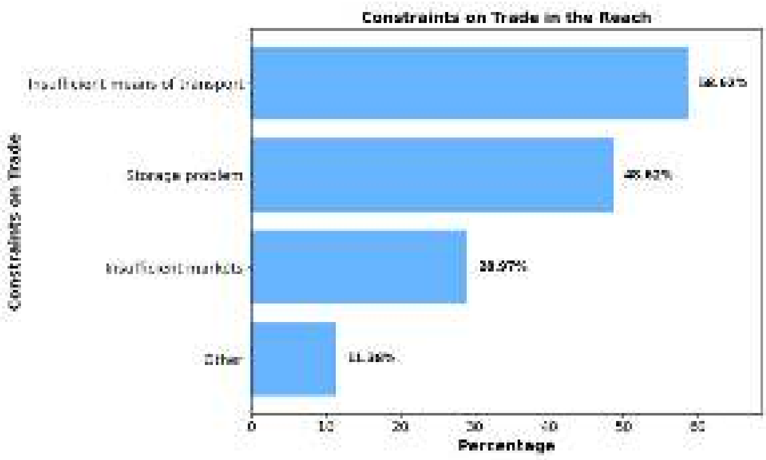


*Figure 53: Respondents' Perception of Trade Constraints in the Surveyed Region*

The evolution of trade activity is influenced by multiple factors as presented in figure 54, with low income (40.69%), poverty (35.17%), and lack of employment (33.79%) being the most frequently mentioned. Other challenges include bushfires, insufficient regulatory control, and strict operational enforcement cited by 22.07, 20.34 and 18.97% respectively. Some respondents also pointed to factors such as the distance from villages from the forest, a decline in engagement in trade activities, and the rarity or disappearance of certain forest species, particularly in sectors reliant on natural resources.

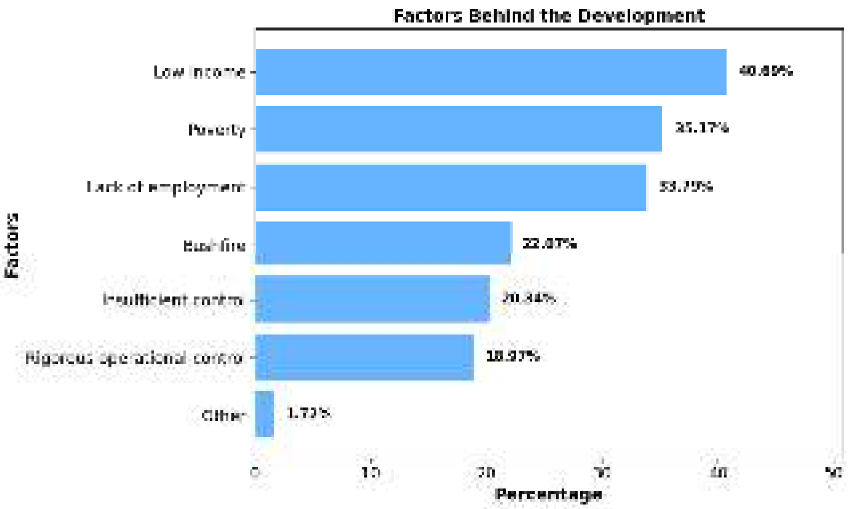


*Figure 54: Respondents' Perception of Factors Responsible for the Trends of the Trading Activities*

The assessment of surface water quality compared to the past (figure 55) indicates that the majority of respondents ()57.93%) perceive no change in water quality. A significant portion of respondents, however, noted a decline in surface water quality (27.93), while a smaller group reported an improvement in water quality (14.14%).

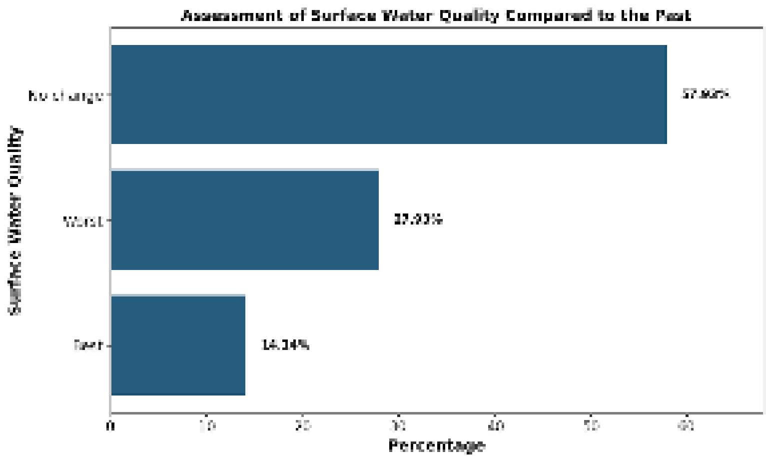


*Figure 55: Perception of Respondents on Surface Water Quality Compared to the Past*

The assessment of groundwater quality compared to the past (figure 56) shows that most respondents perceive no change in the quality of groundwater (59.66%). A notable portion of respondents reported that the groundwater quality has improved (25.17%), while a smaller group considered the groundwater quality to have worsened (15.17%).

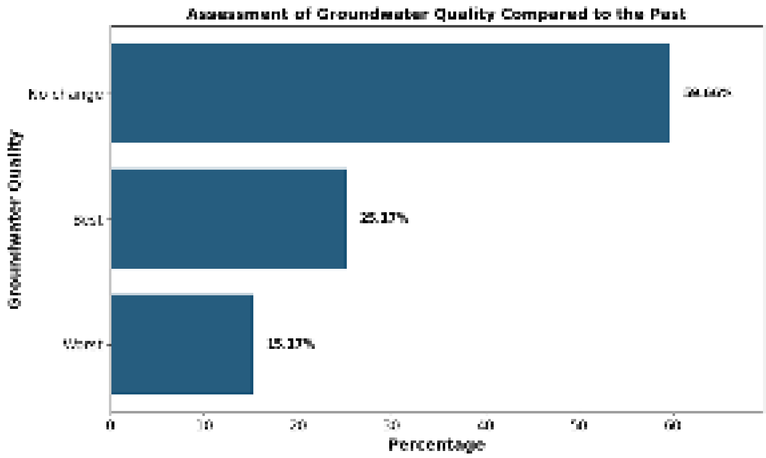


*Figure 56: Perception of Respondents on the Quality of Groundwater Compared to the Past*

## 6.4 Water Resources Management in the Inland Reach of the CGRB

### 6.4.1 Awareness and Participation in Water Governance

Survey results indicate that the majority of respondents (83.45%) were unfamiliar with water rules/regulations in the study region, while only a small proportion (16.55%) reported awareness (figure 57a).

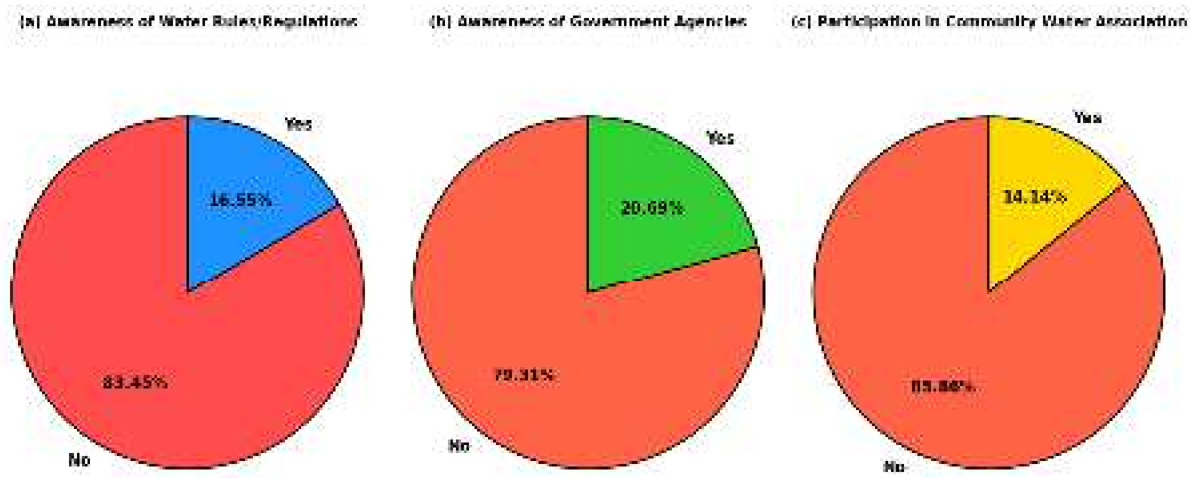


*Figure 57: Respondents' Perception on a) Awareness of Rules/Regulations, b) Awareness of Government Agencies and c) Participation in Community Water Associations in the Study Area*

Similarly, most respondents (79.31%) were unaware of government agencies responsible for water management (Figure 57b), revealing a major knowledge gap regarding institutional roles and regulatory frameworks. This limited awareness suggests that local communities operate largely outside formal water governance systems, posing challenges to achieving inclusive and sustainable management. Furthermore, participation in collective water governance was also low: the vast majority of respondents (85.86%) reported never joining community water associations (Figure 57c). This limited engagement reflects a lack of participatory mechanisms and may constrain the diffusion of governance knowledge and community-led water stewardship.

The respondents who mentioned having joint an association listed several community water associations in the watershed, including COPROVAG (La Coopérative des Producteurs de la Vallée du Fleuve Gambie), Economic Interest Groups (GIE) located in the various villages, Fishermen's Association, "Tilo Tilo", "Koar II", "Saal 1", Zonal Union, "Goor goor", "Adjina diambo", "Jambagoume", "Woulanafa", and "Wato Sita". These associations play various roles in water management, resource utilization, and community development within the watershed.

A chi-square test confirmed a significant association between individuals' knowledge of water rules/regulations and their membership in community water associations ($\chi^2 = 35.91$, $p < 0.001$; Table 11). Among respondents without knowledge of water rules, 91.3% were not members of any association. Conversely, 41.7% of those aware of regulations reported active membership. This pattern indicates that community-based organizations play a crucial role in enhancing awareness and promoting participatory water governance, a key pillar of sustainable water management.

*Table 12: Chi-Square Test between Individuals' Knowledge of Water Rules/Regulations and their Participation in Community Water Associations*

| | Membership in Community Water Associations | | |
|---|---|---|---|
| Knowledge of Water Rules/Regulations | No | Yes | Total |
| No | 221 | 21 | 242 |
| Yes | 28 | 20 | 48 |
| Total | 249 | 41 | 290 |

Pearson Chi2 = 35.91
Prob = 0.0000

### 6.4.2 Attitudes and Rule Perception

The responses indicate a divided attitude toward appropriate water use in the watershed (figure 58), with a slight majority (51.38%) expressing a favourable view, while nearly half of the respondents (48.62%) reported an unfavourable stance.

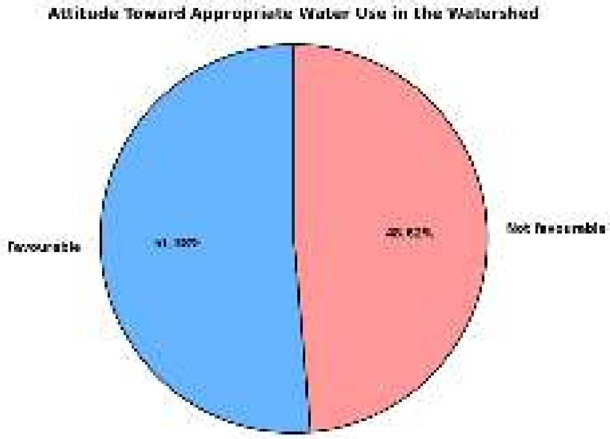


*Figure 58: Respondents' Attitudes Toward Appropriate Water Use in the Watershed*

The respondents who expressed a favourable attitude toward appropriate water use in the watershed provided a variety of reasons for their stance. Some highlighted the importance of water conservation for the collective good, emphasizing that responsible water use benefits the entire community. Others mentioned the prevention of water wastage as a key motivation, promoting access to water throughout the year, especially during low water seasons. Several respondents cited the protection of people and populations from diseases as a crucial factor, while others emphasized compliance with regulations, laws, and penalties as reasons for supporting appropriate water use. Some respondents stressed the significance of water for agricultural activities, including market gardening and banana farms, while others highlighted the role of water in supporting fish reproduction and overall ecosystem health.

