A Catchment Information System to Advance Systems-Based Management of Large Tropical River Basins

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Research Article

Keywords: CB-CIS, Digital Hydrological Infrastructure, Information System, Catchment Classification, Systems-Based River Basin Governance, Hydrology Observatory

Posted Date: July 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10182724/v1

Additional Declarations: No competing interests reported.

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Abstract

Large tropical river basins are complex socio-ecological systems whose sustainable management increasingly depends on integrated information infrastructure capable of supporting prediction, planning, and adaptive governance. The Congo River Basin (CRB), the world's second-largest river basin by discharge and area, remains one of the least monitored major hydrological systems despite its global significance for climate regulation, biodiversity conservation, carbon storage, inland navigation, hydropower development, and regional livelihoods. To address persistent information gaps, fragmented monitoring networks, and growing environmental pressures, this paper presents the Congo Basin Catchment Information System (CB-CIS), a digital hydrological infrastructure designed to support systems-based water resources management. CB-CIS integrates catchment classification, hydrological modelling, remote sensing, geospatial databases, socio-economic information, and governance dimensions within a unified hydro-informatic architecture organized around hydrologically meaningful catchments rather than administrative boundaries. The system employs a multi-level nested catchments framework comprising physiographic, socio-economic, and socio-hydrological dimensions, resulting in 403 operational management units and 1740 detailed catchments across the basin. A multidimensional database incorporating 128 variables across seven thematic domains supports analysis, visualization, modelling, and decision-making. Built on interoperable geospatial and database technologies, CB-CIS enhances prediction in ungauged basins, improves monitoring network design, facilitates knowledge transfer across catchments, and strengthens transboundary water governance. This paper demonstrates how digital hydrological infrastructure can transform fragmented observations into actionable knowledge and provides a transferable framework for strengthening integrated water resources management in large, data-scarce tropical river basins worldwide

Key words: CB-CIS; Digital Hydrological Infrastructure; Information System; Catchment Classification; Systems-Based River Basin Governance; Hydrology Observatory

1. Introduction

Large tropical river basins are among the most complex socio-ecological systems on earth. They regulate continental hydrological cycles, sustain globally important biodiversity, support water-energy-ecosystems-food nexus, store vast quantities of carbon, and provide essential ecosystem services to millions of people (Damasco et al., 2025). At the same time, these basins are increasingly exposed to accelerating environmental changes, rapid population growth, infrastructure expansion, climate variability, and competing resource demands (Bila et al., 2026; Wongchuig et al., 2025; Tshimanga et al., 2022a). Managing such systems therefore requires not only hydrological observations, but integrated information infrastructure capable of supporting systems-based understanding, prediction, and decision-making across multiple spatial and temporal scales.

In this context, information has become a strategic resource for water resources governance. Effective management of large river basins increasingly depends on the capacity to collect, integrate, analyse, visualize, and operationalize heterogeneous environmental and socio-economic data into actionable hydrological information systems. However, many tropical basins remain characterized by fragmented monitoring systems, weak institutional coordination, discontinuous observations, and limited analytical integration between hydrology, ecosystems, infrastructure, and governance systems (Papa et al., 2023; Tramblay et al., 2021; Tshimanga et al., 2021). These limitations constrain forecasting capacity, increase uncertainty in planning, and weaken the scientific basis for climate adaptation, disaster risk reduction, ecosystem conservation, navigation management, hydropower development, and transboundary cooperation.

The Congo River Basin (CRB) represents one of the most critical cases of these global challenges. As the world's second-largest river basin by discharge and one of the least monitored major hydrological systems (Laraque et al., 2020), the basin plays a fundamental role in global climate regulation, tropical hydrology, biodiversity conservation, and regional socio-economic development. The basin covers approximately 3.7 million km² across Central Africa, discharges nearly 1,300 billion m³ of water annually into the Atlantic Ocean, and contains the world's second-largest tropical rainforest, extensive wetlands and peatlands, and one of the Africa's largest inland navigation networks (Tshimanga et al., 2026). Yet despite its global importance, the CRB continues to face profound information deficits (Bila et al., 2026; Tshimanga et al., 2022a, Tshimanga et al., 2022b; White et al., 2021; Alsdorf et al., 2016). Since the 1980s, hydrometeorological observation networks have experienced severe deterioration, resulting in fragmented datasets, sparse monitoring coverage, declining hydrometric records, and major uncertainties in hydrological prediction (Tshimanga, 2022). These information gaps are particularly of major concern due to the basin exceptional hydro-climatic and physiographic complexity (Tshimanga et al., 2022b; Tshimanga and Huges, 2014). Hydrological responses in the CRB are strongly influenced by interactions among climate variability, topography, wetlands, floodplains, groundwater systems, peatlands, river-floodplain exchanges, land-use change, and growing human pressures (Tshimanga et al., 2026; Kechnit et al., 2024). Conventional sectoral information systems organized around administrative boundaries or isolated datasets are poorly suited to capture these dynamic interactions and hydrological connectivity across scales.

The challenge is therefore not simply one of data scarcity, but of developing integrated systems capable of transforming fragmented observations into operational knowledge for basin-scale management. In large tropical river basins, effective governance increasingly requires systems-based approaches that recognize river basins as interconnected socio-ecological systems shaped by feedback among environmental processes, infrastructure systems, human activities, and institutional arrangements (Berkes et al. 2001). Such approaches require new forms of digital hydrological infrastructure capable of integrating multi-source observations, remote sensing products, modelling systems, governance indicators, and local knowledge within coherent analytical architectures (Ma et al., 2025)

Prediction in ungauged basins (PUB) further reinforces the need for integrated catchment-based approaches (Hrachowitz et al., 2013). In poorly monitored environments such as the CRB, catchment classification provides an important mechanism for reducing hydrological complexity by organizing landscapes into hydrologically meaningful units that share similar structural and functional characteristics (Tshimanga et al. 2022b). These approaches improve regionalization, strengthen monitoring network design, support knowledge transfer across ungauged areas, and enhance hydrological prediction under conditions of limited observations (Nkaba et al., 2024; Sivakumar et al., 2015).

This paper presents the Congo Basin Catchment Information System (CB-CIS), a water resources information system and knowledge hub infrastructure designed to address these information and governance challenges through a systems-based approach to integrated river basin management. CB-CIS combines catchment classification, hydrological modelling, remote sensing, geospatial databases, socio-economic information, and governance dimensions within an integrated hydro-informatic architecture structured around hydrologically meaningful catchments rather than administrative units. The system seeks to move beyond conventional environmental databases toward an operational framework capable of supporting prediction, planning, environmental assessment, and adaptive water governance in one of the world's most complex tropical river basins.

Furthermore, the paper contributes to the emerging paradigm of systems-based management of large tropical river basins by demonstrating how digital hydrological infrastructure can strengthen integrated water resources management under conditions of environmental complexity, observational scarcity, and institutional fragmentation (Damasco et al., 2025). The paper makes four principal contributions. First, it develops a multi-level catchment classification framework adapted to one of the world's most heterogeneous and poorly monitored basins. Second, it demonstrates how multi-source environmental information can be transformed into an integrated digital hydrological architecture. Third, it expands conventional hydrological information systems by incorporating socio-hydrological and governance dimensions. Finally, it provides a transferable framework for strengthening hydrological information and systems-based water governance in large data-scarce river basins globally.

2. Study Area

A river basin is a hydrologically interconnected system defined by natural drainage boundaries, within which water, energy, sediments, ecosystems, and socio-economic interactions generate benefits that can be shared among stakeholders across spatial and institutional scales. Consequently, basin boundaries are not only hydrological units for water management but also frameworks for benefit sharing, cooperation, and sustainable development (Sadoff and Grey, 2002; Grey and Sadoff, 2007; World Bank, 2009).

The CRB spans approximately 3.7 million km² across nine countries in Central Africa (Figure 1). The Democratic Republic of Congo (DRC) accounts for the largest share of the basin area (62%) and hosts much of its major hydrological infrastructure and ecological systems. The Congo River discharges approximately 1,300 billion m³ of water annually into the Atlantic Ocean, representing nearly 40% of Africa's total freshwater discharge and making it one of the most hydrologically significant river systems globally. Using satellite observations, Tourian et al. (2023) estimated the CRB's Total Drainable Water Storage (TDWS) at approximately 476-502 km³. Storage is highly uneven, with about 63% concentrated in the southern sub-basins, particularly Kasaï (220–228 km³) and Lualaba (109–169 km³). The Kasaï sub-basin alone stores around 43% of the basin's total drainable water, making it the largest water reservoir in the basin. In contrast, the northern sub-basins (Sangha, Oubangui, and Middle Congo) collectively contain about 173 ± 8 km³. The Middle Congo, despite encompassing the Cuvette Centrale, stores only 90 ± 6 km³, reflecting its higher discharge and evapotranspiration. The Lualaba sub-basin contributes roughly 21% of total basin storage, with most of this water concentrated in the Lualaba-South region.

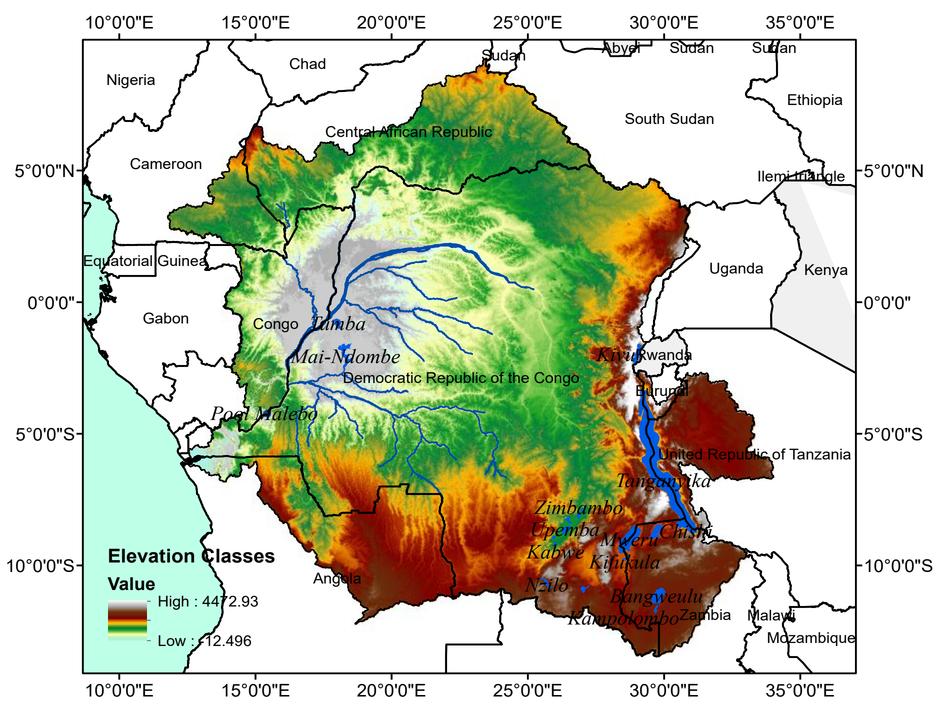

***Figure 1**. Map of the Congo River Basin showing the main physiographic features.*

Geographically, the basin extends approximately between 10°N and 14°S latitude and between 12°E and 34°E longitude. It shares hydrological boundaries with several major African basins, including the Nile Basin to the east, the Lake Chad Basin to the north, and the Zambezi Basin to the south. Its strategic geographic location makes it a critical component of continental hydrological connectivity and regional climate regulation.

2.1 Physiographic features and hydrological complexity

One of the most distinctive features of the CRB is its unique physiographic organization (Runge, 2008; Kadima et al., 2011; Tshimanga, 2012). The basin exhibits an approximately circular morphology centered around the vast low-lying depression of the Cuvette Centrale, which forms the hydrological core of the basin. This central depression is surrounded by elevated plateaus and mountain systems that function as major drainage divides (Kadima et al., 2011). These surrounding uplands include the Atlantic Rise in the west, the northern plateaus, the Mitumba Mountains along the eastern margin, and the Lunda highlands in the south (Figure 1). These topographic formations create a radial drainage configuration in which major tributaries converge toward the main channel of the Congo River (Kitambo et al., 2025). Within the CRB itself, there are tributaries of second and third order which surpass all other African major rivers in terms of their drainage area and discharge (Tshimanga et al., 2026). The principal tributary systems include the Lualaba River in the southeastern basin (970* $10^3 km^2$, 8940 m^3/s) , the Kasai River in the southwestern basin (900* $10^3 km^2$, 11020 m^3/s), the Oubangi River in the northeastern basin (604* $10^3 km^2$, 5320 m^3/s), and the Sangha River in the northwestern basin (220* $10^3 km^2$, 2570 m^3/s), which all meet in the central basin where they form one of the most complex fluvial networks in the world. Figure 2 shows the distribution of these major tributaries.

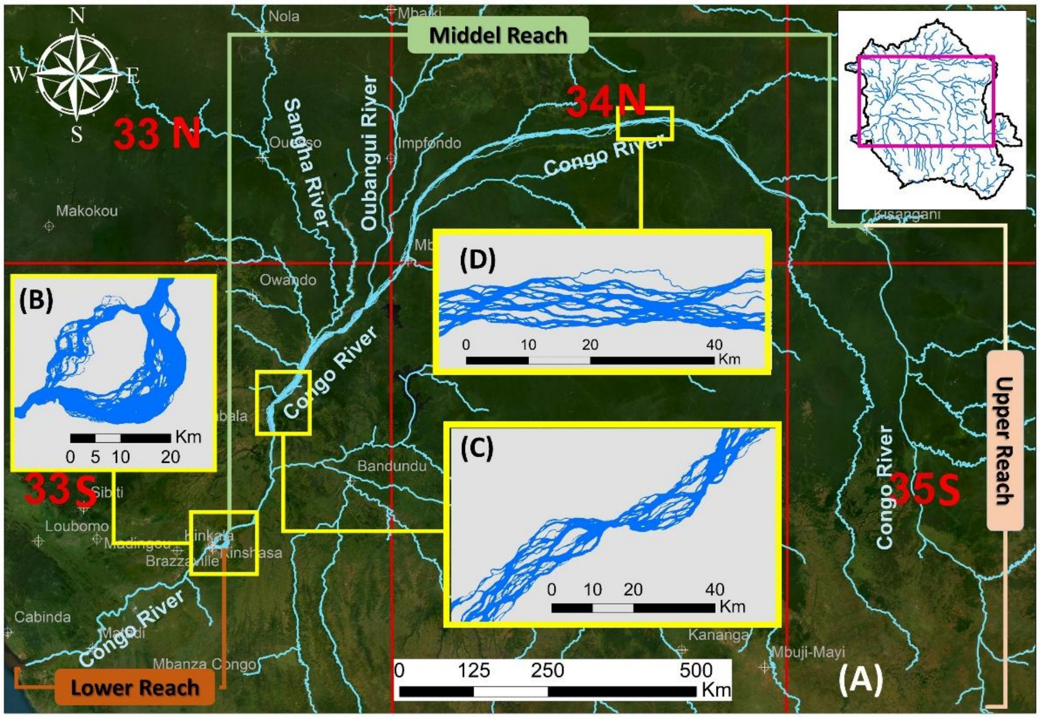

Figure 2. *Overview of the Congo River Reaches, including (A) various reaches, (B) Pool Malebo, (C) the Chenal reach at Tshumbiri, and multithreaded reaches in (D) Lukolela and (E) Bumba*

Another defining hydrological characteristic of the CRB is the presence of extensive internal water storage systems that strongly regulate river discharge dynamics. These include vast wetlands within the Cuvette Centrale, seasonally flooded forests, floodplains, natural lakes, deep groundwater systems, and extensive tropical peatlands (Tshimanga et al. 2026; Dargie et al., 2017; Bwangoy et al., 2011). These storage systems absorb water during high-flow periods and gradually release it during dry seasons, thereby attenuating hydrological extremes and contributing to the unusually stable discharge regime of the Congo River. Wetland-channel connectivity, floodplain storage dynamics, groundwater-river interactions, and peatland hydrology are particularly important processes that remain insufficiently represented in conventional hydrological models (Tshimanga et al., 2026; Tshimanga, 2022). The basin also contains globally significant peatland ecosystems, particularly within the central depression, which play important roles in carbon sequestration, climate regulation, biodiversity conservation, and hydrological buffering (Dargie et al. 2026). These ecosystems have gained increasing international attention due to their implications for global climate mitigation efforts.

2.2 Climate variability

The Congo Basin spans multiple climatic zones, ranging from humid equatorial conditions in the central basin to more seasonal tropical climates along the peripheral margins. Mean annual rainfall varies considerably across the basin due to latitudinal gradients, monsoonal circulation patterns, Atlantic Ocean influences, Indian Ocean teleconnections, and interannual climate variability (Pokam et al., 2026). Rainfall seasonality differs significantly between northern and southern parts of the basin due to the seasonal migration which crosses the equatorial region annually (Nicholson et al., 2022). These climatic contrasts create substantial differences in evapotranspiration rates, groundwater recharge, runoff generation, flood occurrence, and drought vulnerability across sub-basins. Understanding these climatic variations is critical for regional hydrological modelling and climate adaptation planning.

2.3 Ecological significance

The CRB hosts the world's second-largest tropical rainforest after the Amazon Basin and supports globally significant biodiversity. Its terrestrial and aquatic ecosystems provide essential ecosystem services including carbon sequestration, nutrient cycling, sediment regulation, fisheries production, biodiversity conservation, and maintenance of ecological flows. The river system, wetlands, and floodplains support thousands of endemic aquatic species and represent one of the world's most important freshwater ecosystems. However, these ecosystems are increasingly threatened by deforestation, mining expansion, agricultural conversion, urbanization, infrastructure development, and climate change (Bila et al., 2026).

2.4 Socio-economic significance

The CRB supports more than 120 million people whose livelihoods depend directly on water-related ecosystem services. Water resources are central to domestic water supply, agriculture, fisheries, industrial development, and mining activities throughout the region. The basin contains approximately 25,000 km of navigable waterways, making river transportation a crucial infrastructure of regional mobility, trade, and economic integration. This is particularly important in regions where road infrastructure remains limited. The basin also possesses enormous hydropower potential. Earlier feasibility studies estimated more than 40,000 MW of exploitable hydropower potential localised at Inga sites, with further 60000 MW across the basin. This positions the basin as a potentially important contributor to Africa's future energy transition. At the same time, rapid population growth, weak infrastructure systems, institutional fragmentation, and growing competition over natural resources are increasing vulnerability to floods, droughts, pollution, ecosystem degradation, and transboundary tensions.

2.5 Implications for CB-CIS development

The unique combination of vast spatial extent, hydro-climatic heterogeneity, weak monitoring infrastructure, extensive wetlands, high ecological value, major economic potential, and increasing environmental pressures makes the CRB one of the most complex river systems in the world to monitor and manage. These characteristics create substantial challenges for hydrological forecasting, transboundary water governance, infrastructure planning, and climate adaptation. They also highlight the limitations of conventional water information systems that fail to capture hydrological connectivity across landscapes. Therefore, the complexity of the CRB provides the central justification for the development of CB-CIS, which seeks to organize this complexity into hydrologically meaningful units while integrating environmental, socio-economic, and governance dimensions into a unified decision-support framework.