In contrast, respondents with unfavourable attitudes referenced the excessive use of water by mining companies, lack of involvement of the population in water conservation, and the risk of flooding during heavy rain due to the relocation of communities by the state near the watercourse. Poor water quality, and a lack of perceived benefits for following appropriate water use to the unfavourable view. Other Issues such as a permanent water shortage, long distance to the river, limited enforcement of water rules, corruption of agents, lack of interest, and information gaps were also mentioned as challenges relating to appropriate water management in the surveyed region.

A chi-square test revealed a strong link between awareness of water rules and attitudes toward responsible water use ($\chi^2 = 23.51$, $p < 0.001$; Table 12). Among respondents unaware of regulations, only 45% displayed favourable attitudes, compared to 83.3% among those who were informed. This underscores the importance of education and awareness campaigns in shaping positive water-use behaviours, critical for advancing sustainability outcomes.

*Table 13: Association between Respondents' Awareness of Water Rules/Regulations and Their Attitudes toward Appropriate Water Use*

| Knowledge of Water Rules/Regulations | Attitude Towards Appropriate Water Use | | |
|---|---|---|---|
| | Favourable | Non favourable | Total |
| No | 109 | 133 | 242 |
| Yes | 40 | 8 | 48 |
| Total | 149 | 141 | 290 |

Pearson Chi2 = 23.51
Prob = 0.0000

Perceptions of rule compliance also mirrored this pattern. While half of the respondents believed that water rules are respected (50.0%), 43.5% thought otherwise, and only 6.5% felt that rules were very well respected (Figure 59).

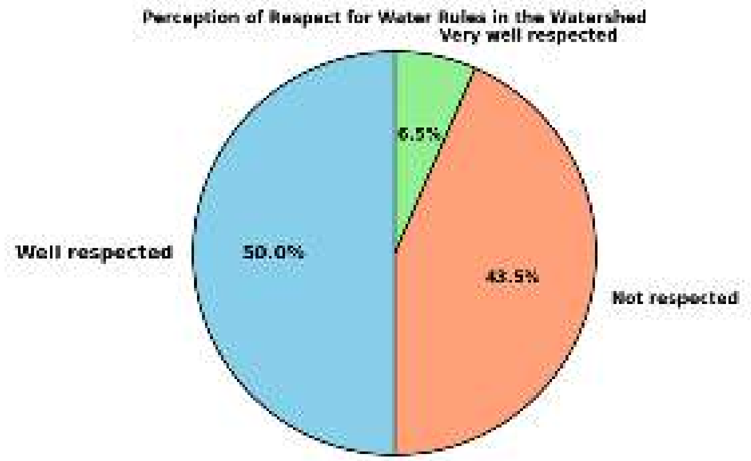


*Figure 59: Respondents' Adherence to Existing Water Rules*

The chi-square test between attitudes and perceptions of rule compliance was highly significant ($\chi^2 = 41.69$, $p < 0.001$; Table 13). Among those with a favourable attitude, 59.7% believed the rules are well respected, 27.5% thought they are not respected, and 12.8% believed they are very well respected. In contrast, among those with a non-favourable attitude, 60.3% believed the rules are not respected, 39.7% said they are well respected, and none believed they are very well respected. This suggests a reciprocal relationship between trust, compliance, and sustainability-oriented governance.

*Table 14: Association between Respondents' Attitudes toward Appropriate Water Use and Their Perception of Compliance with Existing Water Rules*

| Attitude toward the appropriate use of water | Respect of existing water rules | | | |
|---|---|---|---|---|
| | Well respect | Not respected | Very well respected | Total |

| | | | | |
|---|---|---|---|---|
| Favourable | 89 | 41 | 19 | 149 |
| Non favourable | 56 | 85 | 0 | 141 |
| Total | 145 | 126 | 19 | 290 |

Pearson Chi2 = 41.69
Prob = 0.0000

The factors affecting compliance with water regulations in the catchment (figure 60) are primarily linked to a lack of public awareness (42.07%), which is the most frequently cited issue. Other significant factors include a lack of coordination (31.03%), insufficient support or goodwill from the State (25.17%), and weak or inconsistent enforcement of rules (17.24%). Impunity and greed (17.24%) are also mentioned as contributing to non-compliance, while corruption in the execution of water rules (6.21%) is noted by a smaller group. Additionally, some respondents highlighted a lack of perceived benefits (4.14%) as a barrier to compliance, alongside less frequent concerns such as the absence of state structure, a general lack of motivation within the population and purposefully ignoring the regulations by some people. These results suggest that improving public awareness and enhancing coordination and enforcement could play key roles in improving compliance.

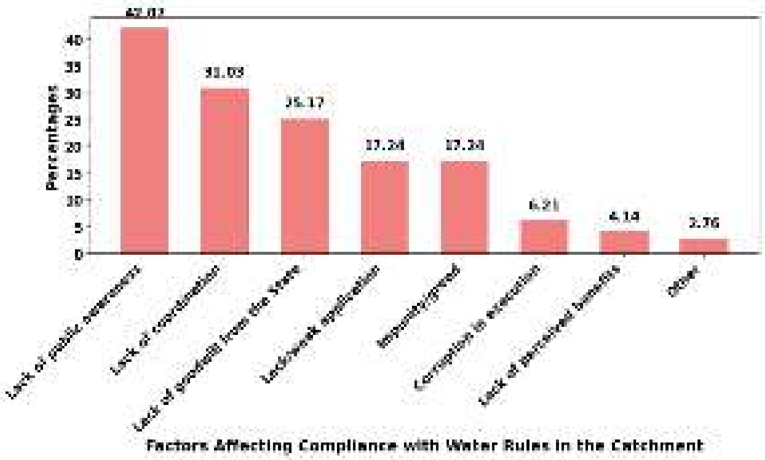


*Figure 60: Factors Influencing Compliance with Water Regulations within the Surveyed Area*

Qualitative insights from focus group discussions supported these findings. Participants reported that perceptions of inequity in water use were widespread, citing insufficient infrastructure, limited government support, and seasonal water shortages as key barriers to compliance. These qualitative observations contextualize and reinforce the survey results, highlighting the structural and institutional factors that shape community attitudes toward water governance.

### 6.4.3 Conflict and Coordination

Nearly three-quarters (71.72 %) of respondents reported no direct experience of water-related conflict, yet about one-quarter (28.28%) indicated that such disputes occur (Figure 61a).

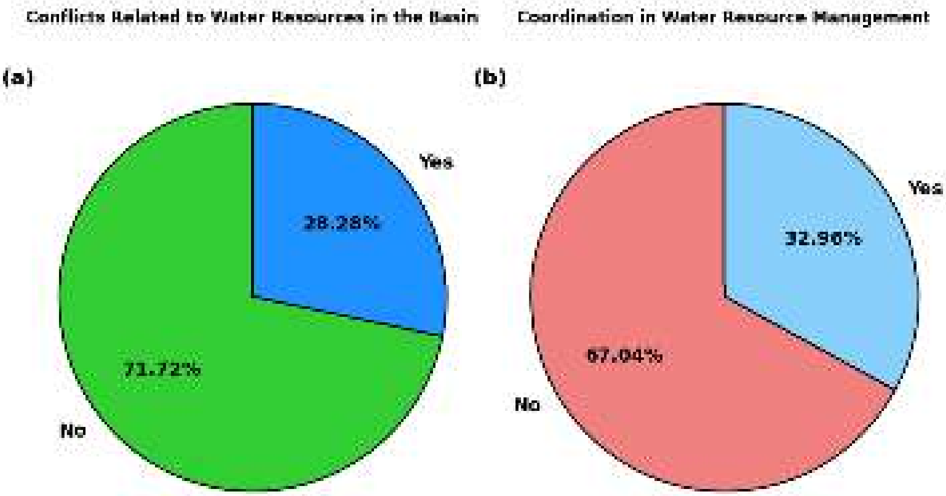


*Figure 61: Respondents' Perception on the Occurrence of Conflicts (a) and Coordination in Water Resource Management in the Study Area*

Among reported cases, the majority (75.61%) involved farmers and livestock herders. reflecting tensions between agricultural and pastoral water uses. Smaller proportions involved farmer–farmer disputes (9.76%) or conflicts among fishermen and between domestic users (14.63%). These findings highlight that although conflicts are not widespread, they are localized and driven by sectoral competition over water, particularly during low-flow periods.

Respondents attributed water-related conflicts to several underlying causes, including, livestock trampling on farmers' fields while heading to the river to drink, non-compliance with established rules, land disputes, and resource scarcity during the dry season. Other tensions were linked to poor water management and violations of local agreements by various groups especially during the dry sea or during periods of low river flow, including conflicts of domestic water uses although these rarely occurred. These insights suggest that water-related conflicts here are often intertwined with broader issues of land use, animal management, and adherence to local regulations.

These survey findings were corroborated by key informant interviews and focus group discussions. For instance, the Imam of Badi reported: *"We only have three functional wells, with depths between 17 and 30 m, supplying the village,"* illustrating the scarcity that can trigger disputes. The village chief of Badi also highlighted limited institutional support: *"We have hardly received any external help in agriculture or water management since arriving here,"* reflecting weak oversight and coordination. FGDs further confirmed that conflicts are exacerbated by unclear land demarcation, competition for irrigated plots, and seasonal water shortages, providing qualitative context to the 25% of respondents reporting water-related disputes.

A large majority of respondents (67.04%) also perceived limited coordination among actors managing water resources, while a smaller proportion (32.96%) perceive that there is some coordination (Figure 61b). This suggests that water resource management may face challenges related to organization and collaboration, which could affect the effectiveness of conservation and utilization efforts in the watershed.

Among those who reported the existence of coordination in the management of water resources, 48.89% mentioned that the management occurs through consultation frameworks, and 51.11% mentioned the involvement of various actors.

A chi-square test confirmed a significant relationship between respondents' awareness of government agencies and their perception of coordination mechanisms ($\chi^2 = 38.07$, $p < 0.001$; Table 14). Individuals aware of government involvement were more likely to perceive existing coordination efforts, suggesting that institutional visibility enhances trust and perceived governance effectiveness, key components of sustainable resource management.

*Table 15: Association between Respondents' Awareness of Government Agencies Involved in Water Management and Their Perception of Coordination in Water Resources Management*

| **Awareness of Government Agencies** | **Coordination in Water Resources Management** | | |
|---|---|---|---|
| | No | Yes | Total |
| No | 179 | 51 | 230 |
| Yes | 22 | 38 | 60 |
| Total | 201 | 86 | 290 |

Pearson Chi2 = 38.07
Prob = 0.0000

Consultation frameworks involve discussions, meetings, and assemblies between different stakeholders, such as GIEs (Economic Interest Groups), state representatives, communities, and forest officials. Consultation also extends to international levels, involving discussions among member countries of the basin. Decision-making processes include delegations responsible for decisions, and consultations with the population to ensure inclusive and participatory water resource management. Additionally, some frameworks address specific issues like market regulation, exploitation of temporary ponds, and coordination of activities in the sub-region. The frequency of meetings varies, with some occurring weekly, quarterly, or on an as-needed basis. The engagement of various organizations, associations, and local communities reflects a concerted effort to ensure effective water resource management in the region.

In the realm of water resource management, coordination among actors involves various actions to ensure effective governance and regulation. These actions include an alert service for monitoring and regulating market prices, river exploitation operations led by the different economic interest groups and fishermen's committees with oversight from park agents, on establishing rules for river use. Additionally, organizations like COPROVAG (La Coopérative des Producteurs de la Vallée du Fleuve Gambie) play a crucial role in coordinating activities among river associations and different GIEs (Economic Interest Groups). COPROVAG contributes to coordination by providing training for producers, emphasizing the importance of knowledge-sharing and capacity building in sustainable water resource management.

The most frequently cited benefits of following water rules in the watershed (figure 62) are access to water and fewer conflicts, cited by 61.72 1nd 44.48% respectively. Respondents also mentioned membership fees (14.83%) and financial benefits (6.9%), although these were less frequently cited.

Other benefits cited by a minority of participants include having an internal organization, does without taps in their neighbourhoods can have access to water, management allows for fishing activities to go on, protection of green spaces and finally, it promotes more partnerships within the community. These perceived benefits underscore the importance of compliance with water rules in fostering improved water access, conflict mitigation, and financial gains within the watershed community.

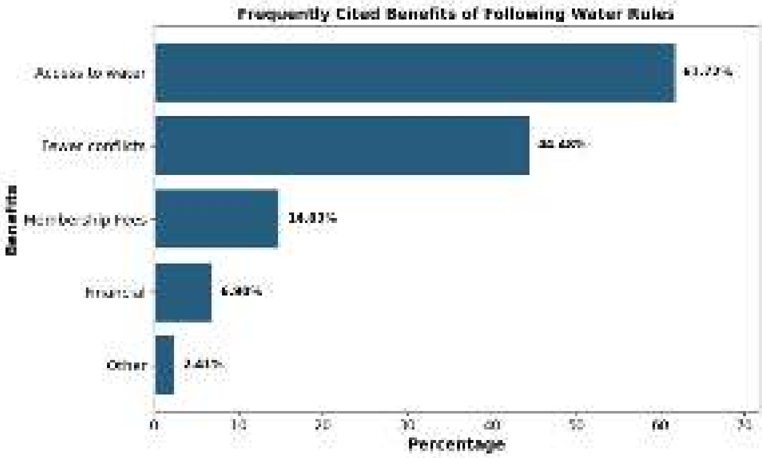


*Figure 62: Perceptions of Respondents on Advantages Associated with Compliance with Water Regulations within the Watershed*

The strategies developed to address the impacts of climate change (Figure 63) in the surveyed area focus primarily on environmental and resource management. The most commonly cited approach is reforestation and the protection of existing forests (74.14%), followed by efforts to combat bushfires (66.9%). Many respondents also emphasized the importance of rational water use (38.97%) to manage the region's water resources more effectively. Measures to reduce water pollution (31.72%) were also highlighted by a significant number of respondents. Other strategies mentioned include the construction of dykes (6.9%) and the development of water storage systems (3.1%) to enhance resource management. A few respondents noted additional actions, such as increasing well depth or expanding the number of pipes to exploit river water for irrigation purposes, although these were less common. These strategies undertaken by the communities have been documented in studies to be important pathways for strengthening water resource resilience in other regions (Sweya et al., 2018; Goffner et al., 2019; Xu et al., 2021; Shen et al., 2022).

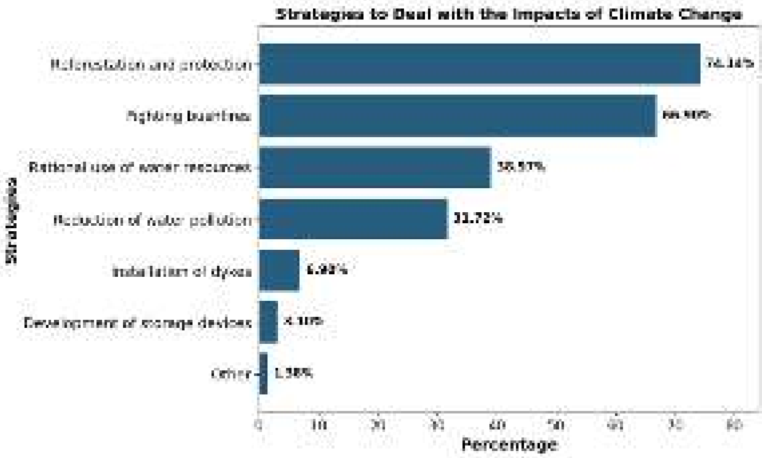


*Figure 63: Strategies Developed by Respondents to Deal with the Impacts of Climate Change*

The strategies developed to cope with the impacts of land use change focus mainly on environmental conservation and sustainable land management practices (figure 64). Reforestation and the protection of forests were the most frequently mentioned strategies mentioned by 71.38% of respondents, followed by efforts to combat bushfires cited by 66.21%. Many respondents (42.41%) also emphasized the importance of using pesticides and fertilizers more rationally to reduce the environmental impact of agriculture. Rational water use was highlighted by a significant number of people (29.31%), indicating an awareness of the need to manage water resources efficiently in the face of changing land use. Strategies to limit water pollution were also cited (24.83%), reflecting concerns about the negative effects of agricultural activities on water quality. Other strategies included the installation of dykes (2.76%) and the reduction of production areas (2.07%), though these were mentioned less frequently. A few respondents noted the importance of activities such as channel digging (1.38%) water drainage (1.03%), and the development of retention basins (0.69%) to better manage land and water resources. These strategies demonstrate an emphasis on sustainability and managing the ecological consequences of land use

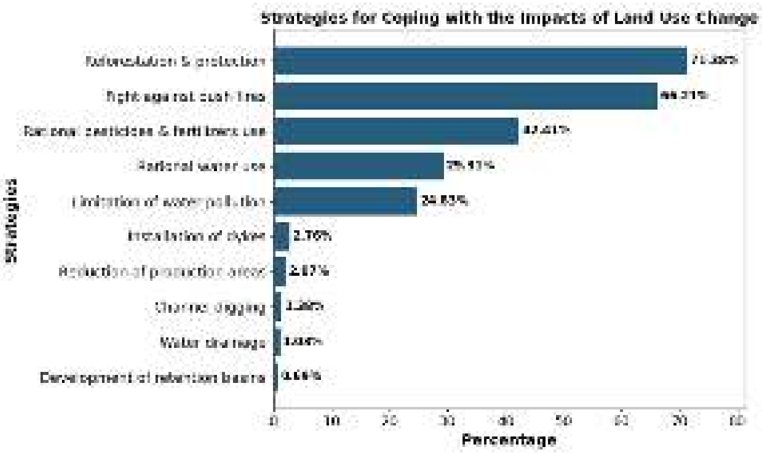


*Figure 64: Strategies Employed by the Community to Fight the Impacts of Land Use Change*

Various actors in the communities are actively involved in the fight against climate and land use change and its impacts related to water pollution reduction, reforestation and protection, fighting bushfires, rational use of water resources, and the implementation of dykes. For water pollution reduction, actors primarily include the population, youth associations, state agencies, and community organizations. In reforestation and protection endeavours, the population and youth associations play significant roles alongside water and forestry agents. Similarly, in the fight against bushfires, the involvement of the population, parks officers, and water and forestry agents are notable. The rational use of water resources involves collaboration among various actors, including the population, youth, and GIE associations. Lastly, in the implementation of dykes, participation from banana producers and state entities is highlighted. Additionally, appreciations and feedback regarding these initiatives reflect varying sentiments, from expressions of support and recognition to concerns about implementation challenges such as lack of follow-up or control. Overall, the responses underscore the importance of multi-stakeholder engagement and community involvement in environmental conservation efforts, while also highlighting areas for improvement in terms of coordination and oversight.

The summary of promoters involved in supporting policies related to climate and land use change reveals a wide array of organizations and entities contributing to these efforts. Diverse organisations such as FAR (Rural Agricultural Women), APROVAG (Gambia River Valley Producers Association), World Vision, private enterprises, African Office for Development and Cooperation (OFADEC), the Banana project, Coris Microfinance, Veolia foundation, individuals like Abé Mathieu, Mishra Town Hall, Senegal Water Management Company (SOGESS), Mennonite Economic Development Associates (MEDA), and religious institutions like the Church, German Society for International Cooperation (GIZ), Group for helping development and health (Gadis ), Food and Agricultural organisation (FAO), Horizon 3000, Action Aid, Tiers Sud, World Food Program (WFP), Rural cooperative for the inclusive development of Missirah (CORDIM), and Tilo Tilo. These promoters represent a diverse range of entities, including governmental agencies, non-governmental organizations, private enterprises, and community-based organizations, demonstrating the multi-sectoral approach to promoting policies related to land use change.

### 6.5 Recommendations of respondents

The recommended solutions for the sustainable management of water resources by the respondents in the basin reflect a broad range of approaches aimed at addressing both immediate needs and long-term challenges. The most commonly suggested strategies include reducing water waste, which was frequently mentioned by respondents, along with increasing public awareness and sensitization to encourage responsible water use. Other recommendations emphasize the importance of infrastructure improvements, such as the construction of dams, boreholes, and dikes, to better manage and store water resources. There is also a strong emphasis on reforestation and protection to maintain the watershed's health and prevent degradation, as well as actions to combat bushfires, which threaten water quality and availability.

Additionally, some respondents highlighted the importance of rationalizing water use and expanding access to water, especially through the construction and improvement of water distribution systems, such as tap water and irrigation systems. There were also calls for better monitoring and enforcement of regulations to prevent misuse of resources, and the involvement of local populations in water management to ensure that strategies are effectively implemented and supported. Overall, these solutions reflect a combination of environmental conservation, infrastructure development, public engagement, and regulatory enforcement to ensure the sustainable management of the basin's water resources.

### 6.6 Discussion

The increase in population and high fertility rate perceived by the majority of respondents is supported by data from the Agence Nationale de la Statistique et de la Démographie (ANSD, 2023). Long-term population trends in Africa are primarily influenced by fertility, with Sub-Saharan African countries, particularly rural communities with lower incomes, generally exhibiting a higher fertility rate. Moreover, economic opportunities, instability in neighbouring countries, and infrastructural improvements have fuelled population growth in some communities in the surveyed area (Ba et al., 2018). Sub-Saharan African countries generally have a high fertility rate which is more predominant in rural communities with low income (Tesfay et al., 2023; Bongaarts, 2020). Moreover, economic opportunities, instability in neighbouring countries, and enhancements in infrastructure have contributed to the increase in population in the surveyed area Ba et al. (2018). It is reported that although the region is not densely populated, it has witnessed a rise in population as well as urbanization in recent years. The population dynamics have also been influenced by factors such as economic opportunities, instability in neighbouring countries, and enhancements in infrastructure. The gold reserves in the vicinity have not only drawn the interest of international corporations but have also led to a significant influx of small-scale and artisanal miners who have migrated from neighbouring countries (Mali, Burkina Faso and Guinea) to Senegal. The development of agricultural activities, trade, fishing, breeding, and market gardening have further contributed to the migration trends in the region. In contrast, a portion of the responses indicated a decline in population in certain villages. A notable cause that was reported was the displacement of certain villages (Badi, Tabadian, Soukouta, Nionghany, and Damantan) from the Niokolokoba National Park in 1969 to expand the park's perimeters in efforts to conserve the forest and wildlife in the said area consequently led to the displacement of some families and reduction of populations of certain villages (Larrue, 2002). As populations and urban areas expand, the interactions between humans and the land will become progressively more intricate. Urbanization diminishes the availability of permeable land, causing a rise in runoff, streamflow/peak discharge, and flooding during intense precipitation occurrences. Over time, the decrease in evapotranspiration and water recycling due to land use alterations might trigger a feedback mechanism leading to decreased rainfall (Savenije, 1995). Mining activities can also have varying degrees of influence on the overall water usage within a particular area, ultimately leading to repercussions on the quantity and quality of freshwater resources, including aquifers, groundwater, and river flow levels (Gao et al., 2013; Guo et al., 2019; Meißner, 2021). The mining and agriculture industries hold promise for generating economic gains, yet their utilization could introduce environmental hazards that exacerbate existing issues such as bushfires, overgrazing, deforestation, soil erosion, water quality and consequently degradation of the land (Lin et al., 2005; Niane et al., 2014; Olanipekun et al., 2019). The primary mining operations in this area are situated alongside the Gambia and Falémé Rivers, as well as in temporary water ponds within the inland regions. Due to the limited availability of hydraulic equipment, individuals in this region heavily depend on water from rivers and wells to meet their daily mining needs (Niane et al., 2014). Mining operations possess the capacity to significantly disrupt natural water environments by modifying hydrological pathways within the surrounding geological layers. All mining activities have the potential to directly influence groundwater flow, consequently impacting surface waters linked to the affected groundwater systems. The consequences of water table depletion caused by mine dewatering may entail diminished flows in interconnected streams, wetlands, and lakes, as well as the reduction of the water table in proximity to a water supply or irrigation wells, potentially resulting in increased pumping expenses or well depletion. Furthermore, land subsidence and the potential for surface water or groundwater contamination may arise, particularly if the extracted mine water is discharged into the environment and is of low quality (Younger and Wolkersdorfer, 2004).

The identification of agriculture, animal husbandry, and fishing as major water-intensive activities highlights their potential impact on water consumption and, consequently, streamflow rates. The destruction of natural vegetative covers, cropland expansion, overgrazing, increased water abstraction during the dry season due to increased human and livestock populations could lead to decreased streamflow. The reliance on wells, watercourses, boreholes, and temporary ponds as primary drinking water sources for animals highlights the direct connection between livestock farming and local water sources, suggesting a potential strain on these resources as huge amounts of freshwater are consumed for animal production and these have implications for streamflow. The perceived decline in animal breeding activity, attributed to factors such as a lack of financial resources, decreasing water availability, reduction of forage areas, and the impact of bushfires, underscores the challenges faced by the livestock farming sector and the potential implications for water resource sustainability and streamflow within the surveyed area. The findings of Bewket and Sterk (2005) in their study in the Chemoga watershed located in the northwestern highlands of Ethiopia provide empirical evidence of adverse changes in stream flow as a result of the above-mentioned land use change and utilization.