3. Methodological approach

3.1. Conceptual framework

In large tropical basins such as the CRB, hydrological behaviors cannot be adequately understood through river discharge observations alone. This is because the mechanisms of runoff generation, storage dynamics, ecological processes, and human water use are governed by multiple interacting processes operating across spatial and temporal scales. CB-CIS is founded on a systems-thinking framework that conceptualizes river basins as complex socio-ecological systems shaped by dynamic interactions among physical processes, ecosystem functions, human activities, and institutional arrangements (Damasco et al., 2025). This conceptual framing builds on a prior work of catchment classification in the CRB (Tshimanga et al., 2022b), which emphasized the need to understand the relationships between landscape structure, hydrological processes, and functional relationships in highly heterogeneous and poorly monitored environments (Brown et al., 2014). The framework recognizes that increasing physical complexity in the absence of adequate information inevitably increases uncertainty in hydrological prediction and water management (Sivakumar and Singh, 2011). Consequently, CB-CIS seeks to reduce this complexity by organizing the basin space into hydrologically meaningful units that preserve dominant process characteristics while improving prediction and decision-making capacity (Sivakumar et al., 2015).

The framework adopts an **a priori classification approach** (Tshimanga et al., 2022b), in which hydrologically meaningful groups are identified using physical catchment characteristics rather than relying exclusively on streamflow observations, which remain sparse across much of the CRB. This approach is particularly appropriate given the widespread deterioration of hydrometric infrastructure, discontinuous discharge records, and the large number of ungauged sub-basins (Tshimanga, 2022). The classification framework assumes that catchments with similar climatic, physiographic, and ecological characteristics may exhibit similar hydrological responses. The conceptual framework is structured around six interdependent components (Figure 3), which include (i) landscape partitioning and catchment delineation; (ii) characterization of catchment structure; (iii) identification of dominant hydrological processes; (iv) analysis of functional relationships between catchment attributes and hydrological responses; (v) assessment of water resource services; and (vi) incorporation of human disturbances and feedback mechanisms. Together, these components create the scientific foundation for a hydrological information system capable of integrating environmental monitoring, modelling, and governance functions.

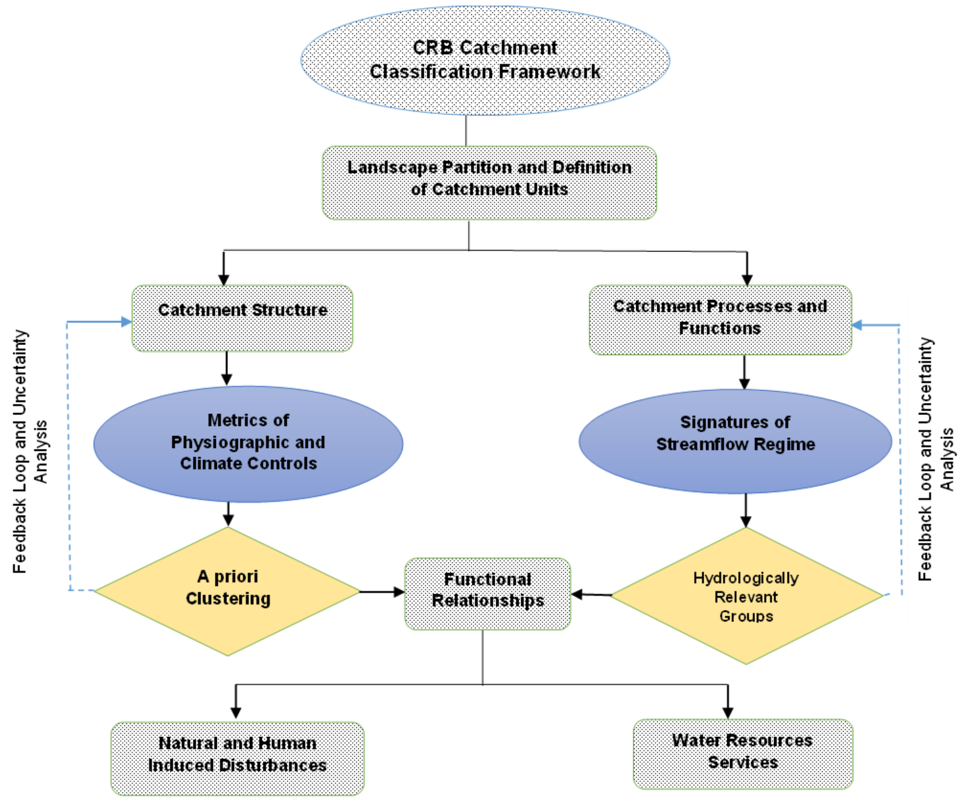

Figure 3. *A conceptual framework of catchment classification for the Congo River Basin*

3.2. Nested catchment hierarchy

Catchment classification constitutes the scientific foundation of CB-CIS. The primary objective is to reduce spatial complexity while preserving dominant hydrological controls and enabling knowledge transfer across ungauged or poorly monitored areas.

Conventional catchment delineation approaches often rely exclusively on topographic boundaries and drainage networks, which may inadequately capture the complex hydrological interactions that characterize large tropical basins with extensive wetlands, floodplains, and socio-economic pressures. To address these limitations, CB-CIS adopts a multi-level catchment delineation framework that integrates physiographic, socio-economic and socio-hydrologic dimensions. The objective is to create nested spatial units that reflect both natural hydrological processes and operational management needs across the basin.

3.2.1 Level 1: Physiographic partitioning

The first level of the delineation framework focuses on identifying the major physiographic units that govern large-scale hydrological behaviours across the CRB. In large river basins, topography represents a fundamental control on drainage organization, runoff generation, groundwater recharge, floodplain development, sediment transport, and water storage dynamics (Wagener et al., 2008). This influence is particularly pronounced in the CRB due to its distinctive geomorphological setting, characterized by elevated peripheral highlands surrounding the extensive low-lying depression of the Cuvette Centrale (See Figure 1).

To characterize basin-scale physiographic variability, a MERIT Digital Elevation Model (DEM) was used to analyse elevation gradients, terrain morphology, and major drainage divides. The MERIT DEM was selected because of its improved correction of vegetation bias, striping artefacts, and elevation errors that commonly affect digital elevation datasets in tropical environments (Yamazaki et al., 2017). Elevation frequency distributions were first examined to identify dominant topographic patterns across the basin. Subsequently, the Jenks Natural Breaks Optimization method was applied to detect significant transitions in elevation and delineate physiographic zones exhibiting relatively homogeneous terrain characteristics (De Smith et al., 2018; Park & Kim, 2019). This analysis enabled the identification of major landform units, including uplands, plateaus, escarpments, valleys, depressions, floodplains, wetlands, and large wetland complexes. To further characterize geomorphological variability, cumulative distribution functions (CDFs) of normalized elevation were derived for each catchment unit. Similar to hypsometric curves, the shape of these CDFs provides valuable information on dominant landscape morphology and associated hydrological functioning (Vivoni et al., 2008). The analysis revealed four principal geomorphological groups: concave-shaped curves (CC), convex-shaped curves (CV), rectilinear curves (R), and S-shaped curves (S), each comprising several internal variants (Figure 4). Concave forms are typically associated with low- flat relief environments such as lakes, wetlands, and floodplains, whereas convex and rectilinear forms are generally indicative of steeper terrain and more pronounced drainage gradients. S-shaped forms represent transitional geomorphological conditions that combine characteristics of both lowland and upland environments. A number of catchments exhibited atypical patterns and were grouped under a category of various forms (VF).

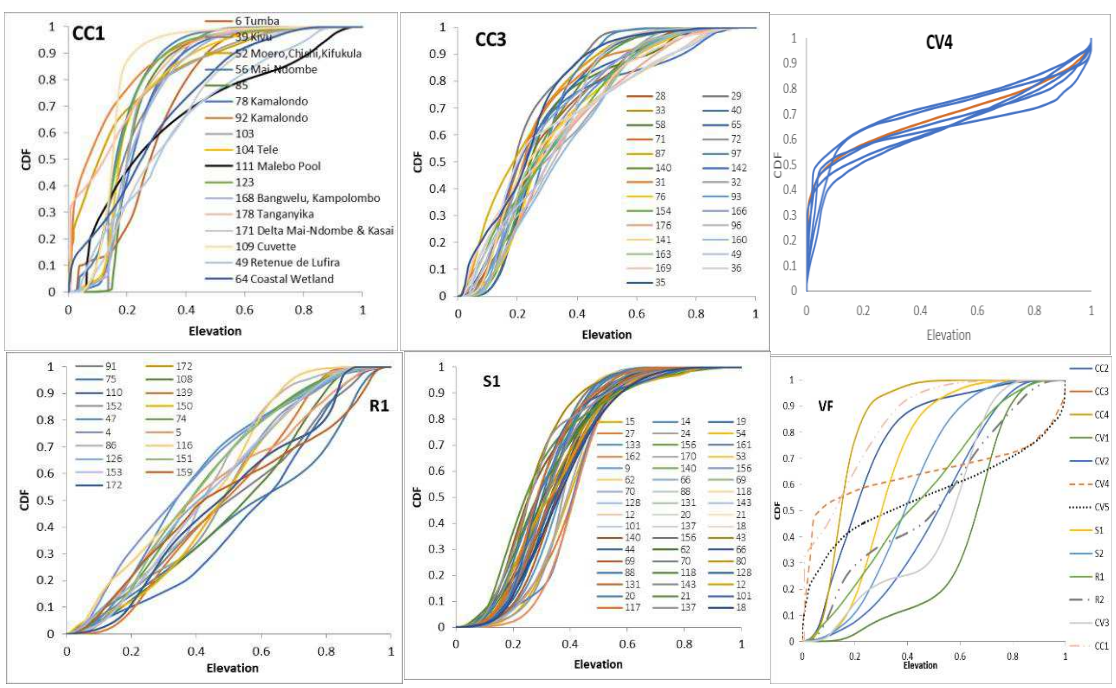

Figure 4. *Cumulative Distribution Functions (CDFs) of landforms across the dominant topographic gradients of the Congo River Basin. Four major geomorphological groups are identified: concave curves (CC), convex curves (CV), rectilinear curves (R), and S-shaped curves (S). Numbers denote internal variants within each group. CC1 corresponds primarily to natural lake and wetland catchments, while VF represents atypical forms that could not be assigned to the principal geomorphological categories.*

These landform units exert strong controls on hydrological processes by influencing infiltration capacity, runoff production, groundwater recharge, sediment transport, flood propagation, and surface water retention. Consequently, the resulting physiographic classification provides the first layer of spatial simplification within the CB=CIS, reducing the complexity of the basin into 199 hydrologically meaningful structural units (Figure 7). These units constitute the foundation for subsequent drainage network delineation, hydrological modelling, catchment classification, and prediction in ungauged basin (PUB) applications.

3.2.2. Level 2: Integrating socio-economic systems

The second level extends beyond conventional physical catchment delineation by explicitly incorporating human systems, governance structures, and socio-economic drivers into the spatial organization framework. This reflects the growing recognition within socio-hydrology that water systems are shaped not only by biophysical processes but also by dynamic interactions between human activities, institutions, infrastructure, and ecosystem services (Damasco et al., 2025).

In the CRB, hydrological processes are increasingly influenced by rapid urban expansion, mining activities, agricultural development, hydropower investments, inland navigation systems, deforestation, and competing land-use pressures (Tshimanga et al., 2026). These anthropogenic factors alter runoff generation, sediment transport, water quality, ecological flows, and infrastructure vulnerability, thereby creating new forms of hydrological risk that cannot be captured through purely physical delineation approaches. To address these dynamics, Level 2 integrates multiple socio-economic and governance-related spatial layers into the catchment framework, including urban centers, mining zones, agricultural production areas, hydropower facilities, navigation corridors, water supply infrastructure, protected areas, administrative jurisdictions, and hydrometeorological monitoring networks (Figure 5). These layers enable the identification of management units that better reflect operational realities and institutional decision-making processes (403 units).

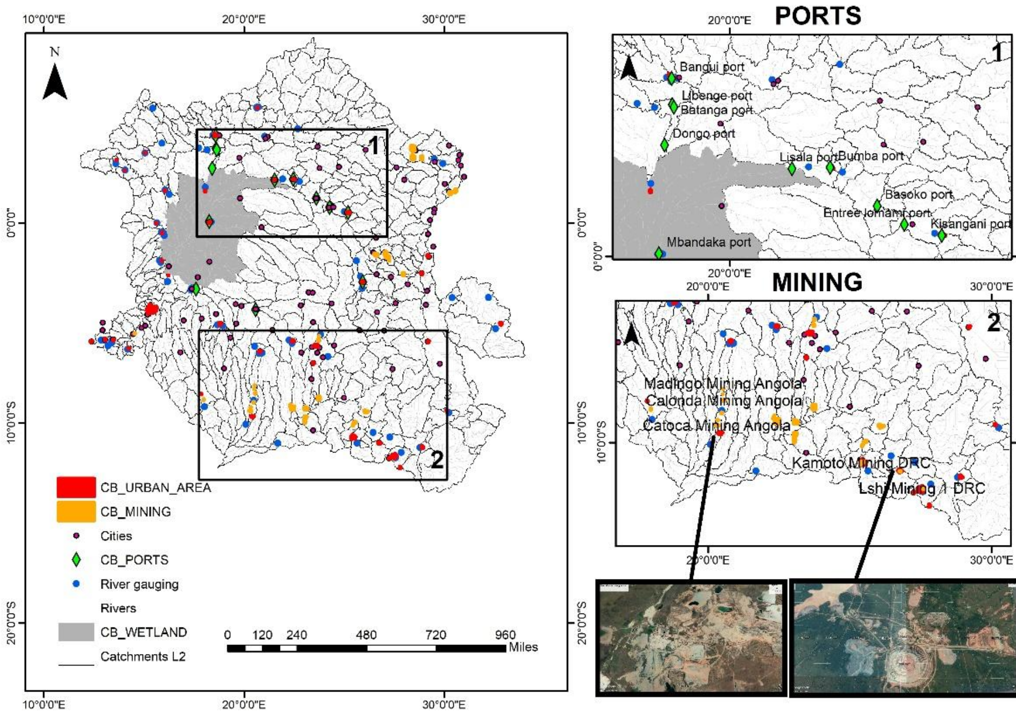

Figure 5. Catchment classification Level 2, including socio-economic systems

3.3.3 Level 3: Hydronym and Socio-Hydrology

Hydronym is the branch of toponymy concerned with the study of names assigned to hydrological features such as rivers, streams, lakes, marshes, springs, and wetlands. It examines the origin, meaning, historical evolution, and linguistic dimensions of water-related names, as well as their connections with local communities, cultures, landscapes, and water uses. Hydronyms often constitute living archives of the long-standing relationships between societies and aquatic environments, reflecting indigenous and local knowledge of hydrological dynamics, ecosystem characteristics, navigation routes, flood regimes, natural hazards, and spiritual or cultural values associated with water bodies (Yance et al., 2024). Local hydronyms frequently provide important insights into the environmental and hydrological characteristics of landscapes, including flood-prone zones, wetlands, seasonal rivers, peatlands, or sacred aquatic spaces. As such, integrating hydronymic knowledge into contemporary scientific research can enrich hydrological investigations, improve environmental mapping, and strengthen approaches to conservation, disaster risk reduction, and participatory water governance (e.g. Budiono et al., 2023; Nardiati et al., 2023; Prastio et al., 2023).

In the context of the Congo Basin, hydronym represents an important tool for documenting the historical dynamics of populations, preserving cultural and linguistic heritage, and enhancing geographical, hydrological, and territorial governance studies. Given the basin's exceptional cultural and linguistic diversity, a single river or wetland may carry different names across communities and territories. Recognizing and harmonizing these hydronyms can therefore improve hydrographic databases, facilitate transboundary water management, and support more inclusive and locally grounded water governance frameworks. Hydronym may also contribute to preserving indigenous environmental knowledge systems that are increasingly threatened by socio-cultural and environmental change. Table 1 provides some examples that illustrate how hydronyms preserve valuable historical, linguistic, and cultural information about the settlement history, migration patterns, territorial occupation, and identity of communities in the Democratic Republic of the Congo. These examples demonstrate that hydronyms are far more than geographical labels. They function as enduring repositories of indigenous knowledge, preserving evidence of ancient settlement patterns, migration routes, territorial boundaries, historical conflicts, cultural identity, and linguistic heritage. Consequently, the study of hydronymy constitutes an important interdisciplinary tool for reconstructing the historical geography and socio-cultural evolution of the Congo Basin.

Table 1. Selected Hydronyms and their historical, linguistic, and cultural significance in the Congo Basin .

Hydronym	**Language of Origin/Tribe**	**Meaning**	**Historical and Cultural Significance**
Makambua	Benge (Bantu)	*Source of happiness* or *source of well-being*	Located in the Duaru Chiefdom, now inhabited by the Zande of Sudanic origin. The preservation of this Benge hydronym indicates that the Benge were the earliest inhabitants of the Bondo territory before being displaced by the Zande. The fact that the river retained its original name demonstrates the persistence of hydronyms despite changes in political control and population. Similar examples include **Zagili** ("dwelling"), **Gangu** ("wealth"), and **Mbili** ("protection"), which also preserve the linguistic heritage of former inhabitants.
Faka	Ngbandi	*Peace*	The Faka River forms the boundary between the two Kassa chiefdoms, historically occupied by the Ngbandi and Ndeni peoples before the arrival of the Zande. Rich in gold and diamonds, the river became the subject of territorial disputes. In 2010, the District Commissioner used the linguistic origin of the river's name as historical evidence to recognize the Ngbandi as the original custodians of the territory since the seventeenth century. This case illustrates the value of hydronyms as evidence in customary land rights and territorial history.
Makala	Budja	*Prosperity* or *wealth*	The Makala River flows through Buta, now regarded as the homeland of the Boa people. However, its Budja origin demonstrates that the Budja previously occupied the region before being displaced by the Boa. The sequence of Budja river names across the landscape traces the historical migration route of this population toward their present homeland in Mongala Province, highlighting the role of hydronyms as indicators of ancient migration pathways.
Bomokandi	Mangbetu	*Greatness*	The Bomokandi River flows through Haut-Uélé before joining the Uélé River at Dingila in Bas-Uélé. Its name reflects the prestige and historical influence of the Mangbetu people. The explorer **Georg Schweinfurth** associated this hydronym with the historical expansion of Mangbetu communities. Remarkably, the river retains its Mangbetu name even in areas never permanently occupied by them, illustrating the enduring nature of hydronyms as markers of cultural influence and historical memory.
Rubi	Boa	*The terminus* or *the final destination* ("the grave of the invaders")	The Rubi River, together with the Tele and Likati rivers, forms the Itimbiri River, a tributary of the Congo River. The name symbolizes the last defensive barrier against invading groups and reflects the collective memory of repeated invasions, conflicts, and territorial struggles. According to local tradition, any invader attempting to cross the river would meet a tragic end. The hydronym therefore preserves historical narratives of conflict, resilience, and territorial identity.

In this regard, the third level of the catchment partition framework focuses on defining the hierarchical organization of river networks and hydrological connectivity across the CRB. River networks were delineated using the D8 flow direction algorithm applied to the MERIT DEM. This approach enabled the identification of dominant flow pathways and drainage directions across the basin. A threshold accumulation value of 3 000 contributing cells was selected to generate stream networks that closely correspond to observed hydrographic systems while avoiding excessive fragmentation of minor drainage pathways. The extracted river network was subsequently classified using the Strahler stream ordering method (Strahler, 1954) to represent hierarchical river organization from headwater streams to major trunk rivers. This hierarchical representation provides an analytical framework for understanding tributary interactions, flow routing processes, and network connectivity across multiple spatial scales. Figure 6 presents the nine levels of river network obtained from this process.

To improve reliability, the extracted network was validated using historical hydrographic maps, national river inventories, and existing hydrographic datasets (IRB, 1950). This validation process was particularly important in low-relief areas such as the Cuvette Centrale, where wetlands, floodplain storage, and multi-channel systems often complicate conventional topography-based delineation methods. The resulting hydrological network framework provides the third analytical layer of CB-CIS by defining functional drainage units that establishes the connectivity architecture required for understanding upstream-downstream interactions across one of the world's most complex river systems.

A particularly innovative component of this level is the incorporation of historically recognized river systems and local hydrographic knowledge. More than 1,300 named rivers were identified through archival hydrographic maps, colonial era records, contemporary inventories, and consultations with local stakeholders. These river names (Hydronym) often reflect customary governance systems, traditional navigation routes, local ecological knowledge, and long-standing cultural relationships with water systems. The integration of these historically embedded hydrographic systems introduces an important socio-cultural dimension into the delineation framework and helps bridge formal scientific approaches with locally grounded knowledge systems (Yance et al., 2024). This is particularly important in regions where formal hydrological monitoring remains limited but local communities possess extensive experiential knowledge of seasonal flows, flood dynamics, navigation conditions, and ecosystem changes.

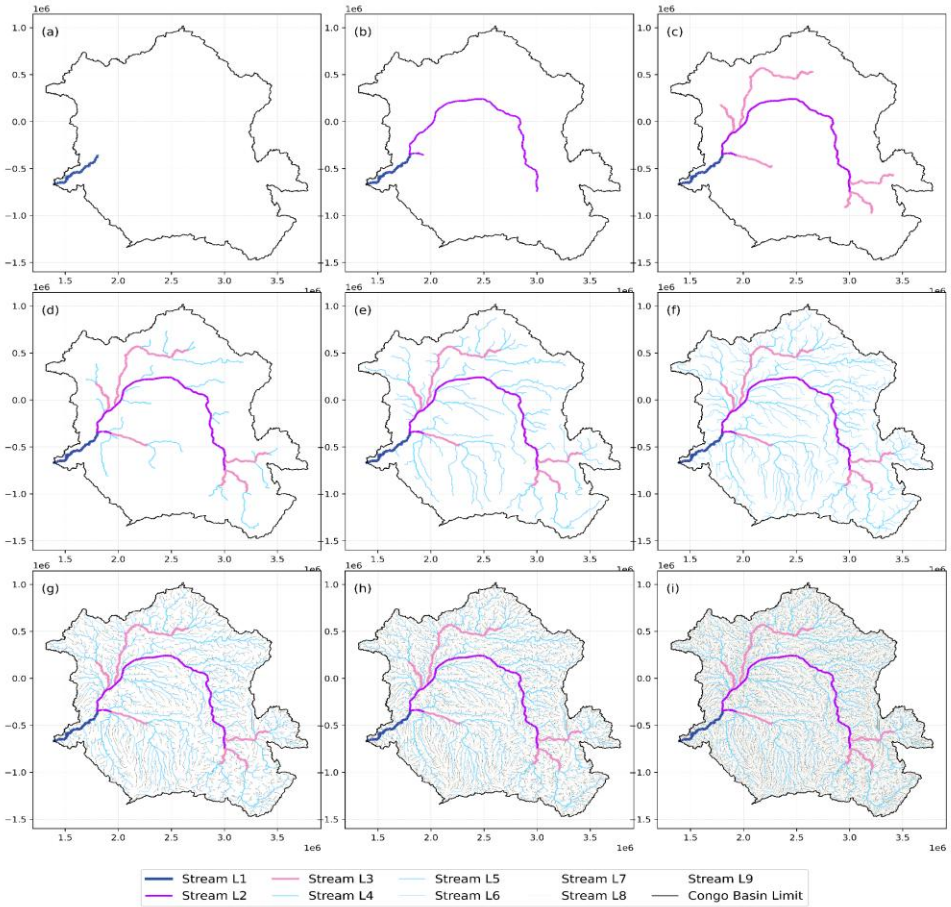

Figure 6 Hierarchical levels of rivers in the CRB based on Strahler order

The three delineation levels described above operate as an integrated nested hierarchy designed to capture the multi-scalar organization of hydrological processes across the Congo Basin. Rather than functioning as isolated classification layers, these levels are structurally interconnected, with each level capturing distinct but complementary dimensions of basin organization. Together, these levels form a nested analytical framework in which broad-scale physical controls influence sub-basin hydrological responses, while localized socio-economic pressures and governance arrangements shape management outcomes. This hierarchical structure enables analysis across multiple spatial scales, ranging from basin-wide climate assessments and transboundary planning to sub-basin modelling, infrastructure design, and community-level water management interventions. Figure 7 presents the hierarchy of the nested levels of the catchment classification framework for the CRB.

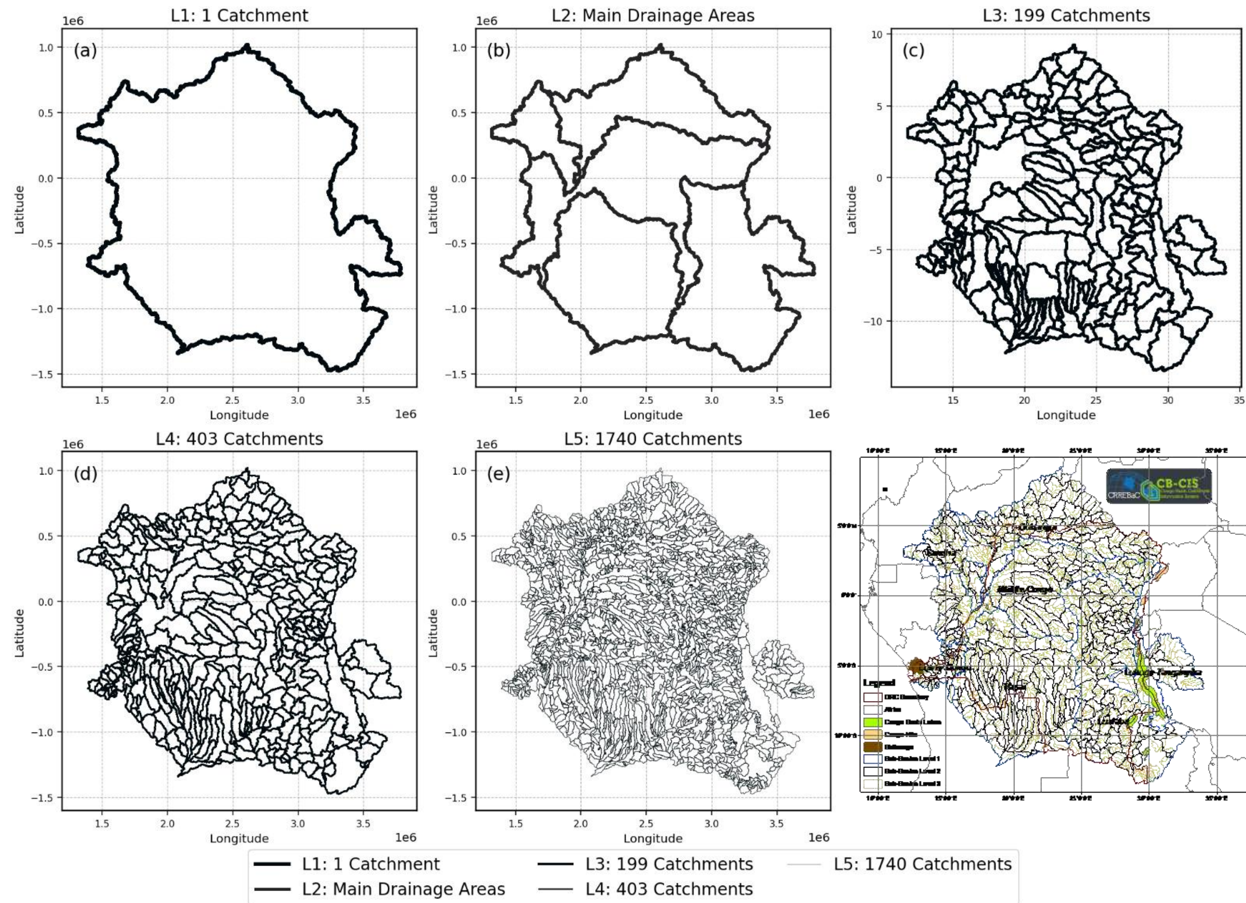

Figure 7. *Nested catchments (Level 1, One CRB catchment; L2: main drainage areas of the CRB: Lualaba, Kasai, Sangha, Oubangui, Central Congo Basin; L3: 199 catchments; L4: 403 catchments ; L5: 1740 catchments)*

The multi-level delineation framework provides a critical methodological foundation for addressing one of the central challenges of hydrological science in the CRB: improving prediction in ungauged and poorly gauged basins. By organizing the basin into hydrologically meaningful and transferable spatial units, the framework reduces the complexity associated with large-scale heterogeneity while preserving the dominant controls that shape hydrological behavior.

This structure enables the transfer of hydrological knowledge across catchments with similar physiographic, climatic, ecological, and socio-economic characteristics, thereby strengthening regionalization approaches for streamflow prediction, model parameter estimation, and uncertainty reduction in areas where observational records remain limited. The delineation framework also improves the spatial targeting of hydrometeorological monitoring investments by identifying critical observation gaps across physiographic zones, river network hierarchies, and socio-economic hotspots. This is particularly important in the Congo Basin, where the collapse of monitoring infrastructure has significantly constrained hydrological forecasting and operational planning.

4. Data infrastructure

4.1. Data source and variable types

The severe decline of hydrometeorological monitoring infrastructure across the Congo Basin has created major observational gaps that constrain hydrological analysis, forecasting, and water resources planning. To address these limitations, CB-CIS adopts a multi-source data integration framework designed to combine heterogeneous datasets from complementary observation systems in order to improve spatial coverage, temporal continuity, and analytical reliability.
The framework integrates four principal categories of data sources: in situ observations, remote sensing products, global environmental datasets, and socio-economic databases. Given the high degree of hydro-climatic, ecological, and socio-economic heterogeneity across the basin, CB-CIS adopted a multidimensional variable selection framework designed to capture both biophysical processes and human influences on water systems. Given the large number of variables and the risk of redundancy, a multi-stage statistical screening process was applied. First, correlation analysis was used to identify highly collinear variables and eliminate redundant predictors. Second, Principal Component Analysis (PCA) was employed to reduce dimensionality and identify dominant patterns of spatial variability across the basin. Third, Kaiser-Meyer-Olkin (KMO) tests were conducted to evaluate sampling adequacy and assess the suitability of variables for multivariate analysis. The final variable set retained those indicators that were statistically robust, hydrologically meaningful, and operationally relevant for classification, modelling, and decision-support applications. This approach ensured that CB-CIS captures multidimensional drivers of hydrological behavior while maintaining analytical efficiency in a highly complex and data-constrained basin system.

An initial pool of 128 attributes was compiled from the above-mentioned four categories of data. These variables were organized into seven thematic domains: Catchment identification, climate, physiographic characteristics, hydrology, water use, water risks, and external information. Figure 8 presents the seven thematic domains and the related variable types. This includes:

i. Catchment Identification: providing unique identifiers and hierarchical drainage relationships;
ii. Climate: describing water and energy availability through meteorological variables and climatic indices;
iii. Physiographic Characteristics: representing terrain, soils, geology, land cover, and geomorphology;
iv. Hydrology: capturing streamflow dynamics, groundwater contributions, water storage, and flow variability;
v. Water Use: documenting human utilization of water resources for domestic supply, irrigation, hydropower, navigation, and other economic sectors;
vi. Water Risks: assessing droughts, floods, sediment transport, pollution, and population exposure; and
vii. Additional Information: including metadata, technical documentation, publications, and links to supporting resources.

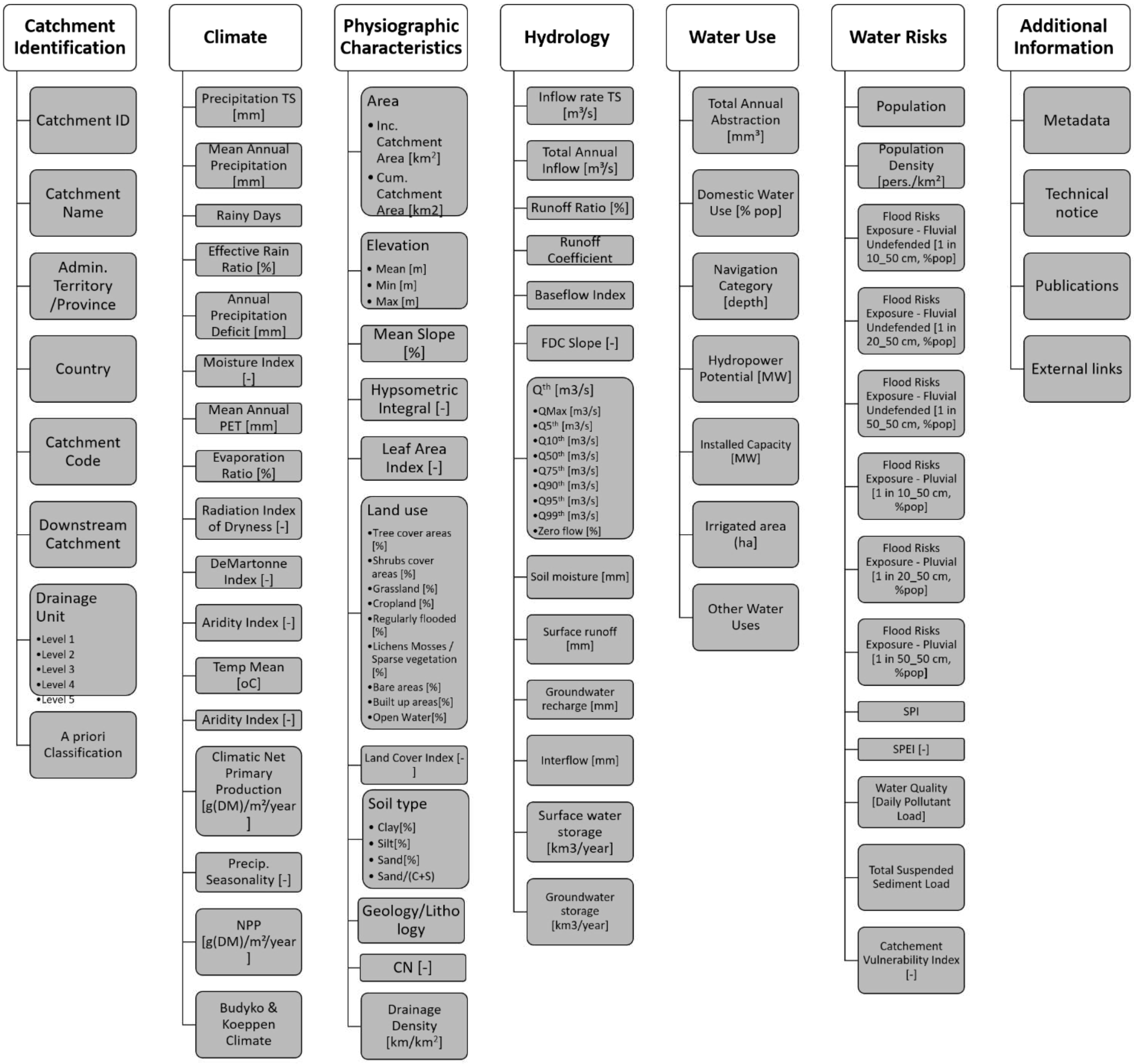

Figure 8. *Core variables and indices for multi-dimensional catchment characterization within CB-CIS (CB-CIS Version 1)*

Rather than relying solely on raw datasets, the framework incorporates a suite of internationally recognized hydrological, climatic, ecological, and risk indices that summarize complex watershed processes into standardized indicators. Together, they constitute the scientific basis for catchment classification, similarity analysis, hydrological regionalization, prediction in ungauged basins, assessment of water availability, evaluation of ecosystem functioning, and quantification of exposure to droughts, floods, sediment transport, water quality degradation, climate change impact assessments, and integrated water resources management across the CRB. Tables 2a-e summarize de description and application of the indices used within CB-CIS.

Table 2a. *Climatic indices for hydrological classification*

Climatic Index	Description	Application
Moisture Index (MI)	Ratio describing the balance between precipitation and atmospheric water demand. Often derived from precipitation and potential evapotranspiration (Thornthwaite, 1948)	Positive values indicate humid climates; negative values indicate water-limited environments. Useful for climate classification.
Effective Rain Ratio	Percentage of rainfall that effectively contributes to soil moisture and runoff after losses (USDA-NRCS, 2004).	Higher values indicate efficient rainfall utilization for hydrological processes.
Evaporation Ratio	Fraction of precipitation returned to the atmosphere through evaporation and evapotranspiration (Budyko, 1974).	High values characterize water-limited catchments with little runoff generation.
Radiation Index of Dryness (RID)	Compares available solar energy with available water (Budyko, 1974).	Indicates climatic dryness and potential evapotranspiration demand.
De Martonne Aridity Index	(AI = frac{P}/{T+10}), where P is annual precipitation (mm) and T is mean annual temperature (°C) (De Martonne, 1926).	Common climatic aridity indicator. Low values indicate arid climates; high values indicate humid climates.
Aridity Index (AI)	Usually the ratio of precipitation to potential evapotranspiration (P/PET) (UNEP, 1997).	AI < 0.65 indicates dry climates; AI > 1 generally represents humid regions. Widely used by UNEP and FAO.
Precipitation Seasonality Index	Measures the concentration of rainfall throughout the year (Walsh and Lawler, 1981).	High values indicate strong wet and dry seasons; low values indicate evenly distributed rainfall.
Net Primary Production (NPP)	Annual biomass produced by vegetation after plant respiration (Running et al., 2004).	Indicates ecosystem productivity and carbon sequestration potential.
Climatic Net Primary Production	Potential NPP estimated from climatic conditions (Lieth, 1975).	Used to assess ecosystem potential under climatic constraints.
Budyko Climate Index	Represents the long-term balance between water availability and energy availability (Budyko,1974).	Fundamental framework for partitioning precipitation into runoff and evapotranspiration.
Köppen Climate Classification	Global climate classification based on temperature and precipitation patterns (Peel et al., 2007).	Categorizes catchments into tropical, temperate, arid, continental, or polar climates.