The fishing practices observed in the surveyed region exhibit diverse temporal patterns, with a significant proportion of respondents engaging in fishing throughout the year, indicating a continuous demand for water resources to support fishing activities. The seasonal nature of fishing, practiced by respondents highlights the consequences that negative hydroclimatic trends could have on the activity. Decreased rainfall and streamflow could create serious water shortage during the dry season which could lead to decrease/cessation of fishing activities.

The trading activities observed in the surveyed region, particularly the marketing of agricultural and animal products, can have significant implications for streamflow and water availability. Firstly, the transportation of goods to markets, including weekly markets, local markets, and big city markets, may require water resources for the irrigation of crops and hydration of livestock, potentially leading to increased water abstraction from rivers and affecting streamflow rates. Insufficient means of transport and storage problems reported by traders, may result in delays in delivering goods to markets, leading to increased perishability of agricultural produce and potentially higher water consumption for irrigation to compensate for lost crops

The perceptions of climate trends and their impacts on water resources within the surveyed region have significant implications for streamflow and water availability. The reported decrease in rainfall, late onset, and early cessation of the rainy season, along with rising temperatures, suggest a shift towards a drier climate regime. These changes can directly affect streamflow by reducing the volume of water flowing into rivers, potentially leading to decreased river levels and availability of surface water resources. Moreover, alterations in precipitation patterns may influence the timing and magnitude of peak river flows, impacting the seasonal variability of streamflow.

The respondents identified several prevalent climatic trends, including reduced rainfall, delayed onset of rain, shortened duration of rainy days, early cessation of rainfall, rising temperatures, and increased evapotranspiration rates**.** Similar trends were reported in various studies over Africa (Neumann et al., 2007; Aguilar et al., 2009; Barry et al., 2017; Kangalawe, 2017; Kew et al., 2021; Jury, 2022; Calvin et al., 2023; Omay et al., 2023). The observed impacts of climate change on water resources were also identified. Widespread impacts such as early drying up of watercourses and wells, groundwater decline, and decreased flow were reported. These issues directly affect the replenishment of river systems, potentially leading to diminished streamflow rates during critical periods. Additionally, the reported decrease in infiltration and increases in groundwater levels, though less frequently mentioned, can indirectly influence streamflow dynamics. Reduced infiltration may lead to increased surface runoff, affecting the timing and magnitude of river flows (Huang et al., 2017), while elevated groundwater levels may enhance baseflow, thereby shaping the overall discharge pattern of rivers (Rumsey et al., 2015). These changes in hydrological processes can alter the balance between surface water and groundwater resources, further affecting water availability in rivers.

The observations on the evolution of land use within the surveyed region have significant implications for hydrological processes, particularly concerning water availability in rivers. The progression of built-up areas and regression of natural vegetation and agricultural areas suggest extensive urbanization and land conversion, leading to increased surface runoff and reduced infiltration capacity of soils (Fenta Mekonnen et al., 2018). This alteration in land cover can disrupt the natural hydrological cycle, leading to changes in streamflow patterns (Guo et al., 2008). The reported early drying up of watercourses and wells, along with decreased flow and groundwater decline, indicate tangible impacts on surface water and groundwater resources. These changes in hydrological processes are likely attributed to shifts in land use, such as increased impervious surfaces from urban expansion and reduced vegetation cover from agricultural intensification. On the positive side, some respondents note positive effects such as increased infiltration and groundwater, indicating potential benefits from certain land use changes. However, challenges in water retention, as indicated by a decrease in infiltration, underscore the complexity of managing hydrological processes in the face of evolving land use patterns.

Overall, the perceptions of climate & land use trends and their impacts on water resources highlight the vulnerability of the surveyed region to changing environmental conditions and underscore the importance of adaptive water management strategies. Efforts to monitor and mitigate the effects of climate change on water resources, including sustainable water use practices and infrastructure development, are crucial for ensuring the resilience of river systems and maintaining adequate water availability for both human and ecological needs within the surveyed area.

Regarding water quality, perceptions vary, with a significant portion of respondents observing no change in both surface water and groundwater quality compared to the past. However, concerns about worsening water quality are notable, particularly for surface water. These observations highlight the need for continued monitoring and management of water resources to ensure their sustainability and quality amidst changing land use dynamics and potential impacts on hydrological processes. Overall, the findings underscore the interconnectedness of land use, hydrology, and water quality, emphasizing the importance of integrated approaches to land and water management for the long-term health of river ecosystems and water availability in the surveyed region.

Lack of Awareness about Regulations and Government Agencies with regards to the rules and regulations relating to water in the watershed, post a hindrance in complying with regulations and effective governance of water resources, potentially leading to unsustainable water use practices and conflicts over water allocation. The diverse attitudes toward appropriate water use in the watershed highlight the complexity of managing water resources. While some express favourable attitudes, emphasizing the importance of responsible water use for community well-being and environmental sustainability, others hold unfavourable views, citing concerns such as water scarcity, pollution, and conflicts over access. The low participation rate in community water associations suggests a need for increased community involvement in water management initiatives. These associations play a crucial role in mobilizing communities, promoting collective action, and implementing sustainable water management practices. The lack of coordination in water resource management and the perceived non-compliance with existing water rules by some respondents indicate challenges in governance and regulation. Strengthening coordination mechanisms, enhancing public awareness, and enforcing regulations are essential for promoting sustainable water use and minimizing conflicts.

Strategies for coping with the impacts of climate change, such as reforestation, protection initiatives, and rational water use have been shown to be essential avenues for enhancing the resilience of water resources in the face of changing climatic conditions (Xu et al., 2021; Shen et al., 2022). However, addressing climate change impacts requires concerted efforts from various stakeholders and effective implementation of adaptation measures.

The recommendations for sustainable management of the basin's water resources include reducing water waste, increasing awareness, improving infrastructure, involving local communities, and ensuring transparency and accountability in water governance. These solutions underscore the importance of holistic and participatory approaches to water management.

## 5. Conclusions

Bridging the gap between scientific research and community needs is essential for sustainable water resource management. Demographically, respondents perceive population growth driven by high birth rates and migration, with groundwater favoured over surface water, potentially leading to overexploitation concerns. Socioeconomic activities primarily revolve around crop & livestock farming, fishing, and trade, with traditional methods prevalent but some adoption of modern tools is observed. Climate change effects are perceived, including decreased rainfall and land use alterations, which impact hydrological processes such as runoff, infiltration, and streamflow. Water management awareness is low among respondents, with diverse attitudes toward water use and challenges in compliance with existing water rules. Recommendations for sustainable water management included enhancing awareness, implementing water-saving practices, and fostering stakeholder consultation processes to prevent conflicts and overexploitation. These findings collectively confirm the importance of inclusive approaches to address water resource challenges, considering that each river basin has its own physical, social, environmental, and economic characteristics in addition to being at a particular development level (Melland et al., 2014). Overall, addressing awareness gaps and promoting collaboration among stakeholders, especially the marginalised or vulnerable groups during decision-making are crucial

Action-wise, initiatives should prioritize raising community awareness about water rules and regulations, fostering collaboration, and implementing sustainable water management practices such as improving the water retention capacities of soils, water reuse, and water conservation. This could involve developing targeted education programs, establishing community-based water management committees, and strengthening enforcement mechanisms to ensure compliance with water rules and regulations. Additionally, investing in infrastructure projects such as dam construction and reforestation efforts can help mitigate adverse effects of climate change and land use alterations on hydrological processes. Ultimately, a comprehensive approach integrating scientific research, community engagement, and policy implementation will be crucial for achieving sustainable basin water management in the surveyed region to ensure the long-term sustainability of this precious resource for livelihoods, economic growth, and future use.

## Chapter 7: Impact of Climate Variability and Land Use Change on Streamflow

This chapter presents the results of the streamflow simulation analysis conducted using the SWAT model. The findings include: (i) calibration and validation of the SWAT model, (ii) assessment of streamflow under various climate variability scenarios, (iii) evaluation of streamflow changes due to different land use scenarios, and (iv) analysis of the combined impact of climate variability and land use changes on streamflow in the continental Gambia River Basin.

### 7.1 Sensitivity Analysis, Calibration, and Assessment of SWAT Model Performance

A total of 16 parameters were chosen and listed along with their final calibrated values for the streamflow simulation using the SWAT model (Table 15). Soil conductivity (SOL_K), SCS runoff curve number (CN2), Soil available water storage capacity (SOL_AWC), Threshold depth in shallow aquifer for re-evaporation (REVAPMN), and groundwater revap coefficient (GW_REVAP) were identified as the most sensitive parameters for the Continental Gambia River Basin.

The observed vs simulated streamflow for the SWAT model calibration (1990-2010) and validation (2011-2022) period is shown in Figures 65 & 66. The values for $R^2$ and NSE during the calibration period were 0.81 and 0.80, respectively, while for the validation period, they were 0.80 and 0.78, respectively. The PBIAS values were -9.7% and 9.1% during the calibration and validation periods, indicating overestimation and underestimation of streamflow, respectively. The resulting statistics for the SWAT model on the CGRB can be considered good because, according to Moriasi et al. (2007), for streamflow simulation, a model is generally considered satisfactory if NSE is greater than 0.50, RSR is less than 0.70, and PBIAS is within 25%.

Importantly, the observed streamflow series exhibits a significant upward trend, particularly after 2010 (see Chapter 4, Figures 15 & 16). This trend corresponds to a documented post-2008 recovery in rainfall and increased frequency of high-intensity events in the basin, resulting in a non-stationary flow regime. Consequently, the calibration period represents predominantly drier to transitional conditions, while the validation period reflects a wetter regime. This hydroclimatic shift explains the model’s slight underestimation during validation, as parameter sets optimized under drier conditions can somewhat dampen higher flows. Nevertheless, the SWAT model reproduced streamflow dynamics well across both regimes, demonstrating its robustness and supporting the conclusion that climate variability, particularly post-2008 increases in rainfall, plays a dominant role in shaping streamflow responses in the CGRB.

*Table 16: Sensitive Parameters for Streamflow Calibration in the CGRB*

| Parameter Name | Definition | Calibrated range | t-Stat | P-Value |
|---|---|---|---|---|
| **r_CN2.mgt** | SCS runoff curve number | -0.67 to -0.56 | 6.32 | $1\times 10^{-9}$ |

| | | | | |
|---|---|---|---|---|
| **r_SURLAG.bsn** | Surface runoff lag coefficient [days] | 3.73 to 3.92 | -1.12 | 0.27 |
| **r_ESCO.bsn** | Soil evaporation compensation factor | -0.15 to -0.03 | -0.57 | 0.57 |
| **r_EPCO.hru** | plant uptake compensation factor | 0.57 to 0.68 | 0.20 | 0.84 |
| **r_SOL_AWC.sol** | Soil available water storage capacity | 1.06 to 1.28 | 3.71 | $2.32 \times 10^{-4}$ |
| **r_SOL_K.sol** | Soil conductivity | -0.96 to -0.81 | -207.84 | 0.00 |
| **v_ALPHA_BF.gw** | Base flow alpha factor | 0.20 to 0.25 | 1.17 | 0.24 |
| **r_GW_DELAY.gw** | Groundwater delay time | 51.32 to 59.77 | 0.11 | 0.91 |
| **r_GWQMN.gw** | Threshold depth of water in shallow aquifer for return flow to occur | 412.46 to 679.14 | 0.37 | 0.71 |
| **r_CH_N2.rte** | Manning's n value for main channel | 0.03 to 0.03 | 1.26 | 0.21 |
| **r_GW_REVAP.gw** | Groundwater revap. Coefficient | 0.03 to 0.09 | 2.30 | $2.19 \times 10^{-2}$ |
| **r_RCHRG_DP.gw** | Deep aquifer percolation fraction | 0.40 to 0.65 | 0.70 | 0.48 |
| **a_CH_K2.rte** | Effective hydraulic conductivity in the main channel | 613.21 to 834.16 | -0.11 | 0.92 |
| **r_CANMX.hru** | Maximum canopy storage | 3.29 to 4.83 | 0.57 | 0.57 |
| **r_REVAPMN.gw** | Threshold depth in shallow aquifer for re-evaporation | 34.23 to 200.72 | -2.66 | $8.05 \times 10^{-4}$ |

| | | | | |
|---|---|---|---|---|
| **r_SOL_CRK.sol** | Potential or maximum crack volume of the soil profile | -0.28 to -0.03 | 1.34 | 0.18 |

a) b)