Table 2b. *Physiographic indices*

Physiographic Indices	Description	Application
Hypsometric Integral (HI)	Describes the distribution of elevations within a catchment (Strahler, 1952).	Indicates geomorphic maturity and erosion stage. High HI suggests youthful landscapes; low HI indicates mature or eroded terrain.
Mean Slope	Average terrain slope (Horton, 1945).	Influences runoff velocity, erosion, and sediment transport.
Leaf Area Index (LAI)	Ratio of leaf surface area to ground area (Chen, Black, 1992).	Indicates vegetation density, interception, transpiration, and ecosystem productivity.
Land Cover Indicator (LCI)	Composite indicator describing the composition and condition of land cover within a catchment based on the relative proportions of major land cover classes [Dimensionless 0–1 or 0–100] ..	Catchment classification, watershed health assessment, hydrological modelling; ecosystem integrity evaluation, land degradation monitoring; climate change assessment; ecosystem services assessment.
Drainage Density	Total stream length divided by catchment area (km/km²) (Horton, 1945).	High values indicate rapid hydrological response and efficient drainage.
Curve Number (CN)	Dimensionless index developed by the USDA Natural Resources Conservation Service (USDA-NRCS, 2004)	Represents runoff potential based on soils, land use, and antecedent moisture. Higher CN values imply greater runoff generation.

Table 2c. *Hydrological signatures and functional indices*

Hydrological Indices	Description	Application
Runoff Ratio	Ratio of runoff to precipitation (McMahon et al., 2007)	Indicates rainfall conversion efficiency into streamflow.
Runoff Coefficient	Fraction of rainfall becoming direct runoff (Chow, 1988).	Used in flood estimation and watershed response analysis.
Baseflow Index (BFI)	Fraction of total streamflow supplied by groundwater (Gustard et al., (1992).	High BFI indicates groundwater-dominated systems; low BFI indicates flashy runoff.
Flow Duration Curve (FDC) Slope	Measures the steepness of the flow duration curve over a selected range of flow exceedance probabilities, indicating the variability and persistence of streamflow (Vogel and Fennessey, 1994; Yadav et al., 2007; Addor et al., 2018).	Steep slopes indicate highly variable flows; gentle slopes indicate stable river regimes.
Flow Quantiles (Qmax, Q5, Q10, Q50, Q75, Q90, Q95, Q99)	Characteristic discharge statistics derived from the flow duration curve (Smakhtin, 2001).	Used in water allocation, ecological flow assessment, and drought analysis.
Zero Flow Percentage	Percentage of time a river has no measurable flow.	Indicates stream intermittency and hydrological permanence.
Groundwater Recharge	Water percolating into aquifers (Healy, 2010).	Essential for groundwater sustainability assessments.
Surface Water Storage	Annual storage in rivers, lakes, and wetlands (Rodell et al., 2018).	Indicates surface water availability.

Groundwater Storage	Annual groundwater reserves (Famiglietti, 2014).	Important for drought resilience and water supply planning.

Table 2d. *Water risk Indices for climate resilience and water security assessment*

Water Risk Indices	Description	Application
Standardized Precipitation Index (SPI)	Quantifies precipitation anomalies over multiple time scales using only precipitation data (McKee et al., 1993).	Monitoring meteorological droughts; early warning systems; water resources planning; agricultural drought assessment; reservoir operation; climate variability analysis.
Standardized Precipitation Evapotranspiration Index (SPEI)	Measures drought severity by considering both precipitation and atmospheric evaporative demand (PET) (Vicente-Serrano et al., 2010).	Climate change impact assessment; agricultural and ecological drought monitoring; water allocation planning; ecosystem vulnerability assessment; adaptation planning under global warming.
Flood Risk Exposure (Fluvial)	Percentage of population exposed to river flooding under different return periods (e.g., 1-in-10, 1-in-20, 1-in-50 years) (Dottori et al., 2016).	Flood hazard mapping; disaster risk reduction; floodplain zoning; infrastructure design; emergency preparedness; prioritization of flood protection investments; insurance risk assessment.
Flood Risk Exposure (Pluvial)	Percentage of population exposed to flooding caused by intense local rainfall and inadequate drainage (European Commission Joint Research Centre and UNDRR, 2019)	Urban flood management; stormwater drainage design; resilient city planning; infrastructure vulnerability assessment; climate adaptation strategies.
Daily Pollutant Load	Daily mass of pollutants transported by rivers (e.g., nutrients, organic matter, heavy metals) (Chapra, 2008).	Water quality monitoring; pollution source identification; wastewater management; Total Maximum Daily Load (TMDL) assessments; compliance with environmental regulations; ecosystem health monitoring.
Total Suspended Sediment Load (TSS)	Quantity of suspended sediment transported by a river (Walling and Webb, 1983).	Soil erosion assessment; reservoir sedimentation studies; navigation channel maintenance; hydropower sustainability; river morphology analysis; watershed conservation planning; aquatic habitat assessment.
Catchment Vulnerability Index (CVI)	Composite index integrating climatic, hydrological, environmental, and socio-economic indicators to assess the overall vulnerability of a catchment [Dimensionless (0–1 or 0–100] . CVI=(PI*CPI+AC*CAC)/(CPI+CAC)	Identification of vulnerable catchments; prioritization of restoration and adaptation measures; basin planning; climate resilience assessment; integrated water resources management.

__Table 2e.__ Water resources use indicators

WRU Indicator	Description	Application
Total Annual Water Abstraction	Total volume of water withdrawn annually from surface water and groundwater resources for all sectors, Mm^3/year	Assessment of water demand, water stress, allocation planning, and sustainable water resources management.
Domestic Water Use	Percentage of the population with access to or supplied by domestic water services within the catchment, [%of population]	Evaluation of water supply coverage, public health, SDG 6 monitoring, and infrastructure planning.
Navigation Category	Classification of navigability based on minimum navigable channel depth and river characteristics [Navigation class/depth (mm)	Inland waterway planning, transport infrastructure development, trade facilitation, and navigation safety assessment.
Hydropower Potential	Estimated technically or economically exploitable hydropower generation potential [MW]	Hydropower planning, renewable energy development, basin-scale energy assessment, and climate mitigation planning.
Installed Hydropower Capacity	Existing installed hydropower generation capacity within the catchment [MW]	Assessment of energy infrastructure, hydropower utilization efficiency, and future development opportunities.
Irrigated Area	Area equipped for agricultural irrigation [ha]	Agricultural water demand assessment, food security analysis, irrigation development planning, and climate adaptation.
Other Water Uses	Additional sectoral uses including industrial, mining, fisheries, tourism, recreation, environmental flows, and ecosystem services.	Comprehensive assessment of competing water demands, ecosystem services valuation, and integrated basin planning.

4.2. Data storage and management

Beyond hydrological classification, modelling, and multi-source data integration, the operationalization of CB-CIS requires a robust digital framework capable of structuring, storing, managing, and retrieving large volumes of heterogeneous hydro-environmental information. The diversity of datasets integrated within CB-CIS necessitates a formal database design framework that ensures scalability, interoperability, and long-term operational sustainability. To address these requirements, CB-CIS adopts a multi-layer database framework that links hydrological features with digital infrastructure design. Figure 9 shows the physical implementation layers (1740 catchment units) for a sample variable types.

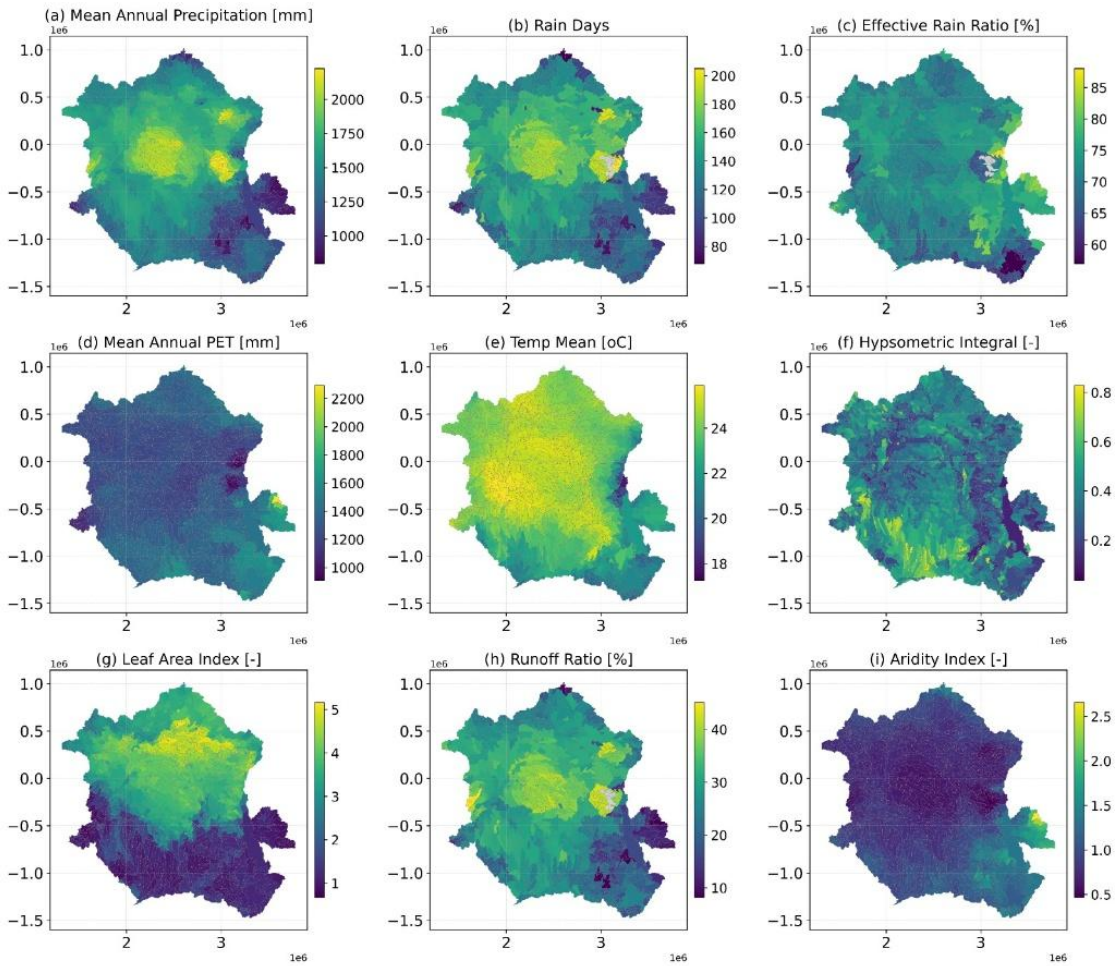

Figure 9. *Physical implementation layers (1740 catchment units) with a sample variable types.*

The physical implementation layer defines how data are stored, queried, protected, and maintained within the operational platform. CB-CIS adopts PostgreSQL as the primary database engine due to its scalability and ability to manage large environmental datasets. The integration of PostGIS enables advanced geospatial operations such as watershed delineation, river network analysis, floodplain mapping, spatial indexing, and proximity analysis. The physical architecture also incorporates backup protocols, user access controls, cybersecurity measures, and cloud redundancy mechanisms to ensure long-term system resilience and operational continuity.

Given the transboundary nature of the CRB, interoperability is essential for effective regional collaboration and data exchange. CB-CIS therefore incorporates internationally recognized standards for metadata management and geospatial interoperability, including protocols developed by the Open Geospatial Consortium (OGC), Web Map Services (WMS), Web Feature Services (WFS), and application programming interfaces (APIs). These standards enable integration with national hydrological agencies, regional basin organizations, research institutions, and international development partners (OGC, 2023; WMO, 2012; Vretanos, 2010; de la Beaujardière, 2006)

Long-term sustainability of the database requires clear institutional arrangements regarding ownership, maintenance, quality assurance, and operational accountability. The Congo Basin Water Resources Research Center (CRREBaC) at the University of Kinshasa is the primary scientific custodian responsible for database administration, quality control, model integration, and technical coordination. This institutional framework helps ensure long-term continuity while strengthening regional collaboration and supporting the evolution of CB-CIS from a research platform into an operational hydrological information system. By integrating hydrological science with digital structuring principles, this framework provides the operational backbone required to transform CB-CIS into a scalable and decision-oriented water information infrastructure for large, data-scarce river basins.

5. CB-CIS Digital Architecture

5.1. Digital architectural design

The digital architecture of CB-CIS was conceived as an integrated and modular hydro-informatics infrastructure designed to support environmental monitoring, hydrological analysis, and decision-support processes across the CRB. The architecture enables the integration of heterogeneous environmental datasets, geospatial services, analytical tools, and interactive visualization functionalities within a unified operational framework adapted to basin-scale applications.

CB-CIS adopts a layered architecture composed of frontend visualization interfaces, backend geospatial services, spatial database systems, and cloud-based deployment components. This structure was selected to ensure scalability, interoperability, flexibility, and long-term operational sustainability under conditions of increasing data complexity and evolving user needs. The modular design also facilitates future integration of additional datasets, analytical services, and operational forecasting applications.

The frontend environment relies on modern web-based geospatial visualization technologies. Interactive cartographic functionalities are implemented through the Leaflet.js library, which supports dynamic visualization of river networks, hydrographic layers, catchment boundaries, and thematic environmental information. Analytical visualization capabilities are strengthened through D3.js, enabling the production of dynamic graphs, statistical analyses, and comparative hydro-climatic visualizations. Additional interface responsiveness and user interaction are facilitated through jQuery, while complementary libraries such as Turf.js, Typeahead.js, and Autolinker provide geospatial analytical functions, search optimization, and metadata integration.

At the backend level, GeoServer constitutes the core geospatial server infrastructure used for publishing and disseminating spatial information through interoperable Open Geospatial Consortium (OGC) standards, notably Web Map Services (WMS) and Web Feature Services (WFS). This infrastructure enables standardized access to hydrological datasets, watershed boundaries, physiographic units, and environmental indicators through dynamic web services.

Spatial data management is ensured through PostgreSQL combined with the PostGIS spatial extension, which provides advanced geospatial storage, indexing, querying, and analytical functionalities. The database architecture stores diverse categories of information, including river networks, catchment units, administrative boundaries, hydrological indicators, physiographic variables, and socio-environmental datasets. Complementary metadata and thematic information are additionally linked through structured repositories connected to the spatial database environment.

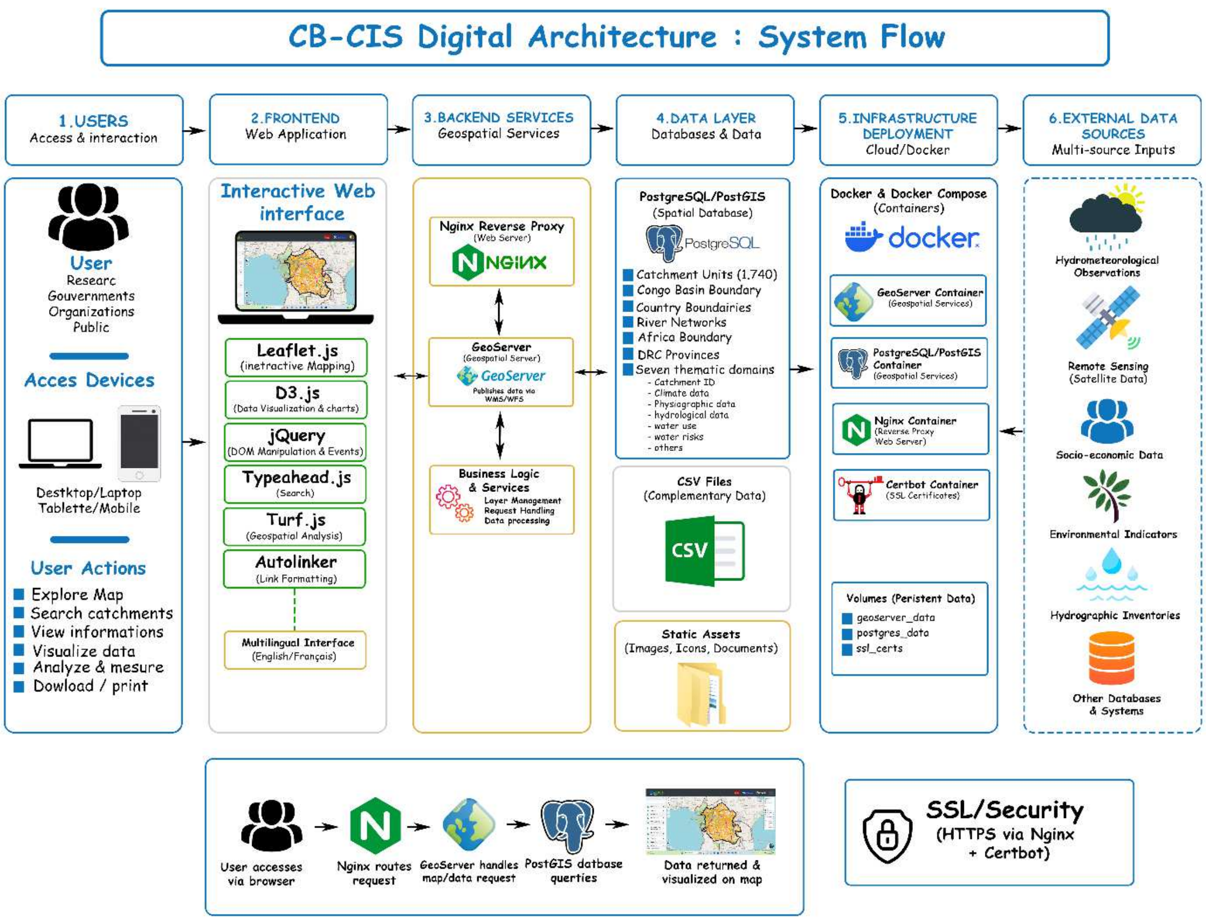

Figure 10. *CB-CIS Digital architecture system flow*

From an infrastructure perspective, CB-CIS adopts a cloud-oriented containerized deployment architecture based on Docker and Docker Compose technologies. Core services, including GeoServer, PostgreSQL/PostGIS, and the Nginx reverse proxy server, are deployed as interconnected containers to improve portability, scalability, resilience, and maintenance efficiency. Nginx manages routing, secure access, and communication between frontend interfaces and backend geospatial services, while Certbot supports SSL certificate management and secure data transmission.

5.2. The web-based interface

The web-based visualization interface of CB-CIS is developed as an interactive hydro-informatics and geospatial decision-support environment designed to facilitate the exploration, visualization, analysis, and interpretation of water resources information across the CRB (Figure 11, https://cbcis.info/). The platform functions as a basin-scale Spatial Data Infrastructure (SDI), integrating hydrographic, climatic, physiographic, environmental, and socio-economic datasets within a unified web GIS framework.

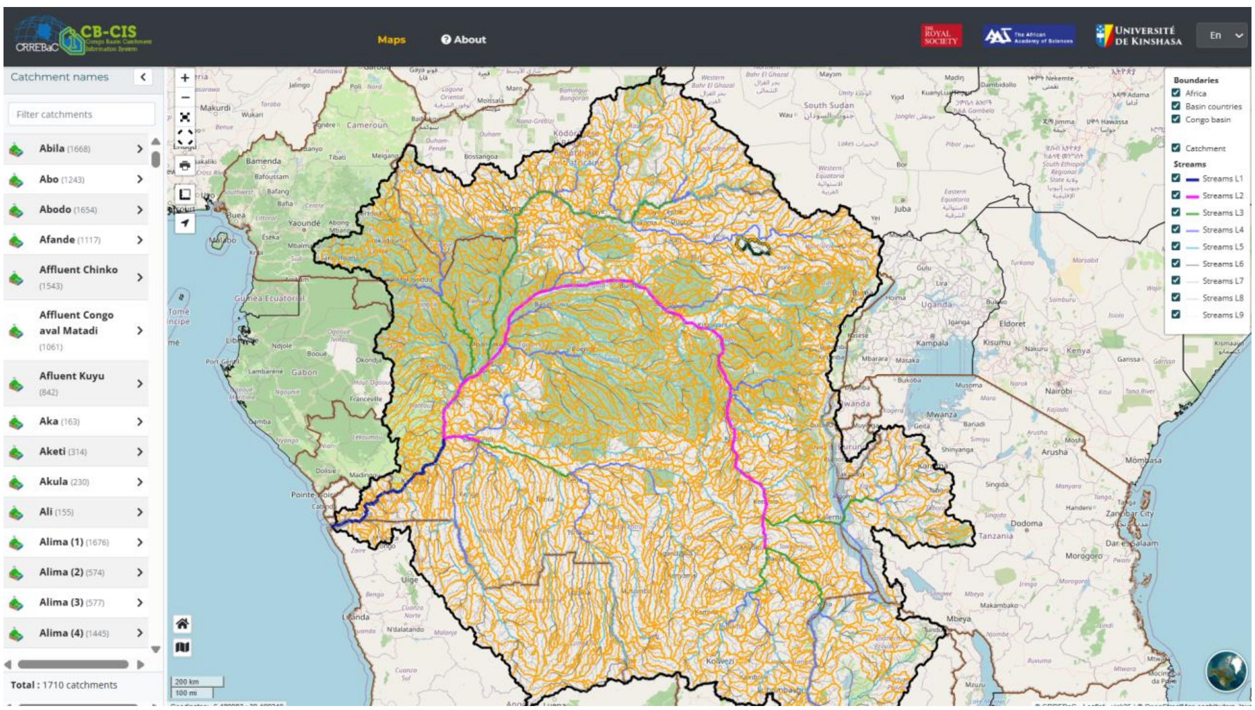

Figure 11. *The web-based visualization interface of CB-CIS (https://cbcis.info/)*

At the core of the visualization system is an interactive map-based interface through which users can navigate the CRB at multiple spatial scales. The interface enables visualization of the entire hydrographic network of the basin, including the main Congo River and its tributaries classified into nine orders Strahler classification (Strahler, 1959), and the 1740 Water Resources Management Units (WRMUs) organized according to a hierarchical hydrographic classification system. This structure allows users to move seamlessly from regional basin-wide perspectives to detailed local-scale catchment analyses.

The visualization interface operates through a dynamic layer-based architecture that allows users to activate, combine, overlay, and compare different thematic datasets. The available layers include hydrographic information such as river networks, watershed boundaries, catchments, the seven thematic domains and their 128 variables. Administrative and governance layers are also integrated, enabling the visualization of provinces, territories, and national boundaries together with hydrological units. This layered visualization system supports integrated environmental analysis by facilitating the interaction between physical, ecological, and socio-economic information.

One of the key technical features of the CB-CIS web interface is its catchment-based navigation and query system. Each WRMU functions as an interactive spatial object connected to an attribute database containing thematic information relevant to that catchment (e.g Figure 11). When users select a specific catchment or management unit on the map, the system dynamically retrieves associated datasets and generates corresponding visual outputs, including thematic maps, statistical summaries, and graphical analyses. This functionality enables localized watershed characterization while maintaining coherence within the broader basin framework. It also facilitates comparative analyses between different sub-catchments, supporting decentralized planning and basin-wide decision-making processes.

The platform also incorporates dynamic graphical visualization capabilities that transform hydrological and environmental datasets into interpretable visual analytics. Users can generate hydro-climatic graphs, comparative charts between catchments, temporal profiles of hydrological variables, and visual representations of environmental indicators. These graphical tools allow researchers and decision-makers to analyze trends, compare spatial units, and better understand hydrological variability across the basin. In this respect, the CB-CIS interface moves beyond static cartographic representation toward a more advanced hydroinformatics environment capable of supporting scientific analysis and evidence-based planning.

Another important characteristic of the visualization interface is its hierarchical hydrographic representation. The platform organizes the CRB according to a nine-level hydrographic classification system that enables visualization of upstream-downstream relationships, nested watershed structures, tributary connectivity, and hydrological linkages between river systems and adjacent wetlands. This functionality is particularly relevant for understanding the hydrodynamics of the CRB, where seasonal floodplain exchanges, wetland storage, and lateral connectivity play critical roles in regulating river discharge and ecosystem functioning.

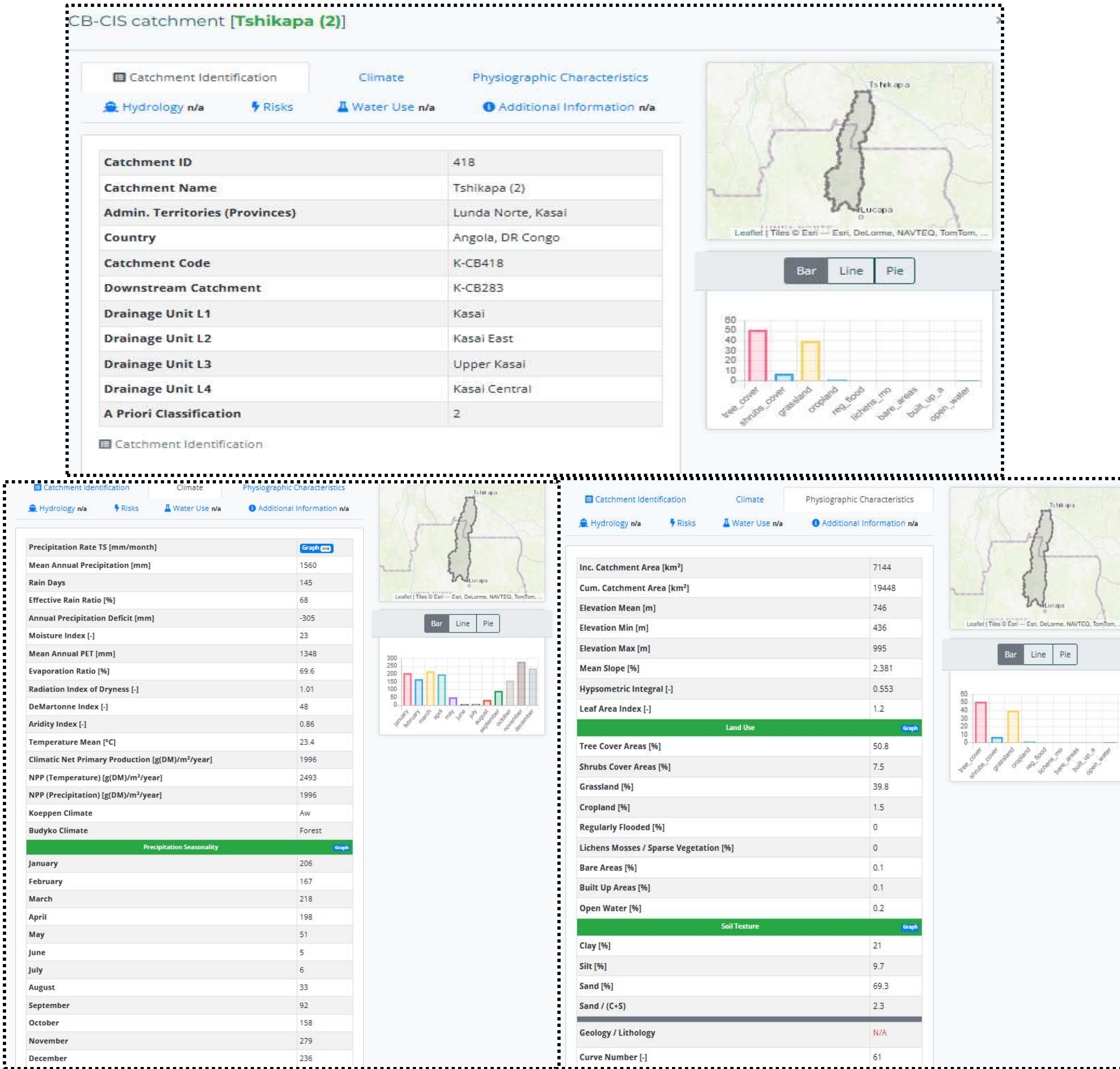

Figure 12. *An excerpt of a query system for a transboundary catchment shared between DRC* and Angola

The web-based visualization environment was also conceived as a spatial decision-support system for water governance and environmental management. The interface facilitates the identification of vulnerable areas, flood-prone regions, drought-sensitive zones, and pollution hotspots. It can support prioritization of investments related to hydropower, navigation, irrigation, water supply, and ecosystem conservation. By integrating hydrological and environmental information within an accessible digital platform, CB-CIS contributes to strengthening science-policy interaction and improving the technical basis for transboundary water governance in the Congo Basin.

The CB-CIS visualization architecture is further designed to accommodate near real-time environmental information and future operational monitoring systems. Although operational capacity depends on data availability and institutional infrastructure, the platform architecture is compatible with dynamic satellite-based monitoring, remote sensing updates, and future hydrological forecasting applications. This creates opportunities for the development of flood early warning systems, climate anomaly monitoring, and real-time hydrological assessment tools in the Congo Basin. Overall, the web-based visualization interface of CB-CIS represents a foundational digital infrastructure for Congo Basin hydrology and environmental governance. It functions simultaneously as a digital hydrological atlas, a hydro-environmental observatory, a scientific information platform, and a decision-support system. By centralizing and visualizing basin-scale information within an interactive and accessible web environment, the platform contributes to improving scientific understanding, strengthening regional cooperation, and supporting sustainable management of water resources in one of the world's most important river basins.

6. Application cases

The practical value of CB-CIS lies in its ability to transform complex hydro-environmental data into operational information that supports decision-making across multiple sectors and spatial scales. While many environmental information systems primarily focus on data storage and visualization, CB-CIS is explicitly designed to support prediction, risk reduction, infrastructure planning, ecosystem management, and transboundary governance in one of the world's most hydrologically complex and least monitored river basins.

6.1. Catchment model parameters estimation and assessment of water balance components in CB-CIS

One of the main objectives of CB-CIS is to establish a robust framework for hydrological model development, intercomparison, and application across the CRB. To demonstrate the predictive capabilities of CB-CIS, two complementary modelling frameworks were implemented across the basin. These are the GW-Pitman model, a semi-distributed conceptual rainfall-runoff model specifically adapted to African river systems (Hughes et al., 2006), and the Water Evaluation and Planning System (WEAP), an integrated water resources assessment platform that combines hydrological simulation with water allocation and management functions (Yates et al., 2005). While both models were calibrated using available streamflow observations from representative gauging stations across the basin, they differ in structure and process representation, thereby providing an opportunity to evaluate the consistency and robustness of simulated hydrological responses under different modelling paradigms (Tshimanga, 2022).

Figures 13 and 15 present the calibrated and simulated Flow Duration Curves (FDCs) for selected stations, indicating that both modelling approaches reproduce the general flow regime characteristics of the major CRB tributaries with satisfactory accuracy. The ability of both models to reproduce these dynamics increases confidence in their use for water resources planning and forecasting in areas lacking direct observations.

Beyond their scientific value, these modelling products constitute a strategic component of the CB-CIS decision-support framework. Figures 14 and 16 present the spatially distributed water balance estimates generated from the models for selected catchments upstream of the gauging sites that were calibrated. The catchment-scale simulations establish a basis for transferring hydrological information to ungauged basins through regionalization approaches, thereby extending the benefits of limited observational networks to large portions of the basin where direct measurements remain unavailable.

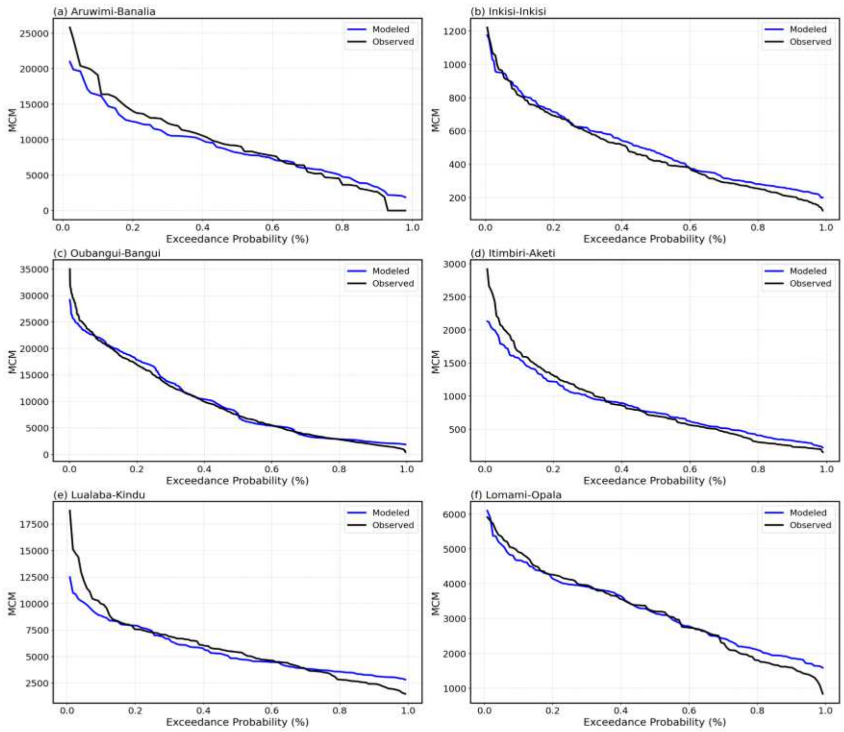

Figure 13. WEAP FDCs simulations across selected gauging stations

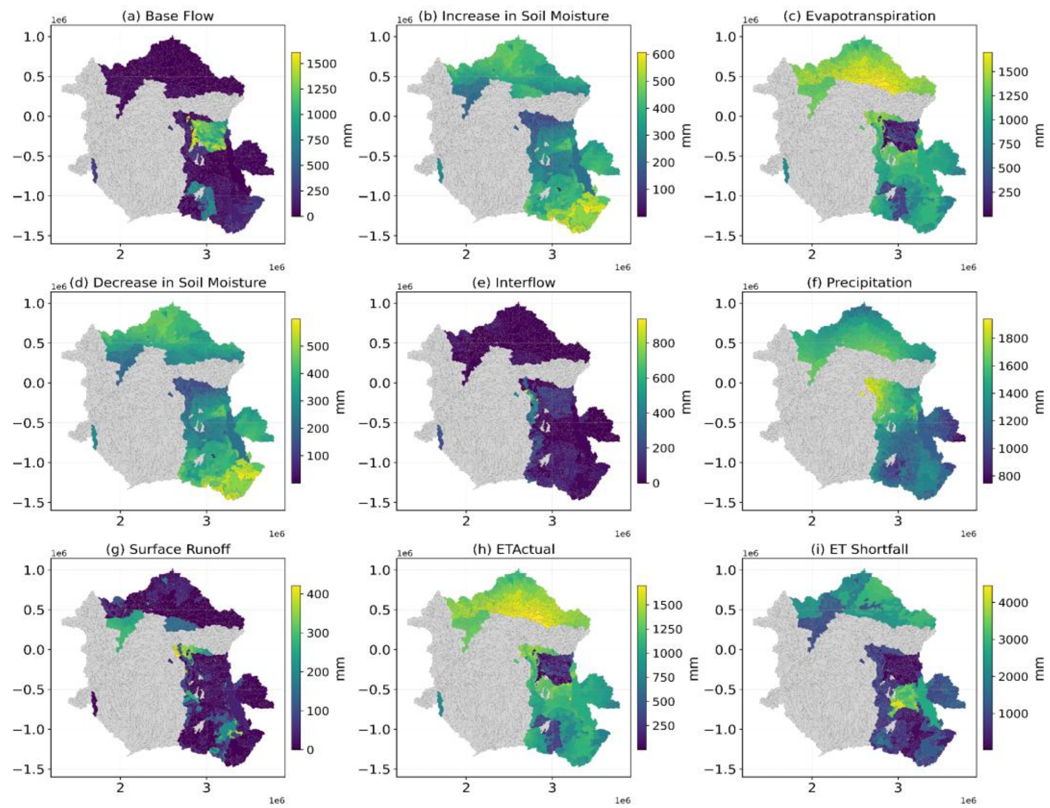

Figure 14. *Spatially distributed water balance components estimate generated from WEAP model for selected catchments in the CRB*

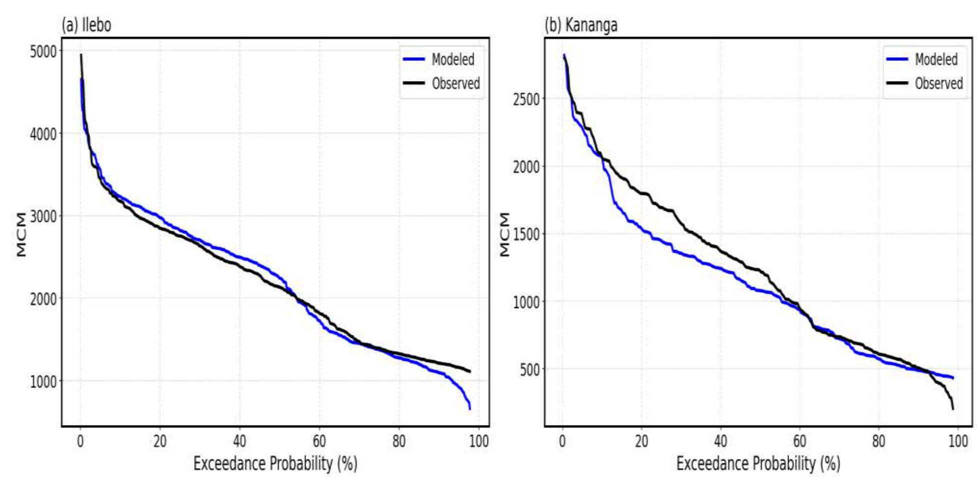

Figure 15. *GW-Pitman FDCs simulations across selected gauging stations*

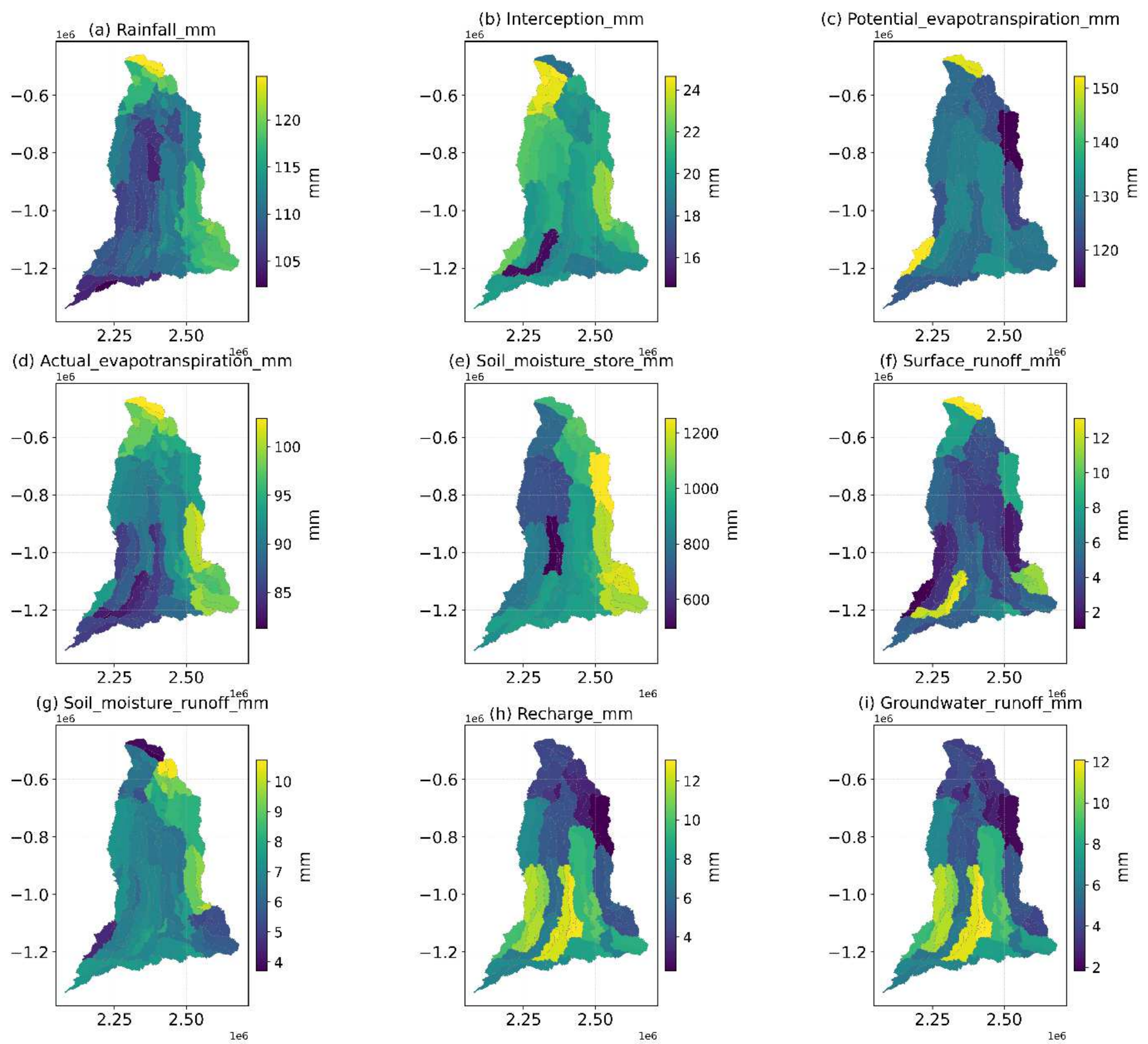

Figure 16. Spatially distributed water balance components estimate generated from GW-Pitman model for selected catchments in the Kasi drainage are

6.2. Integrating satellite observations to characterize catchment water storage and hydrological dynamics in CB-CIS

Given the severe decline of hydrometric observation networks across the CRB since the 1980s, satellite-derived water level observations provide an essential source of information for monitoring river dynamics, floodplain inundation, and surface water storage variations across the basin. CB-CIS integrates satellite observations as a core component of its hydrological monitoring and decision-support framework.