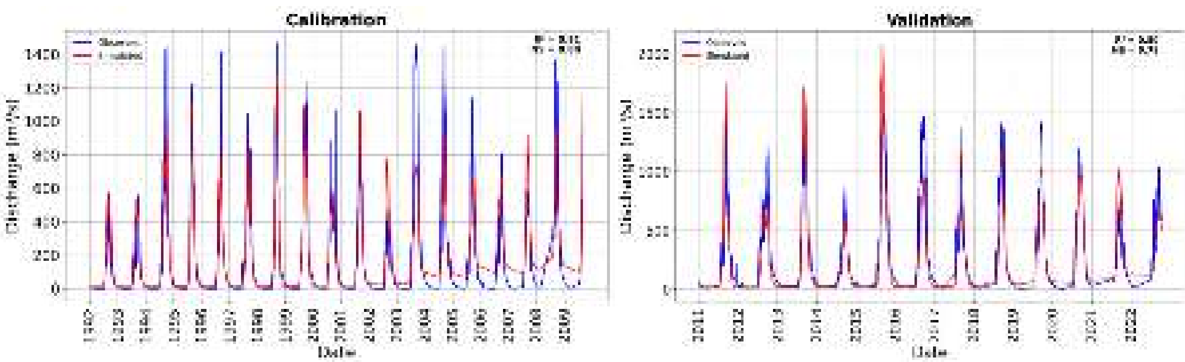


*Figure 65: Calibration (a) and Validation of the SWAT Model in the CGRB*

### 7.2 Mean Annual and Monthly Water Balance Components Analysis

The average annual water balance components simulated by the SWAT model for the Continental Gambia River Basin are summarized in Figure 67a. During the simulation period, the mean annual precipitation was 996.8 mm, of which 611.7 mm (61.4%) was lost through actual evapotranspiration (ET). The basin's potential evapotranspiration (PET) was considerably higher, simulated at 1880.8 mm.

The total simulated water yield (WYLD) was 180.1 mm, accounting for 18.1% of the annual precipitation. Within this, surface runoff (SURQ) contributed 46.6 mm (4.7%), lateral flow (LATQ) was minimal at 0.86 mm (0.1%), while groundwater contribution to streamflow (GWQ) was dominant at 106.8 mm (10.7%) from the shallow aquifer and 25.8 mm (2.6%) from the deep aquifer. Total aquifer recharge (including both shallow and deep aquifers) was 329.1 mm, while percolation from the soil profile totalled 347.0 mm.

Recharge to the deep aquifer alone was estimated at 26.1 mm (2.6%), while 39.8 mm was lost via re-evaporation from the shallow aquifer. These results indicate that a substantial portion of rainfall infiltrates and contributes to subsurface storage before gradually feeding baseflow, a typical behaviour in semi-humid tropical environments with pronounced wet and dry seasons.

The seasonal distribution of monthly components further illustrates this hydrological pattern (Figure 67b). Rainfall begins to increase in May, peaks between July and September, and declines sharply by October. Notably, August records the highest rainfall (303.1 mm) and the highest surface runoff (24.3 mm), as well as the peak in water yield (34.3 mm), aligning with the seasonal flood period. ET also peaks during the rainy season, with monthly values exceeding 90 mm in July through September.

During the dry season (November to April), rainfall is negligible (<5 mm/month), but ET remains significant, exceeding rainfall in all months except July–September. This causes early rainfall to be absorbed mainly by soil moisture replenishment and ET, with little to no surface runoff simulated until June. Surface runoff becomes pronounced only after sufficient soil saturation, peaking in August. Water yield extends into November and December due to the delayed contribution of groundwater baseflow, underscoring the important role of subsurface storage in sustaining streamflow during the transition to the dry season.

These results are consistent with other studies in the region, which report high proportions of ET (typically 60–75% of rainfall), moderate baseflow contributions, and limited lateral flow in similar Sudano-Sahelian environments (Tobella, 2016; Hector et al., 2018; Mahamat Nour et al., 2021). The strong baseflow component and significant aquifer recharge emphasize the importance of groundwater in sustaining dry-season flows in the Continental Gambia River Basin.

a) b)

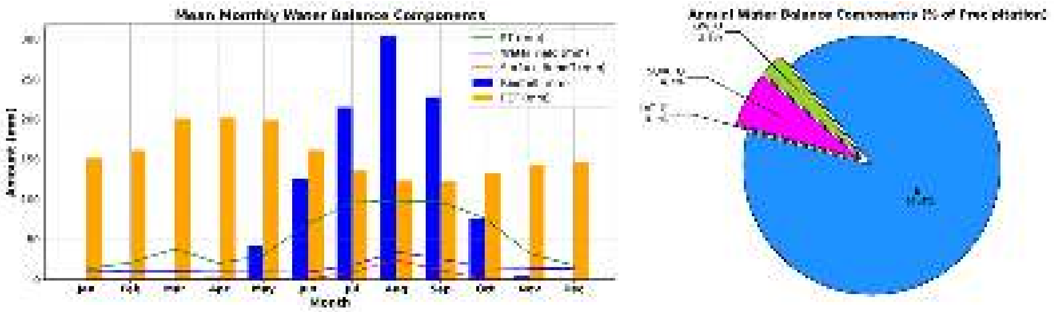


*Figure 66:* Water Balance Components for the CGRB at (a) Monthly (b) Annual Scale as a Proportion of Rainfall

### 7.3 Assessing the Impact of Land Use Change and Climate Variability on Streamflow

Climate variability and changes in land use/land cover (LULC) are key drivers influencing hydrological responses (Berihun et al., 2019; Nyatuame et al., 2020). To evaluate the impact of these factors, the calibrated SWAT model was run for nine different scenarios spanning the period from 1990 to 2022. These scenarios were created by combining three LULC datasets (1988, 2002, and 2022) with three climate periods (1990–2000, 2001–2011, and 2012–2022) summarised in Table 16. The first scenario (S1: 1988 LULC, 1990–2000 climate) served as the baseline, representing the earliest period's climate and LULC conditions. To isolate the impact of LULC changes, scenarios S2 (2002 LULC, 1990–2000 climate) and S3 (2022 LULC, 1990–

2000 climate) were compared against S1 while keeping climate conditions constant. Similarly, climate variability effects were analysed by comparing scenarios with the same LULC but different climate periods, such as S1 vs. S4 (1988 LULC, 1990–2000 vs. 2001–2011 climate) and S1 vs. S7 (1988 LULC, 1990–2000 vs. 2012–2022 climate). The combined effects of LULC and climate change were assessed by comparing scenarios where both factors varied, such as S1 vs. S9 (1988 → 2022 LULC, 1990–2000 → 2012–2022 climate) and S2 vs. S9 (2002 → 2022 LULC, 1990–2000 → 2012–2022 climate). This approach, covering a time span of over 30 years (1990–2022), allowed for the quantification of the individual and combined contributions of LULC change and climate variability to hydrological changes in the watershed.

*Table 17: Summary of Scenarios Used to Assess the Impacts of Climate Variability and Land Use/ Land Cover Changes on Streamflow*

| Scenario | LULC Year | Climate Period | Purpose |
|---|---|---|---|
| **S1** | 1988 | 1990–2000 | Baseline for first period |
| **S2** | 2002 | 1990–2000 | Isolate LULC change from 1988 to 2002 (no climate change) |
| **S3** | 2022 | 1990–2000 | Isolate LULC change from 1988 to 2022 (no climate change) |
| **S4** | 1988 | 2001–2011 | Isolate climate variability from 1990–2000 to 2001–2011 (no LULC change) |
| **S5** | 2002 | 2001–2011 | Combined LULC (1988 to 2002) and climate change (1990–2000 to 2001–2011) |
| **S6** | 2022 | 2001–2011 | Combined LULC (1988 to 2022) and climate change (1990–2000 to 2001–2011) |
| **S7** | 1988 | 2012–2022 | Isolate climate variability from 1990–2000 to 2012–2022 (no LULC change) |
| **S8** | 2002 | 2012–2022 | Combined LULC (1988 to 2002) and climate change (1990–2000 to 2012–2022) |
| **S9** | 2022 | 2012–2022 | Combined LULC (1988 to 2022) and climate change (1990–2000 to 2012–2022) |

### 7.4 Annual Hydrological Components across Scenarios

The annual mean hydrological fluxes simulated by the SWAT model under the nine climate–LULC scenario combinations are presented in Figure 67. The variables include precipitation, streamflow, surface runoff (SURF_Q), lateral flow (LAT_Q), evapotranspiration (ET), and groundwater discharge (GW_Q). All hydrological components are expressed in millimetres per year (mm/a) to allow direct comparison across scenarios. Hydrological responses remain relatively stable across scenarios S1–S6, with minor variations in streamflow and other flow components despite changes in land use. In contrast, scenarios S7–S9 exhibit a pronounced increase in streamflow and runoff components, coinciding with higher precipitation. Streamflow increases by more than 70%, accompanied by higher surface runoff, lateral flow, and groundwater contributions, while evapotranspiration shows only modest variations.

The annual mean simulated hydrological variables by SWAT under varying land use and climate conditions are presented in Table 17. The comparison of hydrological effects across all nine hypothetical scenarios was based on the simulated results, rather than measured data.

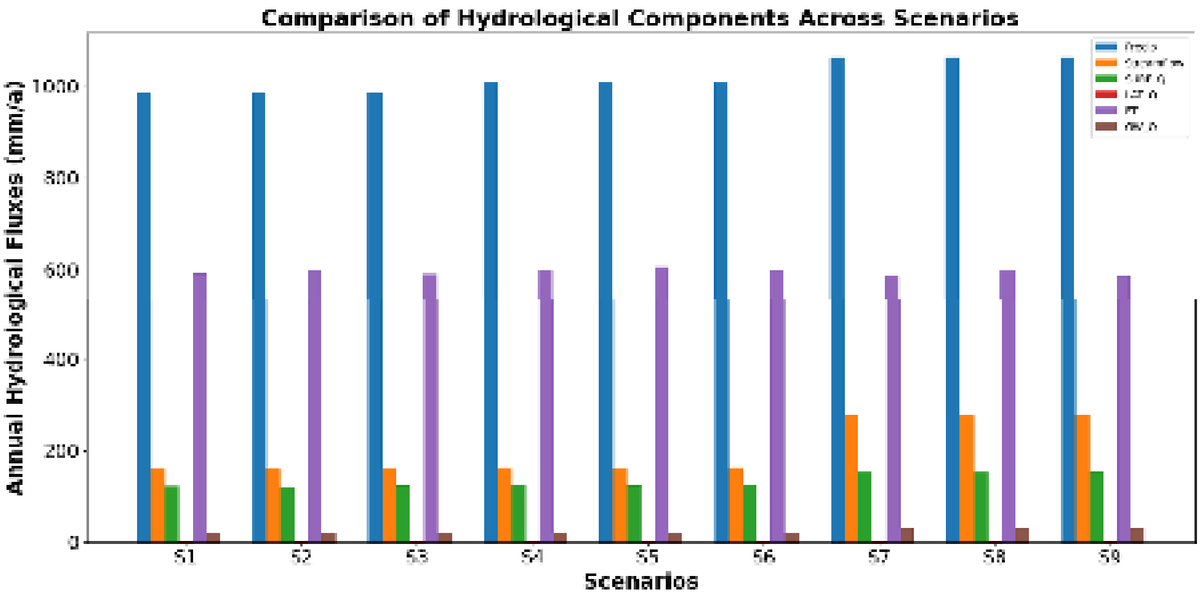


*Figure 67: Annual Simulated Hydrological Processes in the CGRB*

### 7.5 Land Use Change Effects on Hydrological Processes

The comparison of scenarios S1 vs S2 and S1 vs S3 highlights the hydrological impacts of land use changes between 1988–2002 and 1988–2022, respectively, under the same climate conditions (1990–2000). For S1 vs S2 (1988 to 2002), the slight decrease in streamflow (-0.44%) and surface runoff (-0.87%) can be attributed to the reduction in forest cover (-6.66%) and savanna (-2.8%). The significant increase in bowe & steppe (+8.64%) and burn areas (+1.47%) altered soil properties, reducing lateral flow (-1.99%). It has been documented in several studies that burn areas can lead to hydrological changes due to reduced vegetation cover and soil degradation. While these conditions may initially cause increases in peak streamflow as a result of enhanced infiltration-excess runoff (Shakesby and Doerr, 2006), the loss of vegetation and litter cover can alter runoff production over time (Cerdà and Doerr, 2005). Additionally, the formation of water-repellent soils (Debano, 2000) can affect both surface and subsurface flow, potentially influencing overall streamflow patterns. Interestingly, evapotranspiration (ET) increased by 1.06% and groundwater contribution (GW_Q) decreased by 1.33%, likely due to reduced infiltration from the decline in forested areas, which are key to groundwater recharge.

For S1 vs S3 (1988 to 2022), streamflow increased slightly (0.29%) along with surface runoff (0.72%). These changes likely result from shifts in land cover. The recovery of forest cover (+3.91%) typically enhances infiltration due to improved soil structure, but the sharp decline in savanna (-8.85%) and the expansion of bowe & steppe (+6.9%) appear to have counteracted this effect. The spread of bowe, characterized by impermeable laterite outcrops that restrict root penetration, likely reduced infiltration capacity and promoted surface runoff. Lateral flow decreased (-1.32%), probably due to the reduced subsurface water movement caused by the impermeable nature of bowe areas, which limit water percolation and horizontal flow. Evapotranspiration (ET) decreased slightly (-0.32%), possibly because of vegetation shifts. While reduced burn areas (-1.8%) may have encouraged regrowth that typically increases ET, this effect may have been offset by the expansion of bowe & steppe, which, with sparse vegetation and shallow rooting systems, likely has lower water use efficiency compared to denser savanna or forest areas. Overall, land use shifts from 1988 to 2022 seem to have reversed some hydrological trends observed from 1988 to 2002, with forest recovery playing a key role in increasing streamflow and groundwater recharge.

The comparison of scenarios S4 vs S5 and S4 vs S6 highlights the hydrological impacts of land use changes between 1988–2002 and 1988–2022, respectively, under the same climate conditions from 2001- 2011.

For S4 vs S5 (1988 to 2002), streamflow decreased slightly (-0.52%), along with surface runoff (-0.86%) and lateral flow (-2.61%). These reductions are likely linked to land cover changes, including a decline in forest cover and savanna areas, which typically reduce transpiration and interception, leading to higher runoff. The decrease in runoff can also be attributed to the expansion of bowe & steppe (+8.64%). Bowe areas, with impermeable laterite layers, reduce subsurface water infiltration, potentially limiting lateral flow and affecting overall hydrological connectivity. The significant decline in lateral flow (-2.61%) supports this, as the impermeable nature of bowe restricts subsurface movement. Evapotranspiration (ET) increased (1.18%), possibly due to the reduction in agricultural & bare land (-0.9%), which was likely replaced by vegetation types with higher water demand. Groundwater contribution to streamflow (GW_Q) decreased (-1.29%), likely reflecting reduced infiltration rates associated with bowe expansion.

For S4 vs S6, streamflow showed a slight increase (0.15%) alongside surface runoff (0.56%). This suggests a shift in hydrological responses compared to the earlier period (S4 vs S5). The increase may be driven by forest cover recovery, which can enhance soil structure and promote infiltration, partially offsetting the impacts of the decline in savanna areas. However, the continued expansion of bowe & steppe likely contributed to the decrease in lateral flow (-

1.96%) by restricting subsurface water movement due to the impermeable laterite. Evapotranspiration decreased slightly (-0.33%), potentially due to changes in vegetation composition, such as the reduction in savanna and forest areas. Groundwater contribution (GW_Q) increased (1.25%), possibly reflecting improved infiltration in forested areas, compensating for the reduced lateral flow in bowe-dominated regions. Additionally, the decrease in savanna and shift in vegetation types may have reduced root water uptake, allowing more water to recharge groundwater systems.

For S7 vs S8 (1988 to 2002, under the climate period 2012–2022), streamflow decreased by -0.42%, while surface runoff also decreased by -0.78% and lateral flow by -1.76%. This could be due to the combination of the reduction in burn areas and changes in land cover, especially the decline in savanna and the expansion of bowe & steppe. These changes likely reduced water availability through surface runoff and lateral flow, as bowe & steppe areas tend to limit subsurface water movement. Evapotranspiration increased by 1.22%, potentially due to vegetation composition changes with less fire disturbance leading to more stable vegetation and possibly higher transpiration rates. Groundwater discharge (GW_Q) decreased by -0.65%, which could be linked to the changes in vegetation and less water infiltrating the soil due to the impermeable bowe & steppe areas.

For S7 vs S9 (1988 to 2022, under the climate period 2012–2022), trends similar to the scenarios for 1988-2022 are observed with a slight increase in streamflow by 0.14%, and surface runoff by 0.48%. These increases could be attributed to the long-term recovery of forest cover and a slight increase in agricultural area and bare land. Despite the expansion of bowe & steppe, lateral flow decreased by 1.18%. Evapotranspiration decreased by -0.31 and Groundwater discharge also increased slightly by 0.39%.

In conclusion, streamflow generation between 1988-2002 and 1988-2022, show that the recovery of forest cover from 1988-2022 generally enhanced streamflow, with slight increases in surface runoff and water yield. In contrast, the period from 1988-2002 saw a slight decrease in streamflow due to the reduction in forest and savanna cover, alongside the expansion of bowe & steppe, which restricted infiltration and reduced lateral flow. The results are summarised in Table 18.

*Table 18: Effects of Land Use Change on Streamflow under the Same Climate Conditions*

| Scenarios | streamflow | SURF_Q | LAT_Q | ET | GW_Q |
|---|---|---|---|---|---|
| **S1 vs S2** | **-0.4409664** | **-0.871** | **-1.9868** | **1.06455** | **-1.3251** |
| **S1 vs S3** | **0.2856965** | **0.71632** | **-1.3245** | **-0.3211** | **1.13583** |
| **S4 vs S5** | **-0.5244971** | **-0.8586** | **-2.6144** | **1.18294** | **-1.2927** |

| | | | | | |
|---|---|---|---|---|---|
| **S4 vs S6** | **0.1480933** | **0.56448** | **-1.9608** | **-0.3332** | **1.24654** |
| **S7 vs S8** | **-0.4191054** | **-0.7776** | **-1.7647** | **1.22262** | **-0.6506** |
| **S7 vs S9** | **0.1409061** | **0.48357** | **-1.1765** | **-0.3057** | **0.39037** |

These simulated land use change impacts are consistent with local perceptions collected during field surveys, where respondents reported a decline in savanna vegetation, expansion of degraded land surfaces, and reduced water availability reflected in the early drying of wells and watercourses. These observations support the modelled reductions in infiltration and lateral flow associated with the expansion of bowe and steppe areas, while also highlighting the socio-environmental consequences of land degradation at the community level.

### 7.6 Impacts of Climate Variability on Hydrological Processes

The impact of climate variability on hydrological processes is summarized in Table 19. For the comparison of climate variability impacts on streamflow between scenarios S1 vs S4 (1990–2000 vs 2001–2011) and S1 vs S7 (1990–2000 vs 2012–2022), the results suggest significant differences in hydrological responses driven by changes in climate conditions.

In S1 vs S4, streamflow increased slightly by 0.65%, with corresponding increases in surface runoff (2.39%) and lateral flow (1.32%), indicating that climate change between the periods of 1990–2000 and 2001–2011 likely promoted more runoff and enhanced water yield. Groundwater contribution also increased by 2.51%, suggesting that the climate conditions during 2001–2011 improved infiltration and groundwater recharge.

In contrast, for S1 vs S7, streamflow experienced a dramatic increase of 71.90%, with massive increases in surface runoff (24.57%). These results reflect the more extreme climate shifts between the periods, with the increasing trend in rainfall contributing to more runoff and water availability. However, evapotranspiration slightly decreased (-0.49%) and groundwater discharge saw a sharp increase of 45.48%, suggesting that the higher runoff and altered water dynamics led to increased groundwater recharge.

In the comparison between S2 and S5, streamflow showed a slight increase of 0.57%, while surface runoff experienced a rise of 2.40%. This suggests that the shift from 1990–2000 to 2001–2011 brought changes in precipitation patterns or intensity, increasing runoff and water availability. Evapotranspiration also increased by 1.54%, potentially due to increased vegetation cover or changes in temperature that boosted water demand. Groundwater contribution (GW_Q) also rose by 2.54%, likely due to enhanced infiltration resulting from the changes in precipitation and land use.

In S2 vs S8, the impacts of climate variability were much more pronounced, with streamflow increasing dramatically by 71.94%, along with substantial increases in surface runoff (24.68%).

These sharp increases suggest that the 2012–2022 period experienced extreme climatic changes, possibly linked to more intense rainfall events or changes in the seasonal distribution of precipitation. Although evapotranspiration decreased slightly (-0.33%), groundwater discharge showed a significant increase of 46.47%. suggesting that excess surface runoff during this period contributed to substantial groundwater recharge. This large increase in groundwater contribution suggests that more water was available for recharge, likely due to the excess surface runoff that increased groundwater infiltration.

In the comparison between S3 and S6, streamflow increased by 0.51%, accompanied by a 2.23% rise in surface runoff. These trends indicate that the shift from the 1990–2000 period to the 2001–2011 period brought a slight enhancement in precipitation contributing to more runoff and water availability. Evapotranspiration (ET) increased by 1.41%, suggesting that vegetation demand for water was slightly higher during this period, likely due to changes in temperature or vegetation growth. Groundwater contribution (GW_Q) also increased by 2.62%, indicating that the increased runoff and precipitation helped recharge groundwater supplies.

In the comparison between S3 and S9, the changes were significantly more pronounced, with streamflow rising sharply by 71.65% and surface runoff increasing substantially by 24.28%. These sharp increases point to more intense climatic changes between the 1990–2000 and 2012–2022 periods, such as higher rainfall amounts or extreme weather events, which led to significantly higher runoff and water availability. However, evapotranspiration decreased slightly (-0.47%), possibly due to changes in vegetation type or reduced water use efficiency under stress conditions. Groundwater contribution also showed a substantial increase of 44.41%, likely due to more surface water infiltrating and replenishing groundwater resources following the extreme rainfall events.

In conclusion, streamflow changes between the periods 1990–2000 vs 2001–2011 and 1990–2000 vs 2012–2022 reflect the significant influence of climatic factors, particularly changes in precipitation and temperature. Between 1990–2000 and 2001–2011, streamflow showed moderate increases, with enhanced surface runoff and water yield, indicating changes in precipitation patterns or intensity that boosted runoff and water availability. This period saw a slight improvement in groundwater contribution due to increased infiltration.

However, the comparison between 1990–2000 and 2012–2022 reveals much more pronounced changes. Streamflow increased dramatically, accompanied by significant rises in surface runoff and water yield, suggesting extreme climate shifts during the more recent period. These changes were likely driven by higher rainfall intensity, more frequent extreme weather events, and rising temperatures, all of which contributed to higher runoff and greater water availability. This period also saw substantial increases in groundwater recharge, driven by excess surface runoff and improved infiltration.

Overall, the results indicate that the period from 1990–2000 to 2012–2022 experienced more extreme climatic shifts, resulting in a considerable increase in streamflow, runoff, water yield, and groundwater contribution. In contrast, the 2001–2011 period experienced more moderate changes in streamflow and hydrological processes.

*Table 19: Effects of Climate Variability on Streamflow under Constant Land Use Conditions*

| Scenarios | Streamflow | SURF_Q | LAT_Q | ET | GW_Q |
|---|---|---|---|---|---|
| **S1 vs S4** | **0.6521334** | **2.38502** | **1.3245** | **1.4194** | **2.50828** |
| **S1 vs S7** | **71.902366** | **24.5665** | **12.5828** | **-0.49** | **45.4804** |
| **S2 vs S5** | **0.5676856** | **2.39777** | **0.67568** | **1.5382** | **2.54197** |
| **S2 vs S8** | **71.940112** | **24.6839** | **12.8378** | **-0.3344** | **46.4748** |
| **S3 vs S6** | **0.5140274** | **2.23066** | **0.67114** | **1.40702** | **2.6205** |
| **S3 vs S9** | **71.654177** | **24.2787** | **12.7517** | **-0.4747** | **44.408** |

These modelled climate-driven increases in streamflow contrast with local perceptions gathered during field surveys, where the majority of respondents reported decreasing rainfall, shorter rainy seasons, and worsening drought conditions. This apparent discrepancy can be attributed to the high temporal variability of rainfall in the basin, where periods of intense rainfall and increased annual totals may coexist with delayed onset, early cessation, and longer dry spells. Additionally, rising temperatures and increased evapotranspiration may reduce effective water availability, contributing to perceptions of water scarcity despite overall increases in simulated streamflow. These findings highlight the importance of integrating local knowledge to better understand how climatic changes are experienced at the community level.