In the CRB, recent studies enabled to establish more than 2000 virtual stations (VSs) from different satellite missions spanning the period from 1995 up to now helping to overcome the difficulties of the lack of in situ water levels (Kitambo et al., 2022). A major advancement has been the incorporation of data from the Surface Water and Ocean Topography (SWOT) mission, which provides high-resolution measurements of water surface elevation, extent, and slope (Normandin et al., 2024). Within CB-CIS, water level observations from multiple satellite altimetry missions are harmonized to generate long-term hydrological records spanning from 1995 to the present. The system currently incorporates more than 2000 VSs distributed across the Congo River and its major tributaries, covering a wide range of hydrological environments including large rivers, wetlands, lakes, and floodplains (Figure 17). These observations provide unprecedented spatial coverage across a basin characterized by vast inaccessible regions and sparse monitoring infrastructure. The integration of observations from successive satellite missions allows the construction of continuous time series ranging from 10 to more than 25 years, supporting both operational monitoring and long-term hydroclimatic analyses (Kitambo et al., 2023; Kitambo et al., 2022; Paris et al., 2016; Papa et al., 2015). Through SWOT and other Earth observation products, CB-CIS is able to derive key hydrological variables including water surface elevation, flood extent, surface water storage (SWS), water surface slope (WSS), and river-floodplain connectivity. These products significantly improve the characterization of hydrological processes in the Congo Basin, particularly in the Cuvette Centrale wetlands where conventional monitoring remains extremely limited.

Within CB-CIS, satellite altimetry serves as a transformative technology that bridges observational gaps across the CRB, enabling real-time monitoring, forecasting, modelling, navigation support, climate analysis, and evidence-based water governance. Together with meteorological observations, remote sensing products, and hydrological models, it forms a cornerstone of a modern Digital Catchment Information System for the Congo Basin

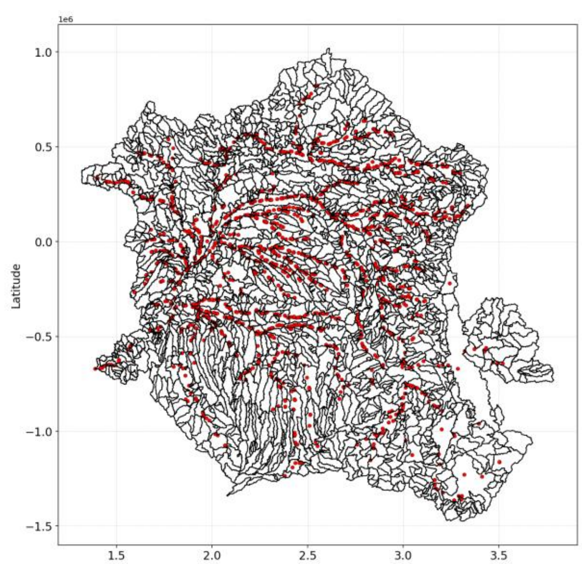

Figure 17. *Virtual stations location from different satellite missions spanning the period from 1995 up to present*

Groundwater resources play a crucial role as the primary source of freshwater for CRB's human population in both urban and rural settings (Braune and Xu, 2010). The strategic role that groundwater (GW) assumes in the CRB emphasizes the significance of systematic data collection and hydrogeological studies in the efficient and sustainable planning of GW resources use. However, GW resources remain poorly understood due to a lack of comprehensive monitoring frameworks, consequently resulting in their undervaluation, mismanagement and inadequate protection (Pointet, 2022).

Recent CRB studies showed that subsurface water storage (including groundwater [GW] and soil moisture) contributes significantly (~82%) to the total water storage variation rather than the surface water storage (~18%), which is the focus of attention for both the scientific community and the general public (Kitambo et al., 2025). The work conducted by Kitambo et al. 2025 based on the decomposition of total water storage anomalies (TWSA) has revealed notable spatial and temporal GW storage dynamics patterns linked to the basin's hydrogeological formations and baseflow behavior. In CB-CSI, the integration of satellite-derived GW information with other sources of data such as regional hydrogeological maps (i.e., Africa groundwater atlas), borehole databases, land use, rainfall, evapotranspiration, and both in situ and modelled river discharge datasets offers a unique opportunity to support GW monitoring, identify priority zones for field measurements, compare GW variability across aquifer systems, and provide indicators for drought preparedness, water supply planning, and conjunctive surface-groundwater management. Figure 18 shows the characterization of the spatial distribution of Groundwater Storage Anomaly from 2002 to 2015, over the 1740 CB-CIS catchments.

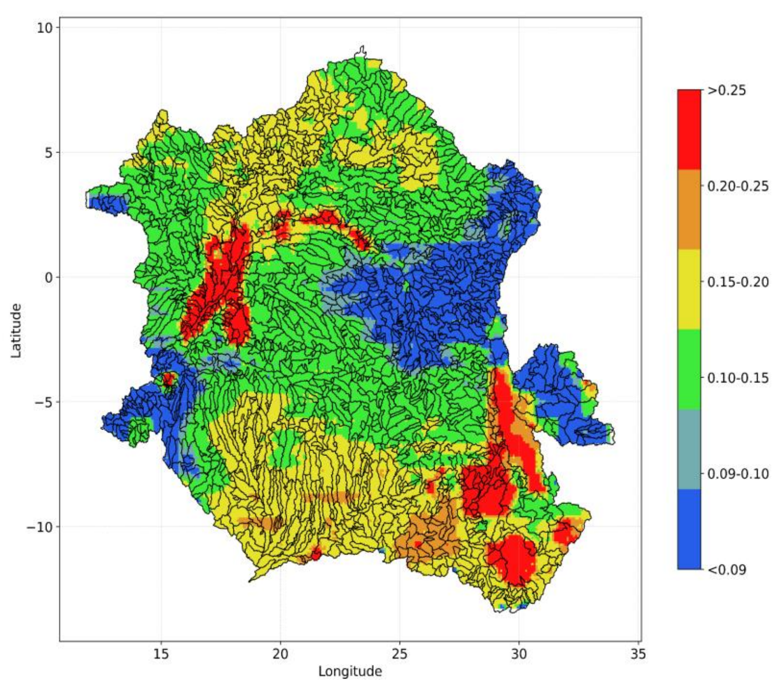

Figure 18. *Characterization of the spatial distribution of Groundwater Storage Anomaly from 2002 to 2015, over the 1740 CB-CIS catchments: Amplitude expressed in km*^{3}

6.3. Advancing navigation safety through integrated bathymetry, hydrodynamic modelling, and risk assessment in CB-CIS

The CRB supports one of the most extensive inland waterway systems in the world, with approximately 25000 km of navigable waterways classified according to available draft under high- and low-flow conditions (Trigg et al., 2022). Within these networks, the middle reach, specifically the Kisangani-Kinshasa axis (Figure 19 A), falls within the first category, extending over 1 740 kilometers and providing an estimated draft of 2 m and 1.3 m during high and low flow seasons, respectively (CICOS, 2024). Despite its strategic importance for regional connectivity and freight transport, safe navigation remains severely constrained by complex channel morphology, shifting flow paths, and the near absence of operational hydrographic information (Tshimanga et al., 2022d).

A major challenge along this reach is the transition from relatively confined single-thread sections to highly braided and multichannel river segments characterised by dense island complexes, unstable banks, and multithread reaches (Carr et al., 2022; Kechnit et al., 2024a). These morphological conditions make navigable routes highly variable in space and sensitive to hydrological fluctuations. In practice, river navigation still depends heavily on outdated maps and local pilot knowledge, contributing to substantial safety risks, including an estimated 2,000 fatalities annually (Tshimanga et al., 2022d). In this context, CB-CIS is not limited to the role of a geospatial repository. However, it provides a structured information-system framework for organizing and managing river morphology as interoperable spatial layers suitable for navigation analysis and operational decision support. The morphological component of this framework is illustrated in Figure 19, which assembles the key static and semi-static geospatial layers required for navigation, including basin-scale localisation, chainage referencing, water masks, island and riverbank delineation, and bathymetric data.

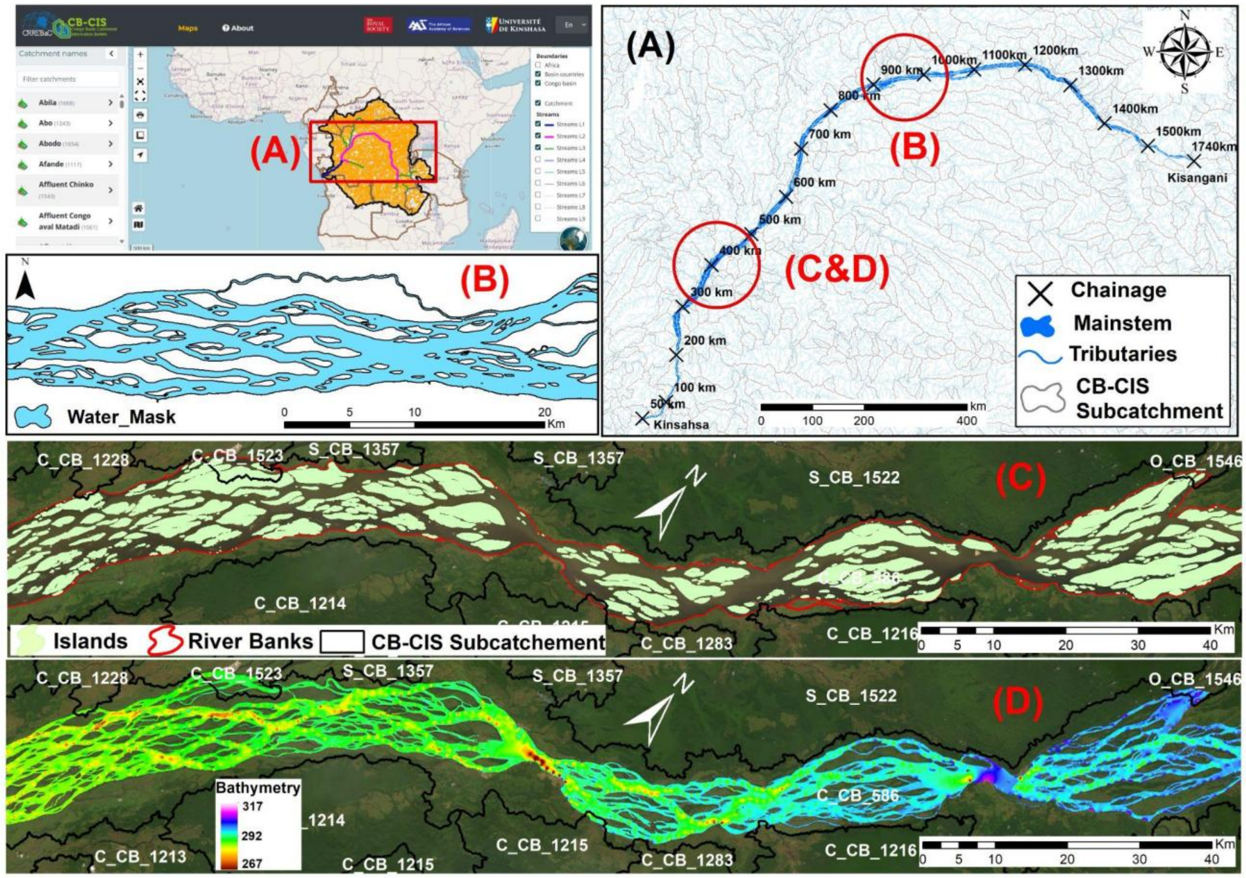

Figure 19. *Morphological and geospatial information layers for navigation assessment in the Congo River middle reach. (A) CB-CIS interface showing basin-scale localization of the study corridor; (B) chainage-based spatial referencing of the Kisangani–Kinshasa reach within the CB-CIS hydrographic framework; (C) water-mask, island, and riverbank layers derived from integrated geospatial observations; and (D) bathymetric context of multichannel sections used to characterize morphological complexity and support navigation-related information management.*

Recent field investigations along the middle reach have generated a comprehensive observational basis through the integration of in situ bathymetric surveys, Sentinel-2 land-use/land-cover information, continuous GNSS-derived water-surface elevations, and ADCP discharge measurements (Carr et al., 2019; Tshimanga et al., 2022; Kechnit et al., 2024b). Within CB-CIS, these heterogeneous datasets can be standardised, georeferenced, and linked to catchment units and chainage-based referencing, thereby converting fragmented observations into a coherent set of interoperable digital layers. This integration provides the data infrastructure required for hydraulic modelling, spatial analysis, and subsequent operational deployment within a common geospatial environment.

These datasets were subsequently integrated to develop and calibrate a two-dimensional multichannel hydraulic model able to resolve spatially distributed depth, water-surface elevation, and velocity patterns along the 1,740 km study corridor under low-flow steady-state conditions. The resulting analytical layers are presented in Figure 20, which highlights the simulated hydraulic state of the corridor through water-surface elevation fields, flow velocity distributions, and depth patterns across selected reaches. Their inclusion within CB-CIS is of particular significance from an information-system perspective, since model outputs are thereby transformed into operational geospatial layers that can be archived, queried, visualized, compared, and revised as new observations become available.

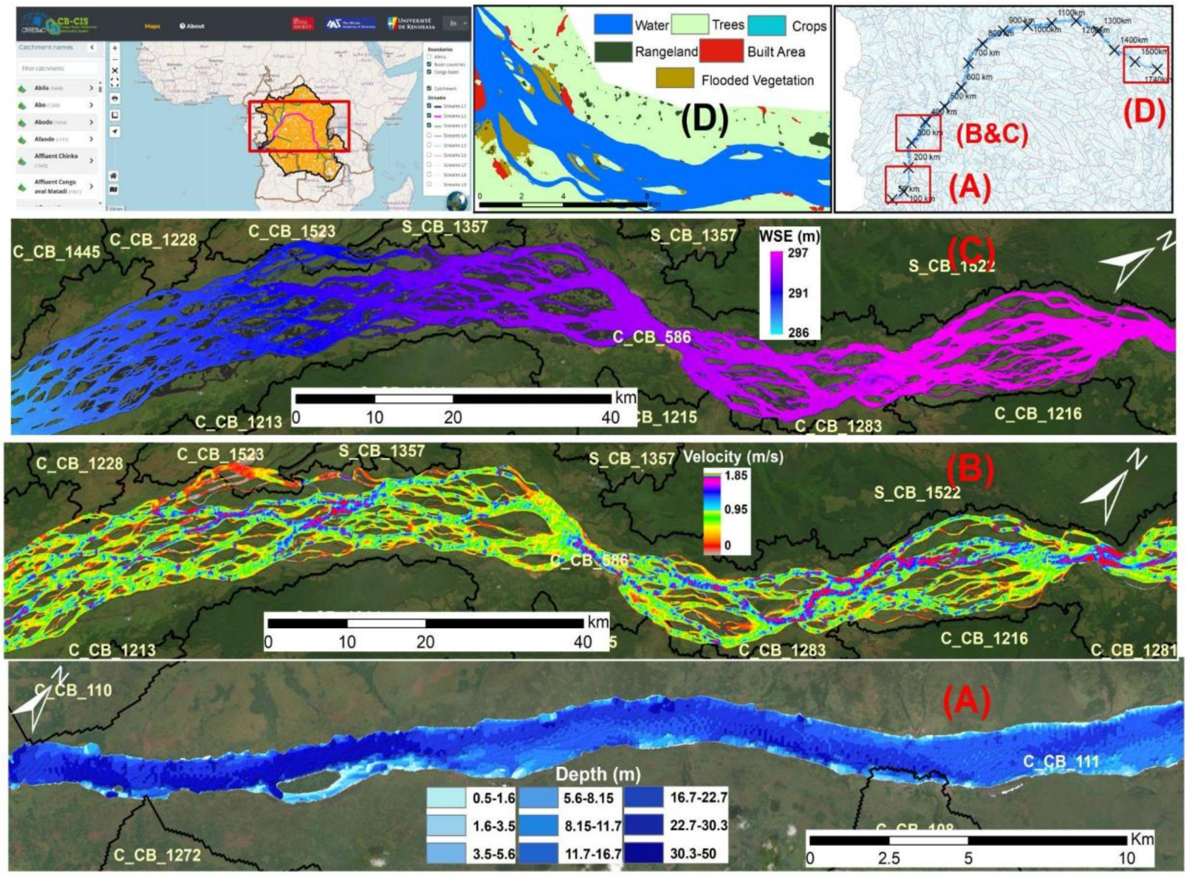

***Figure 20**. Simulated hydraulic information layers for navigation risk assessment in the Congo River middle reach. (A) depth distribution in a representative river section; (B) spatial variability in simulated flow velocity across multichannel reaches; (C) longitudinal pattern of water-surface elevation; and (D) associated land-use/land-cover and reach-selection context used to interpret hydraulic models*

Based on depth and velocity thresholds, the hydraulic analysis identified approximately 619 km² of high-risk navigation zones, corresponding to 9.87% of the total navigable water surface within the middle reach. These zones represent areas where shallow depths or elevated flow velocities may compromise safe vessel passage. The resulting spatial products provide the analytical basis for identifying constrained reaches, screening hazardous channel segments, and delineating preferred navigation corridors. When integrated within CB-CIS, these outputs acquire operational relevance through their direct association with hydrographic units, chainage segments, and other thematic layers relevant to inland waterway management. The result is a transition from static map-based interpretation toward dynamic, reach-specific navigation risk assessment.

The principal contribution of CB-CIS in this application lies in its capacity to integrate morphological observations, bathymetric measurements, and hydraulic simulations within a unified geospatial information architecture. Bathymetric surfaces, island extents, riverbank boundaries, hydraulic state variables, and navigation risk indicators can thereby be managed as scalable and continuously updateable information layers. Such an architecture supports progressive refinement as additional field measurements, remote-sensing products, or modelling updates become available, while preserving consistency with the basin's hierarchical hydrographic framework. CB-CIS thus constitutes an integrated hydroinformatic environment through which previously fragmented datasets are transformed into a structured, queryable, and operational decision-support system for inland navigation management in the Congo Basin.

6.3. Flood hazard risk assessment

Within the Congo Basin, flood risk assessment remains challenging because large portions of the basin are poorly gauged and characterized by limited hydrometeorological observations. Traditional flood analysis approaches relying exclusively on in-situ measurements are therefore insufficient to capture the spatial complexity of flood processes across such a vast region. Advances in Earth observation, global hydrodynamic modelling, and geospatial data integration now provide opportunities to assess flood hazards consistently across large tropical river systems.

This case study applies CB-CIS to evaluate both fluvial and pluvial flood hazards across 1,740 hydrological catchments of the Congo Basin. The assessment combines state-of-the-art hydrodynamic flood modelling with spatial population datasets to quantify exposure under different flood recurrence intervals and identify catchments with elevated flood risk.

Fluvial flood hazards were derived from global inundation maps generated using the LISFLOOD-FP hydrodynamic model (Sampson et al., 2015). LISFLOOD-FP simulates riverine flooding at approximately 90-m spatial resolution and has been widely applied for large-scale flood risk assessments worldwide. The model incorporates river networks derived from the MERIT Hydro dataset (Yamazaki et al., 2019), while sub-grid hydraulic formulations enable representation of river channels that are smaller than the computational grid resolution (Bates et al., 2010; Neal et al., 2012). This modelling approach is particularly valuable in the Congo Basin, where many flood-prone areas lack adequate hydrometric monitoring and remain effectively ungauged. Flood hazard layers corresponding to 10, 20, and 50-year return periods were integrated into CB-CIS to assess exposure under events of increasing magnitude.

In addition to riverine flooding, pluvial flood hazards were analysed to capture inundation resulting from intense rainfall events that exceed local infiltration capacities and drainage system performance. Pluvial flooding represents a growing concern in urbanizing regions, low-lying landscapes, and poorly drained catchments where runoff accumulation can generate substantial impacts independently of river overflow. Through the integration of pluvial inundation layers with catchment boundaries, land-cover information, and population datasets, CB-CIS identifies locations where extreme precipitation may generate significant flood impacts beyond major river corridors.

Population exposure was estimated by overlaying flood hazard extents with gridded population datasets. For each catchment, the proportion of population exposed to inundation was calculated for the 10, 20, and 50-year return periods. Exposure statistics were subsequently aggregated according to the CB-CIS catchment classification system, enabling systematic comparisons across hydrological regions and facilitating the identification of flood-risk hotspots at multiple spatial scales. This catchment-based approach provides a scientifically robust framework for prioritizing flood risk management interventions and supporting evidence-based decision making.

Figure 21 shows spatial distribution of population exposure to undefended fluvial hazards, revealing high risks along the Congo main stem and major tributaries. Exposure increases with flood magnitude as inundated areas expand. Figure 22 illustrates exposure to pluvial hazards, which are more dispersed and shaped by local topography, rainfall intensity, land cover, and drainage. Several catchments with moderate fluvial exposure show high pluvial vulnerability, underscoring the need to consider both mechanisms in risk assessments.

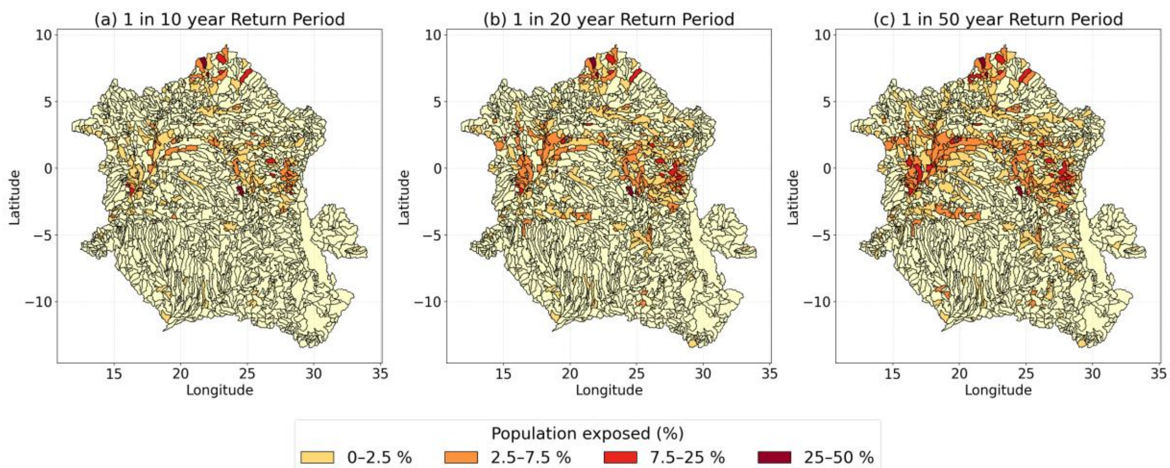

Figure 21 *Fluvial undefended Flood Risk population Exposure over the CB-CIS catchments*

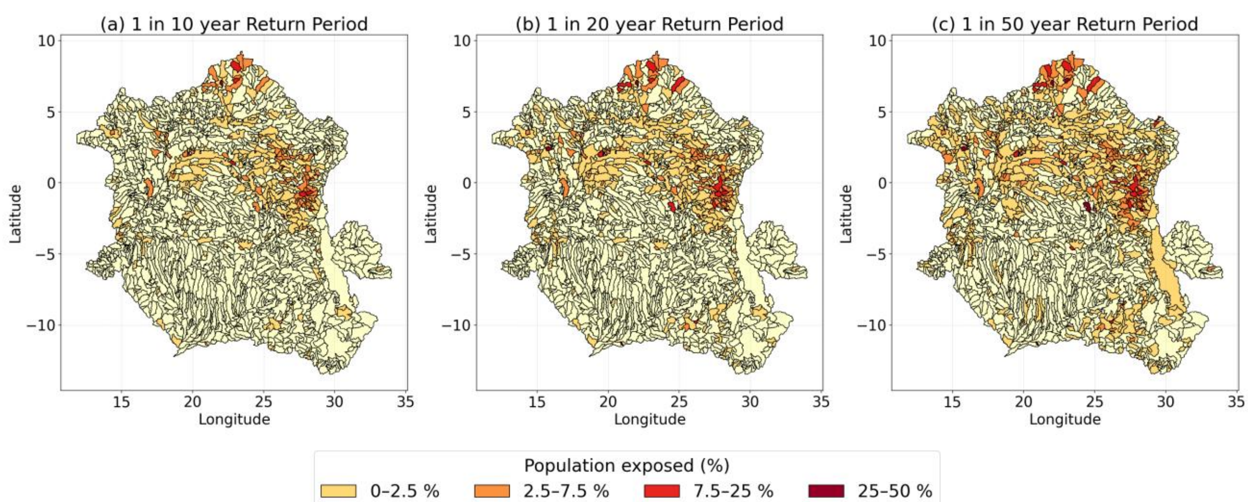

Figure 22 *Pluvial Flood Risk population Exposure across CB-CIS catchment*

The results reveal substantial spatial variability in flood exposure across the Congo Basin. High levels of fluvial flood risk are concentrated along the Congo River main stem and major tributaries, where extensive floodplains support large populations and critical economic activities. As expected, exposure increases with flood magnitude as inundated areas expand under higher return-period events. In contrast, pluvial flood hazards exhibit a more dispersed spatial pattern, influenced primarily by local topography, rainfall intensity, land cover characteristics, soil properties, and drainage conditions. Several catchments exhibiting relatively moderate riverine flood exposure nevertheless show elevated vulnerability to pluvial flooding, highlighting the importance of considering multiple flood-generating mechanisms within comprehensive risk assessments.

The integration of flood hazard information within CB-CIS demonstrates the value of digital hydrological infrastructures for enhancing flood resilience across the Congo Basin. By linking hydrodynamic modelling outputs with socio-economic exposure indicators and catchment classification frameworks, CB-CIS provides a scalable platform for supporting early warning systems, climate adaptation strategies, infrastructure planning, and disaster risk reduction initiatives. Such integrated assessments are essential for improving preparedness and reducing vulnerability in one of the world's largest and most hydrologically complex river basins.

6.2. Climate change impact assessment

Figure 23 presents an application case of climate change impact assessment across 81 catchments of the central parts of the Congo Basin, Aruwimi sub basin. The analysis demonstrates the operational value of CB-CIS as an integrated platform for hydrological modelling, climate risk assessment, and decision support. The assessment used an ensemble of twelve climate models under three Shared Socioeconomic Pathways: SSP1-2.6, SSP2-4.5, and SSP5-8.5. These scenarios were applied to evaluate projected changes in key water balance components at catchment scale, relative to the historical baseline. The analysis provides spatially explicit information on potential changes in precipitation, evapotranspiration, runoff, soil moisture, groundwater recharge, and related hydrological processes. This case study highlights the scientific role of CB-CIS in translating climate projections into hydrologically meaningful indicators. It supports the identification of climate-sensitive catchments, hydrological hotspots, and areas where future water availability may be altered. By linking climate scenarios with catchment-based hydrological modelling, CB-CIS strengthens the capacity to assess climate impacts on flow regimes, water resources, forested landscapes, and wetland systems.

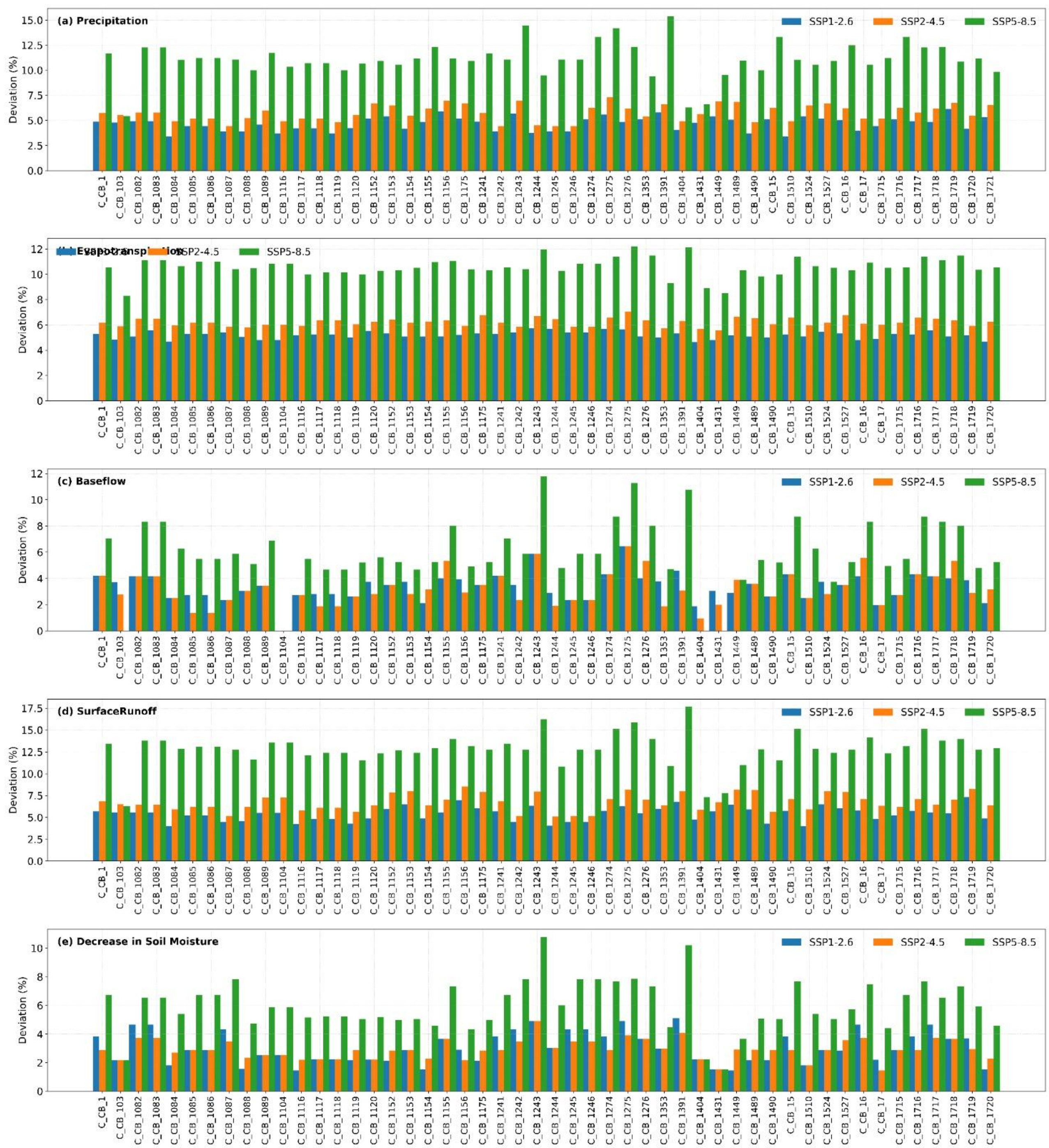

Figure 23. *Climate change projections of water balance component scenarios: deviation from the historical in percentage*

6.6. Catchment Vulnerability Analysis: Application to the Aruwimi, Itimbiri, and Uele Catchments

An important application developed within the CB-CIS is the Catchment Vulnerability Index (CVI). This index serves as a comprehensive tool for assessing vulnerability and for supporting the design of targeted adaptation strategies that address environmental, socio-economic, and institutional challenges related to climate change. By doing so, the CVI contributes to strengthening the resilience of communities and ecosystems to future climate pressures.

This application case applies to three main drainage areas of the north-eastern region of the CRB - the Uele, Aruwimi, and Itimbiri rivers- which undergo huge pressure in terms of climate variability, water stress, migrations and conflicts. Congo Basin systems: (Lutonadio et al., 2026; Tshimanga et al., 2022c). This encompasses extensive peatland systems and hold significant potential for hydropower generation, agriculture, livestock production, water supply, and inland navigation. However, the region is also recognized as a hotspot of multiple and interconnected challenges (Tshimanga et al., 2021; Tshimanga et al., 2022c), which include the impacts of climate change on agricultural and livestock systems (Karam et al., 2022; Tshimanga et al., 2026), limited access to food and safe water, weak institutional capacity and limited access to appropriate technologies to support livelihoods (UNEP, 2011; Tshimanga et al., 2026), as well as high rates of deforestation and natural resource degradation (Atyi, 2022). In addition, the region faces recurring outbreaks (e.g., cholera and ebola) and ongoing politico-military instability (Kabamba, 2015; Furlow, 2022). Furthermore, over recent decades, the Itimbiri, Aruwimi, and Uele region have been increasingly affected by the migration of Mbororo pastoralists from the Lake Chad region (Tshimanga et al., 2021). This movement has intensified agro-pastoral conflicts, driven by climate variability, water scarcity, and competition over natural resources. Women and girls are disproportionately affected by these dynamics (Lutonadio et al., 2026). As a result, the climate-water-migration-conflict nexus has become more pronounced, further increasing regional vulnerability.

To help address these overlapping and interlinked challenges, the CVI was developed as an aggregated vulnerability index and a structured framework (Figure 24), providing policymakers and researchers with a practical tool to prioritise interventions in catchment scale, monitor systemic fragility, particularly in ecologically sensitive and fragile environments such as Congo Basin peatlands and mangroves. Most importantly, the CVI enables the integrated assessment of hydrological and climate-related risks and supports the design context-sensitive adaptation and resilience pathways in complex tropical socio-ecological systems.

The development and application of the CVI demonstrate how the CB-CIS can transform integrated hydrological, environmental, socio-economic, and governance data into actionable decision-support tools for climate adaptation and resilience planning. Methodologically, the approach adopts a systems-based perspective (Figure 24), consistent with the CB-CIS framework. It integrates three core dimensions of vulnerability: climate exposure, ecosystem sensitivity, and adaptive capacity.

- Climate exposure is represented by the Standardised Precipitation Evapotranspiration Index – 12 months (SPEI-12), a hydro-climatic indicator that combines key climatic variables, including precipitation, evapotranspiration, and temperatures. This index is flexible and well-suited to capturing climate variability, long-term change, and extreme events in the Congo Basin (Lutonadio et al., 2026; Karam et al., 2022).
- Ecosystem sensitivity is characterised using a land-cover indicator (LCI) derived from the CB-CIS. It reflects the proportion of the catchment area covered by forest and serves as a proxy for ecosystem stability and resilience (Tshimanga et al., 2022c). Together with exposure, sensitivity forms the subsidiary forms the subsidiary component of vulnerability known as potential impact, which illustrates the combined effects of climatic and environmental pressures on ecosystems.
- Adaptive capacity is assessed through a set of socio-economic and governance indicators, including food security, access to water supply, migration and conflict linked to climate and water stress, gender inequality, and the presence and effectiveness of catchment management authorities (Lutonadio et al., 2026; Tshimanga et al., 2021).