### 7.7 Combined Effects of Climate Variability and Land Use Change on Hydrological Processes

In the comparison of the combined effects of climate variability and land use change (S1 vs S9, S2 vs S9, and S3 vs S9), the results show significant alterations in streamflow and other hydrological processes due to the combined impacts of both factors. The results are summarised in Table 20.

In the comparison between S1 and S9 (1988 land use vs 2022 land use under the 2012–2022 climate), streamflow increased significantly by 72.14%, while surface runoff also showed a substantial rise of 25.17%. These changes highlight the compounding effect of both land use shifts, such as forest recovery and expansion of bowe & steppe, and the more extreme climate conditions during the 2012–2022 period, which together resulted in much higher runoff and water availability. Evapotranspiration (ET) decreased by -0.79%, likely due to changes in vegetation composition areas and shifts in vegetation types leading to lower overall water use. Groundwater contribution (GW_Q) increased dramatically by 46.05%, suggesting that the combination of increased runoff and soil changes (such as improved infiltration from forest recovery) facilitated greater groundwater recharge.

In the comparison between S2 and S9 (2002 land use vs 2022 land use under the 2012–2022 climate), streamflow increased significantly by 72.91%, with surface runoff showing further growth of 26.27%. The combination of land use changes, including a decline in savanna and the spread of bowe & steppe, with the more extreme climate conditions in 2012–2022, amplified the runoff and water yield. Evapotranspiration decreased by -1.84%, and groundwater contribution (GW_Q) also saw a significant increase of 48.01%, pointing to improved groundwater recharge from increased precipitation and surface runoff.

For **S3 vs S9** (2022 land use under 2012-2022 climate), streamflow increased by 71.65%, with surface runoff rising by 24.28%, following similar upward trends. While land use changes in 2022, including forest recovery and the continued expansion of bowe & steppe, contributed to the increase in runoff, the more intense climate conditions during 2012–2022 were the primary drivers of the observed changes in streamflow. Evapotranspiration slightly decreased by -0.47%, which could be attributed to changes in vegetation cover. Groundwater contribution also increased by 44.41%, indicating that the changes in both land use and climate helped enhance groundwater recharge, even as lateral flow was likely reduced due to the dominance of bowe areas.

In summary, the combined effects of climate variability and land use change resulted in substantial increases in streamflow across all scenarios from 1988 to 2022. In the comparison between S1 and S9, streamflow increased by 72.14%, driven by both land use changes, such as forest recovery and the expansion of bowe & steppe, as well as the more extreme climate conditions of 2012–2022. Similarly, in S2 vs S9, streamflow rose by 72.91%, with increased runoff further amplified by these combined factors. The changes in S3 vs S9 also show a 71.65% increase in streamflow, where climate conditions were the dominant driver, although land use changes still played a role. In all three comparisons, significant increases in groundwater contribution were observed, highlighting the enhanced recharge facilitated by the combined land use shifts and extreme climate conditions.

*Table 20: Combined Effects of Climate Variability and Land Use Change on Streamflow*

| **Scenarios** | **Streamflow** | **SURF_Q** | **LAT_Q** | **ET** | **GW_Q** |
|---|---|---|---|---|---|
| **S1 vs S9** | **72.1446** | **25.1689** | **11.2583** | **-0.7942** | **46.0483** |
| **S2 vs S9** | **72.907** | **26.2687** | **13.5135** | **-1.8392** | **48.0096** |
| **S3 vs S9** | **71.6542** | **24.2787** | **12.7517** | **-0.4747** | **44.408** |

In summary, in the analysis of streamflow changes, both climate variability and land use changes have had significant impacts, but climate variability appears to be the dominant driver, especially in the most recent periods (2012–2022).

For the period from 1988 to 2002, land use changes, particularly the reduction in forest and savanna cover and the expansion of bowe & steppe, led to a slight decrease in streamflow and surface runoff. These land use shifts reduced infiltration and lateral flow, with a corresponding decrease in groundwater contribution. However, the period from 1988 to 2022 shows the recovery of forest cover, which helped enhance streamflow and groundwater recharge despite the spread of bowe & steppe.

When comparing the effects of climate variability, the results indicate that climate changes between 1990–2000 and 2012–2022 had a far more pronounced impact on streamflow, with dramatic increases in streamflow, surface runoff, water yield, and groundwater contribution. The extreme shifts in climate during 2012–2022, characterized by higher rainfall and more intense weather events, drove these increases, as more water was available for surface runoff and groundwater recharge. These climate changes outweighed the effects of land use changes in the most recent periods.

The combined effects of land use changes and climate variability further amplify the impacts. In scenarios comparing 1988, 2002, and 2022 land use under the 2012–2022 climate, the increases in streamflow, runoff, and groundwater recharge were substantial, highlighting the combined effect of land use shifts (like forest recovery and the spread of bowe & steppe) and the extreme climatic conditions of the most recent period. However, evapotranspiration generally decreased, possibly due to shifts in vegetation composition and less frequent burning, which reduced water use by vegetation. In conclusion, while land use changes played a role in shaping hydrological processes, the most significant driver of the observed increases in streamflow was climate variability.

To provide a clearer visual comparison of the hydrological responses across all scenarios, Figure 68 summarises the percentage changes associated with land-use effects, climate variability effects, and their combined impacts, as presented in Tables 13–15.

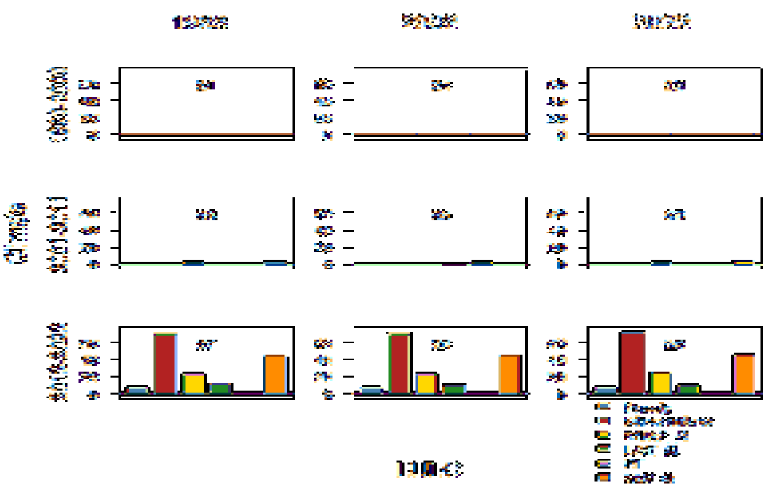

*Figure 68: Summary of Hydrological Responses Showing the Isolated and Combined Effects of Land Use Change and Climate Variability, Based on Results from Tables 13–15*

### 7.8 Discussion

The relative impacts of land use changes and climate variability on streamflow over three distinct climate periods (1990–2000, 2001–2011, and 2012–2022) using different land use/land cover (LULC) datasets from 1988, 2002, and 2022 were analysed. The results of this study underscore the significant influence of both climate variability and land use changes on hydrological processes.

Climate variability played a dominant role in shaping hydrological responses, with variations in precipitation and evapotranspiration patterns strongly influencing streamflow dynamics. Results of the analyses reveal that streamflow responses are highly sensitive to variations in climate, consistent with the observations by Roudier et al. (2014), who emphasized the strong correlation between runoff changes and rainfall variability, with potential evapotranspiration playing a secondary role. Our study corroborates this relationship, as significant fluctuations in streamflow were primarily driven by changes in precipitation patterns across the different climate periods. Additionally, the combined effects of land use changes, particularly the expansion of bowe and steppe areas and forest cover alterations, have further modulated hydrological responses, demonstrating that land cover dynamics can either amplify or mitigate climate-induced hydrological changes. The sensitivity of water resource systems to climate variations, as highlighted by NĚmec and Schaake (1982) is evident in our analysis. The comparison of streamflow across the three climate periods (1990–2000, 2001–2011, and 2012–2022) revealed notable fluctuations, which align with observed climatic trends. For instance, streamflow simulations comparing the earliest (1990–2000) and latest (2012–2022) periods showed significant increases in streamflow of more than 70%.

In contrast, land use changes exerted a more localized but still significant impact on streamflow characteristics. The expansion of bowe and steppe and reduction in forest and savanna cover altered infiltration rates, surface runoff, and lateral flow. Between 1988 and 2002, forest cover declined by 6.66%, while savanna decreased by 2.8%, contributing to a slight reduction in both streamflow (-0.44%) and surface runoff (-0.87%). These results suggest that deforestation and land conversion processes have influenced catchment hydrology, primarily by modifying evapotranspiration and water retention capacities. Conversely, between 1988 and 2022, forest cover increased (+3.91%), while savanna declined further (-8.85%), suggesting a complex interaction between land cover recovery and water availability.

The combined effects of climate and land use changes were most evident in Scenarios S1, S2, and S3 compared to S9, where both variables acted synergistically to influence hydrological responses. The results indicate that changes in both climate and land cover led to substantial variations in streamflow, surface runoff (SURF_Q), lateral flow (LAT_Q), evapotranspiration (ET), and groundwater contribution (GW_Q). Specifically, streamflow differences ranged from 71.65 to 72.91%, with corresponding increases in surface runoff (24.28–26.27%) and lateral flow (11.26–13.51%), suggesting that altered land cover conditions influenced water redistribution within the watershed. Additionally, a decrease in ET (-0.79 to -1.84%) indicates possible reductions in vegetation water use, further modifying hydrological dynamics. According to Schilling et al. (2008), higher ET leads to a decline in baseflow and streamflow, while a decrease in ET results in the opposite effect. When ET decreases, less water is lost to the atmosphere via plant transpiration and soil evaporation, allowing more water to remain in the soil and groundwater, which boosts streamflow and baseflow.

These modelled hydrological responses show both consistencies and contrasts with local perceptions reported by communities in the basin. While the SWAT simulations indicate substantial increases in streamflow and groundwater contribution, particularly under the 2012–2022 climate conditions, local respondents widely perceived declining rainfall, reduced water availability, early drying of watercourses, and decreasing groundwater levels. This divergence can be explained by the high intra-seasonal variability of rainfall, where increases in total annual rainfall may coincide with delayed onset, early cessation, and longer dry spells, which are more perceptible to local populations. Additionally, rising temperatures and increased evapotranspiration may reduce effective water availability, reinforcing perceptions of water scarcity despite increases in simulated discharge. Furthermore, land use changes such as the decline in savanna and expansion of bowe and steppe—characterized by low infiltration capacity—may contribute to localized reductions in soil moisture and groundwater accessibility, aligning with community observations. These findings highlight the importance of integrating local knowledge with hydrological modelling to better capture both the physical and experiential dimensions of environmental change.

While climate variability primarily dictated the overall magnitude of these changes, land use modifications played a crucial role in amplifying or mitigating specific hydrological components. The observed increases in surface runoff and lateral flow indicate reduced infiltration and enhanced overland flow, primarily driven by land cover changes such as forest loss, savanna reduction, and the expansion of bowe and steppe. While fires may initially cause short-term increases in peak runoff due to reduced infiltration capacity (Shakesby and Doerr, 2006), prolonged post-fire conditions characterized by vegetation loss and soil degradation can ultimately reduce the total runoff volume and streamflow (Moody et al., 2008; Wine and Cadol, 2016). This is especially true in areas where the recovery of vegetation is slow, limiting evapotranspiration-driven moisture recycling and reducing contributions to both surface and subsurface flow. Conversely, the fluctuations in groundwater contribution (44.41–48.01%) suggest that shifts in recharge mechanisms may be linked to both precipitation variability and land surface changes.

These results align with findings from previous studies in similar semi-arid and tropical regions, where climate fluctuations were identified as the primary driver of hydrological variability, but land use changes played a critical secondary role. For instance, Setyorini et al. (2017) reported that climate variability significantly decreased streamflow in the Upper Brantas Basin, Indonesia, while land use/land cover (LULC) changes increased surface runoff, similar to the observed variations across the three climate periods in this study. Additionally, studies by Nyatuame et al. (2020) and Onyutha et al. (2021) found that land cover transformations, particularly deforestation and agricultural expansion, contributed to increased surface runoff and reduced infiltration, consistent with the observed impacts of forest loss, savanna reduction, and the expansion of bowe and steppe in this study. Furthermore, Shao et al. (2018) found that land use changes in the Hailiutu River Basin, China, led to a decrease in streamflow, whereas climate variability had a more profound effect, highlighting the need to account for both factors in assessing hydrological changes. Moreover, Nyatuame et al. (2020) also noted similar trends in Ghana, where land use change contributed to increased surface runoff and altered water balance, reinforcing the relevance of LULC changes in hydrological dynamics.

The findings of this study underscore the importance of incorporating both climate variability and land use changes into watershed management and water resource planning. The observed fluctuations in streamflow and surface runoff, driven by both climate variability and land use transformations, highlight the need for integrated management approaches that address both environmental and anthropogenic factors.

For watershed management, the results suggest that land use changes, particularly deforestation, agricultural expansion, and the expansion of bowe and steppe areas, can have significant localized effects on hydrological processes such as surface runoff and infiltration. As such, future water resource planning should emphasize land conservation strategies, including forest restoration and sustainable land management practices, to mitigate adverse impacts on hydrological regimes.

From a climate adaptation perspective, the study emphasizes the need for adaptive strategies that account for both short-term climate fluctuations and longer-term land use transformations. This could include measures such as improving watershed resilience through reforestation or optimizing land use to reduce runoff and enhance water retention, which would help maintain a more stable water balance in the face of climate variability.

While the results of this study offer valuable insights into the combined effects of climate variability and land use changes on hydrology, there are several limitations that need to be considered. One significant limitation is the reliance on satellite-derived precipitation and temperature data. Additionally, wind speed, solar radiation, and relative humidity were simulated by SWAT due to the unavailability of observed data, which could introduce uncertainties in the model simulations.

### 7.9 Conclusion

In conclusion, the SWAT model effectively simulated streamflow dynamics in the Continental Gambia River Basin, providing vital insights into the hydrological impacts of land use/land cover (LULC) changes, climate variability, and their combined effects over the period from 1990 to 2022. The model demonstrated satisfactory performance with strong calibration and validation statistics ($R^2 > 0.80$, NSE > 0.78, and PBIAS within acceptable ranges), confirming its reliability for hydrological assessments in the region.

The analysis revealed that LULC changes influenced streamflow and related hydrological processes differently across time periods. Between 1988 and 2002, reductions in forest and savanna cover, coupled with the expansion of bowe & steppe areas, led to slight decreases in streamflow and groundwater recharge due to reduced infiltration and lateral flow. Conversely, from 1988 to 2022, the recovery of forest cover contributed to modest increases in streamflow and groundwater contributions, despite the continued expansion of bowe & steppe.

Climate variability exhibited a more pronounced impact on hydrological processes compared to LULC changes. The period from 1990–2000 to 2001–2011 showed moderate increases in streamflow and runoff, linked to shifts in precipitation patterns. However, the period from 1990–2000 to 2012–2022 experienced dramatic increases in streamflow (over 70%) and groundwater recharge, driven by extreme climate conditions, including higher rainfall intensity and more frequent extreme weather events.

The combined effects of climate variability and LULC changes amplified hydrological responses, with the most significant changes observed when both factors varied simultaneously. The comparison between baseline (S1) and recent scenarios (S9) highlighted substantial increases in streamflow, surface runoff, and groundwater recharge, underscoring the compounding influence of climate extremes and land cover dynamics.

Overall, the study underscores the critical role of both climate variability and LULC changes in shaping hydrological processes in the Continental Gambia River Basin. These findings highlight the importance of integrated watershed management strategies that consider the synergistic effects of land use practices and climate change to ensure sustainable water resource management in the region.

## Chapter 8: General Conclusion

This study presents a comprehensive assessment of hydroclimatic trends, land use changes, and socio-hydrological dynamics in the Continental Gambia River Basin (CGRB) from 1990 to 2022, offering critical insights into the interplay between environmental variability and human dimensions of water resource management.

The biophysical analysis reveals a statistically significant increase in annual precipitation around 2008, marking the end of a predominantly dry period and aligning with a regional Sahelian rainfall recovery. The shift, confirmed by both the Modified Mann-Kendall test and standardized precipitation indices (SPI and SPEI), is attributed to global and regional drivers such as changes in sea surface temperatures, declining aerosol emissions, and strengthening of the West African monsoon. Streamflow, particularly at the Simenti gauge, responded with increased flow, although with a noticeable lag due to hydrological buffering processes such as soil moisture replenishment and baseflow contributions.

Concurrently, the region experienced a steady rise in average temperatures, amplifying potential evapotranspiration and placing added stress on water resources and ecosystems. Land use and land cover changed substantially over the 34-year period. From 1988 to 2002, the basin saw widespread deforestation, savanna degradation, and agricultural expansion—mainly driven by human activities such as wood harvesting, burning, and land clearing during a period of rainfall deficit. In contrast, the 2002–2022 period saw partial vegetation recovery, especially in the southern zones, alongside forest regrowth, reduction in burn areas, and stabilization of land cover patterns, reflecting improved climatic conditions, conservation efforts, and land abandonment. However, challenges remain: the expansion of agricultural areas, built-up zones, and bowe and steppe areas indicates ongoing pressure on land and water resources, especially in the context of reduced water bodies.

Hydrological modelling using SWAT further reveals that climate variability exerts a stronger influence on streamflow than land use change, particularly in the most recent period (2012–2022), which experienced dramatic increases in streamflow (up to +72%), surface runoff (up to +26%), and groundwater contribution (over +44%), driven by more intense rainfall and shifting precipitation patterns. In contrast, land use changes between 1988 and 2002, marked by forest and savanna decline, resulted in a slight reduction in streamflow and lateral flow, whereas forest recovery by 2022 contributed to modest increases in water yield and groundwater recharge. The combined effect of land use and climate change amplified hydrological responses, highlighting the need to address both factors in water resource planning.

Socioeconomic and perceptual data complement these findings, offering local perceptions on how climate variability, land changes, and demographic pressures affect water use and availability. Communities widely recognize population growth, driven by both birth rates and migration, as a central driver of water stress. Farming remains the dominant livelihood and water-consuming activity, followed by livestock rearing and fishing. Groundwater is the preferred source of water for both domestic and productive uses, raising concerns about potential overexploitation of aquifers, particularly as drought periods intensify.

Nearly half of respondents perceive water availability as insufficient, and many report declining agricultural productivity due to water scarcity, rural exodus, and a lack of modern farming equipment. Livestock and fishing activities are also reported to be in decline, largely due to water shortages, pasture loss, and lower fish abundance. Climatic changes, such as shortened rainy seasons, rising temperatures, and altered rainfall patterns, are widely acknowledged and seen to have tangible effects on surface water flows and ecosystem stability. Statistical analysis further confirms that land use changes ($p = 0.000$) significantly influence hydrology, whereas climate change perceptions ($p = 0.9992$) did not show a significant statistical effect, despite strong anecdotal associations.

A key weakness is the limited awareness regarding water governance structures, policies, and rules. This results in low community participation in water management institutions (only 16.47% reported membership in water associations), limited compliance with regulations, and perceptions of weak coordination among stakeholders. However, strong statistical associations between awareness and participation ($p = 0.000$), and between attitudes and compliance ($p = 0.000$), suggest that community education and inclusion could significantly improve water governance outcomes.

Water conflicts, although limited, typically arise during dry seasons and involve competing needs among farmers, herders, and fishermen. Local conflict-resolution mechanisms, coupled with state-led rules, help mitigate such tensions, but more proactive and inclusive water planning is needed.

Despite these challenges, communities are initiating adaptive strategies, ranging from rational water use and infrastructure improvements (dykes, deeper wells) to reforestation and local sensitization campaigns. The population strongly recommends greater involvement of local actors in decision-making, better enforcement of water rules, anti-corruption efforts, and broader awareness-raising initiatives.

The CGRB is undergoing profound hydroclimatic and land cover changes, which intersect with demographic and governance challenges to shape water sustainability. Modelling results highlight the dominant role of climate variability in driving streamflow increases, particularly in recent decades, while also underscoring the modulating effect of land use changes, especially forest recovery and the expansion of bowe & steppe. Addressing these intertwined issues requires integrated, participatory, and knowledge-driven approaches that combine scientific data with local knowledge to foster resilience, equity, and long-term sustainability in water resource management.

**Perceptions or Future Work**

Future work should strengthen both the technical and socio-economic understanding of hydrological change in the CGRB. Improving model accuracy remains a priority. This includes the use of higher-resolution climate datasets and more detailed land use classifications. Extending the analysis to future climate projections and land use scenarios will support long-term planning and water resource sustainability. Field-based validation using observed data such as soil moisture and groundwater levels will reduce model uncertainty and improve reliability. In addition, further investigation of human interventions, including irrigation practices and water extraction, is necessary to better capture their influence on hydrological processes. Advanced tools, including satellite-based assessments and hydrogeological models, should be used to improve understanding of groundwater storage and variability.

Future research should also examine water use patterns and the extent of both surface and groundwater exploitation, along with their impacts on water availability and quality. Greater attention is needed on the socio-economic drivers of population dynamics and their implications for water demand and resource pressure. As population increases, water demand rises, which places additional strain on already stressed systems and increases the risk of scarcity and water quality degradation.

There is also a need to deepen understanding of local water governance structures. Research should examine the roles of traditional institutions and community-based organizations in shaping water management practices. Exploring local knowledge systems will support more inclusive and context-specific strategies, as communities play a central role in protecting water resources on which their survival depends.

Integrating these technical and social dimensions will support the development of adaptive and sustainable water management strategies. Strengthening stakeholder collaboration and aligning scientific research with community realities will improve decision-making and help address the growing challenges of climate variability, land use change, and increasing water demand.

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**Annex : Publication**

1. Kah, M.; Faye, C.; Mbaye, M.L.; Yalo, N.; Gunnar, L. Hydroclimatic Trends and Land Use Changes in the Continental Part of the Gambia River Basin: Implications for Water Resources. Water 2025, 17, 2075. https://doi.org/10.3390/w17142075

Born in New Jeshwang – The Gambia, Matty Kah is a PhD student in Climate Change and Water Resources at the University of Abomey-Calavi (Benin) within the WASCAL program. She is currently an Assistant Lecturer in Environmental Sciences at the University of The Gambia. She holds a BSc in Chemistry (University of The Gambia) and an MSc in Meteorology (Nanjing University of Information Science and Technology, China), where her research focused on the influence of South Tropical Atlantic Sea surface temperatures on West African rainfall. In 2023, she was a Visiting Scholar at the Leibniz Centre for Agricultural Landscape Research (ZALF), Germany. Her research interests include climate change, water resources, hydrology, and remote sensing, with expertise in SWAT, GIS, and statistical analysis.

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***Abstract*:**

This study assessed the impact of climate variability and land use change on streamflow in the Continental Gambia River Basin (CGRB) using the Soil and Water Assessment Tool (SWAT). The study aimed to: (i) analyse hydroclimatic trends (rainfall, temperature, streamflow), (ii) map LULC changes (1988, 2002, 2022), (iii) integrate local perceptions on water use and management, and (iv) evaluate combined climate–land use effects on streamflow. Data included observed and satellite hydroclimatic series and Landsat imagery. Results showed major shifts between 1990–2022: rainfall increased after 2008, temperature rose steadily after 2000, and streamflow increased after 2010. LULC analysis revealed declines in burned areas (–88.8%), water (–55.8%), and savanna (–15.9%), with increases in bowe and steppe (+120%), forest (+12%), and agriculture/bare soil (+10.7%). Forest recovery enhanced infiltration and recharge, while bowe expansion reduced lateral flow. From 1988–2002, streamflow slightly decreased due to forest/savanna loss; from 1988–2022, it increased with forest regrowth, partly offset by bowe expansion. Climate variability had the stronger effect, with streamflow rising up to 72% between 1990–2000 and 2012–2022, driven by wetter conditions and extreme events. Combined climate–land use effects further amplified these responses.

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***Key words:*** land use and land cover, climate variability, SWAT model, Continental Gambia River Basin, water management, hydrological processes

**PhD**

**Aside page**

**Matty KAH**

**IMPACT OF CLIMATE VARIABILITY AND LANDUSE/LANDCOVER CHANGES ON STREAMFLOW IN THE CONTINENTAL GAMBIA RIVER BASIN**

**GRP/CCWR/WASCAL – UAC March, 2026**