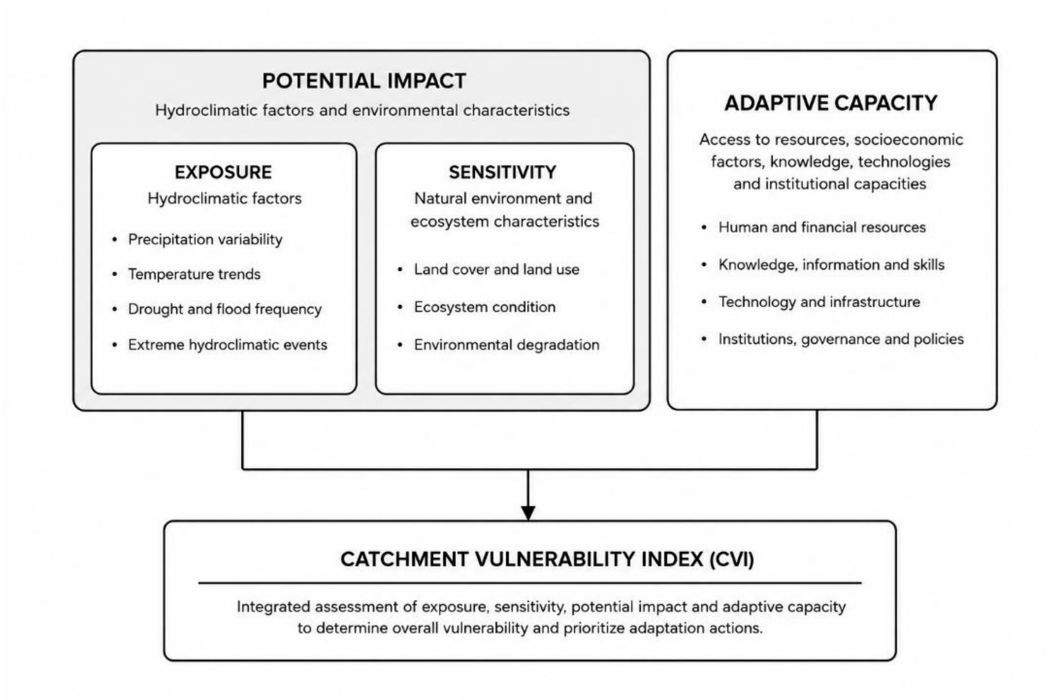

***Figure 24**. Conceptual framework for the development of the CVI*

All indicators were standardised, weighted, and aggregated to produce a composite vulnerability index, following established approaches in vulnerability assessment (Parry et al., 2007; IPCC, 2022; Lutonadio et al., 2026).

Standardisation of indices

Standardisation ensures that vulnerability indices are comparable before aggregation by assigning meaning to their values. In this process, "0" represents an optimal situation where no improvement is needed, while "1" indicates a critical condition where the system is no longer functioning. Lower scores reflect lower vulnerability, whereas higher scores indicate higher vulnerability. The maximum-minimum method was used to standardise the indices, according to the following equation:

$$\mathbf{Xi\ 1\ to\ 0} = \frac{\boldsymbol{Xmax - Xi}}{\boldsymbol{X\ max - Xmin}}$$

Where Xi 1 to 0 represents the standardised value within the field from 0 to 1; Xi represents the value of the individual data to be standardised; Xmin represents lowest value of the index; and Xmax represents the highest value of the index.

Aggregation of indices

Aggregation combines multiple indices into a single composite indicator of vulnerability. A weighted arithmetic method is used due to its transparency and ability to minimise distortion when integrating diverse factors. Weights are assigned based on expert judgement, grounded in the realities of the catchments and informed by the experience of water users, local communities, and domain experts, ensuring that the relative importance of each indicator and component is accurately represented (Parry, 2007; OCDE, 2017; Lutonadio et al., 2026). The aggregation is carried out in three main steps.

- Aggregation of component indices involves combining individual indicators to produce indices for each vulnerability component. The formula below summarises this method. It is important to note that this formulation is applied, for this case, only to adaptive capacity, for which nine socio-economic indicators were identified to derive the composite adaptive capacity index.

$$\mathbf{Ic} = \frac{\boldsymbol{I1} * \mathbf{C1} + \boldsymbol{I2} * \mathbf{C2} + \cdots \boldsymbol{In} * \mathbf{Cn}}{\Sigma\mathbf{C}}$$

Where Ic represents the composite index representative of a vulnerability component; I represents the individual index of a vulnerability; C represents the weighting coefficient assigned to the index; and n: nth index or coefficient.

- Aggregating exposure and sensitivity into a potential impact index: recognising that these two components contribute to the same level of vulnerability and highlighting the interdependence between vegetation dynamics (e.g., deforestation) and local hydroclimatic patterns. The formula is as follows:

$$\boldsymbol{PI} = \frac{\boldsymbol{EX} * \boldsymbol{CEX} + \boldsymbol{SE} * \boldsymbol{CSE}}{\boldsymbol{CEX} + \boldsymbol{CSE}}$$

Where PI represents the composite index of potential impact; EX represents exposure (measured using the SPEI); SE represents sensitivity (represented by the land cover indicator); and C represents the weighting coefficient assigned to each factor (1/2).

- Aggregating potential impact with adaptive capacity to derive the CVI reflects their relative contributions, with adaptive capacity accounting for three-quarters (3/4) and potential impact, resulting from exposure and sensitivity, for one-quarter (1/4). The formula is presented below:

$$CVI = \frac{PI * CPI + AC * CAC}{CPI + CAC}$$

Where CVI represents the catchment vulnerability index; PI represents the composite potential impact index; AC represents the composite adaptive capacity index; C represents the weighting assigned to vulnerability components (CPI=1/4 and CAC=3/4).

Figure 25 illustrates catchment exposure based on the SPEI scale, where values of −2.5 indicate extreme drought conditions and +2.5 indicate extremely wet conditions. Overall, the three catchments (Uele, Aruwimi, and Itimbiri) show conditions ranging from moderate drought to moderately humid environments. A clear spatial gradient is observed, with drier conditions in the eastern part of the region and progressively more humid conditions towards the west. This variation is also evident along the latitudinal gradient, with increasing dryness observed as distance from the Equator increases, highlighting significant heterogeneity across sub-catchments. These spatial differences underline the importance of considering local-scale variability when understanding exposure patterns.

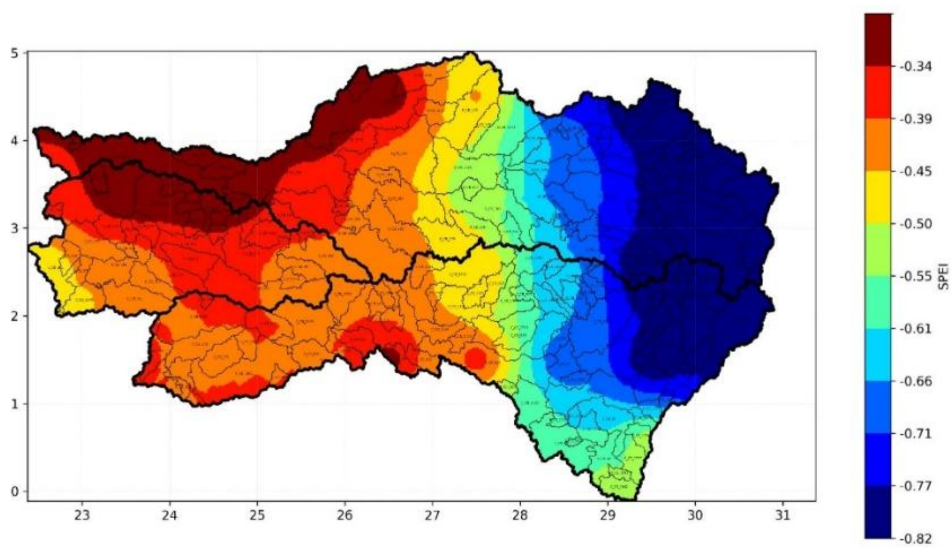

Figure 25. *Spatial distribution of climate exposure based on the Standardized Precipitation Evapotranspiration Index (SPEI)*

Figure 26 presents catchment sensitivity based on the LCI, where a value of 0 represents an optimal situation with full forest cover, and 1 indicates areas with little or no vegetation cover. The map highlights spatial patterns of forest cover across the sub-catchments. The Aruwimi and Itimbiri catchments, generally located closer to the Equator within the central basin, remain largely forested, although some sub-catchments show localised areas of deforestation linked to logging and mining activities. Lower forest cover is observed in some eastern sub-catchments, likely associated with hilly terrain and mining activities. In contrast, the Uele sub-catchments, located further from the Equator, exhibits lower overall forest cover, indicating higher sensitivity.

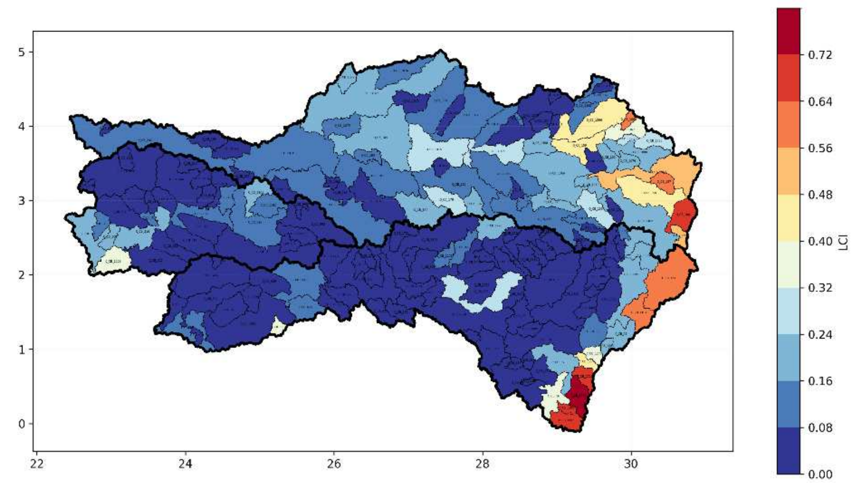

Figure 26. *Spatial distribution of ecosystem sensitivity based on the Land Cover Indicator (LCI)*

Figure 27 presents catchment adaptive capacity based on the standardised adaptive capacity indicators across the Uele, Aruwimi, and Itimbiri catchments. It is based on household survey data representative of basin-wide socio-economic and institutional conditions (Lutonadio et al., 2026; Tshimanga et al., 2021). Adaptive capacity is assessed using a set of socio-economic, water, and governance indicators linked to the climate risks and broader context of climate-water-migration-conflict identified in these catchments, including Food Accessibility Index (FAI), Poor Food Consumption Index (PCI), Poor Diet Quality (PDQ), No Decline in Production (NDP), No Storage of Agricultural Production (NSAP), No Resilient Crops and Breeds (NRCB), No Downstream Water Consideration (NDWC), Conflict on Property (COP), Displaced or Migrant Households (DMH), Non-Women-Headed Households (NWHH), Women in Non-Agricultural Sector (WNAS), No Structural Mitigation (NSM), No Alternative Water Source (NAWS), No Drinking Water Access (NDWA), No Irrigation System (NIS), and No Watershed Management Organisation (NWMO). The consistently high values of No Structural Mitigation (NSM), No Resilient Crops and Breeds (NRCB), No Irrigation System (NIS), and No Watershed Management Organisation (NWMO) indicate that adaptive capacity is strongly constrained by structural and institutional limitations. While some variability exists, particularly in No Alternative Water Source (NAWS) and No Drinking Water Access (NDWA), vulnerability is primarily driven and exacerbated by socio-economic and governance factors rather than environmental conditions.

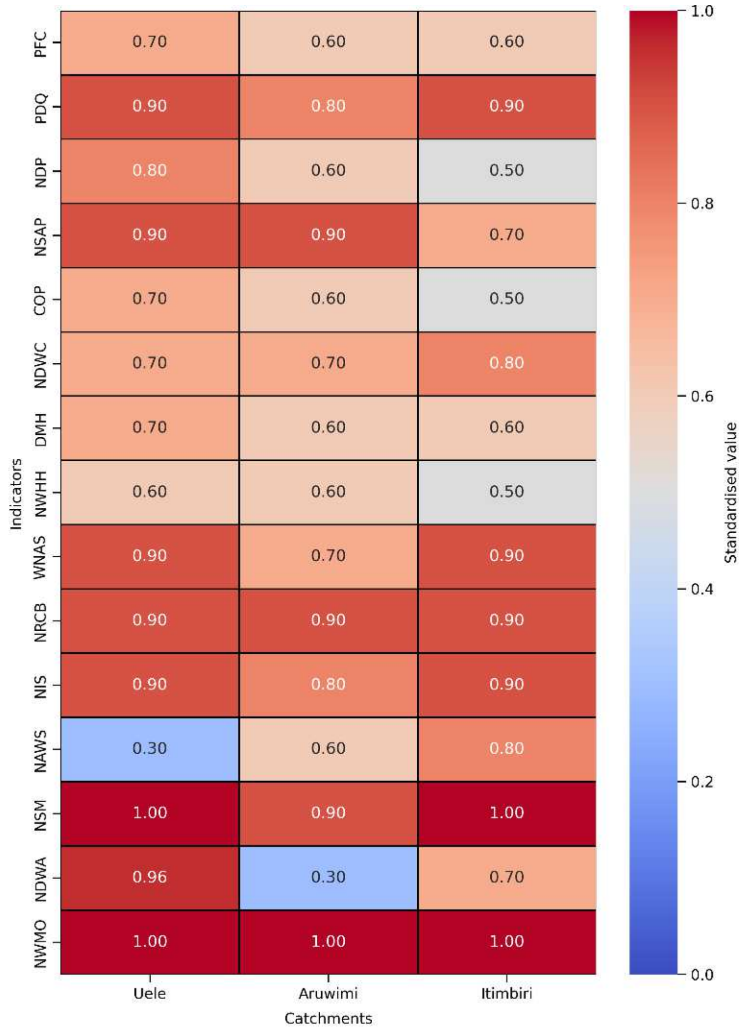

Figure 27. *Matrix representation of standardised adaptive capacity indicators across the Uele, Aruwimi, and Itimbiri catchments*

The ultimate result of this process is the Catchment Vulnerability Index presented in Figure 28, showing that the three catchments exhibit moderate to high vulnerability, with CVI scores ranging from 0.6 to 0.7. The Uele sub-catchments appear to be the most vulnerable overall, whereas the Itimbiri and Aruwimi sub-catchments show slightly lower vulnerability levels. However, localized areas of higher vulnerability are also observed within these catchments.

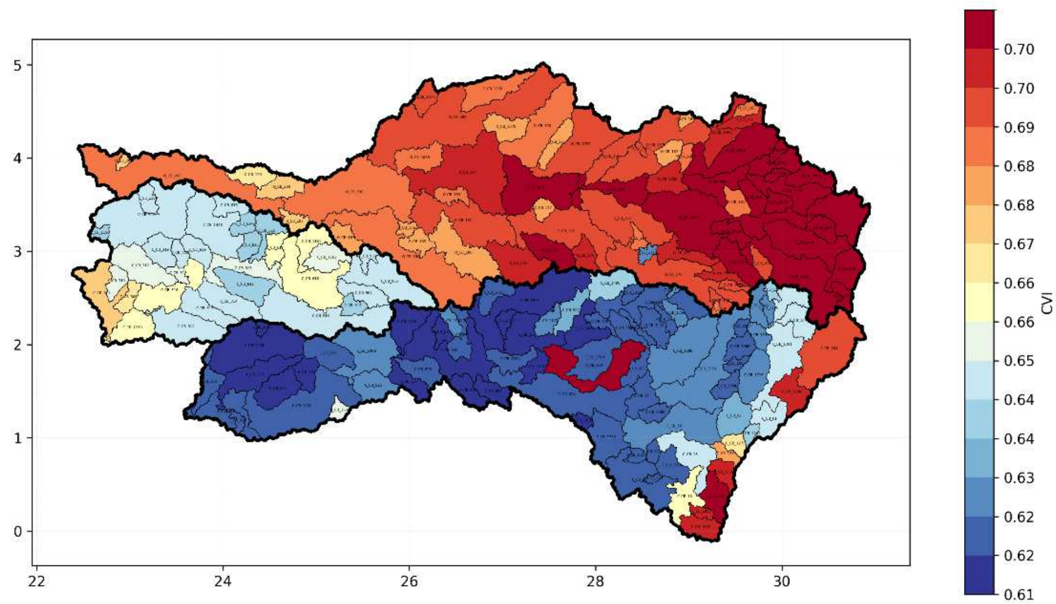

Figure 28. *Catchment Vulnerability Index (CVI) map highlighting vulnerability hotspots and spatial variability across the Uele, Aruwimi, and Itimbiri sub-catchments*

In summary, the CVI offers a practical tool for identifying vulnerability hotspots, prioritising adaptation investments, targeting climate-resilient interventions, strengthening water services efforts, and monitoring progress towards sustainable catchment development. Within the CB-CIS framework, it shows how integrated, catchment-scale information can support evidence-based decision-making and more coherent, systems-based management of the Congo Basin under increasing climate and socio-economic pressures. Although climate exposure and ecosystem sensitivity are relatively similar across the catchments, notable differences emerge at the sub-catchment level. These variations provide important insights into local or sub-catchments dynamics and highlight the need for targeted, context-specific adaptation and management strategies.

By bringing together multiple dimensions of vulnerability into a single framework, the CVI provides a clear and structured way to understand climate risks and their underlying drivers. In doing so, it helps address key practical questions: where the most vulnerable sub-catchments are, which factors should guide adaptation and resilience priorities, and what underlying constraints or barriers contribute to increasing vulnerability to climate change.

7. Discussion and Conclusion

Despite decades of PUB research (Hrachowitz et al., 2013), hydrological prediction remains particularly challenging in tropical regions where monitoring networks are sparse and environmental heterogeneity is high. This global trend suggests that effective basin-scale management cannot rely solely on isolated observations or sector-specific datasets, but requires analytical frameworks capable of integrating physical, ecological, socio-economic, and governance dimensions within a coherent systems architecture. It aligns with the growing recognition that river basins function as coupled socio-ecological systems characterized by nonlinear interactions, feedback mechanisms, and cross-scale dynamics (Berkes et al., 2001; Sivapalan et al., 2012). Recent studies have emphasized that environmental change, infrastructure development, and human interventions increasingly influence hydrological processes, creating management challenges that transcend traditional disciplinary boundaries (Wagener et al., 2010; Damasco et al., 2025).

The CRB represents an extreme example of this challenge because of its vast spatial extent, extensive wetlands and peatlands, complex physiography, and long-term deterioration of hydrometric networks (Tshimanga et al., 2026). CB-CIS represents an important step toward addressing one of the fundamental challenges of water resources management in large tropical and ungauged river basins: transforming fragmented environmental observations into actionable knowledge for decision-making. The results obtained in this study demonstrate that effective management of the CRB requires more than hydrological monitoring alone. It also requires integrated digital infrastructures capable of linking hydrological, ecological, socio-economic, and governance information within a common analytical framework. By integrating these dimensions into a single hydro-informatic framework, CB-CIS contributes to the emerging paradigm of systems-based river basin management.

A major scientific contribution of CB-CIS lies in its operationalization of catchment classification as a foundation for prediction in ungauged and poorly gauged basins (PUB). The nested classification framework developed in this study demonstrates how physiographic controls, socio-economic drivers, and hydronymic information can be combined to create hydrologically meaningful units that support regionalization and knowledge transfer (REF). By reducing basin complexity while preserving dominant process controls, the framework strengthens the scientific basis for hydrological modelling, monitoring network design, and uncertainty reduction in data-scarce environments.

The study also highlights the growing importance of digital hydrological infrastructure in contemporary water governance. Traditional water information systems often focus on data storage and visualization, whereas CB-CIS was designed as an integrated hydrological infrastructure platform that combines multi-source observations, geospatial databases, modelling tools, and decision-support functions. This approach reflects broader developments in environmental informatics, where advances in remote sensing, cloud computing, and geospatial analytics increasingly enable the integration of heterogeneous datasets into operational management systems (Ma et al., 2025). For the CRB, where observational gaps remain extensive, the integration of in situ measurements, remote sensing products, environmental databases, and socio-economic information provides a practical pathway for improving information availability and supporting evidence-based decision-making. Importantly, the value of such infrastructure extends beyond technological innovation. By improving data accessibility, interoperability, and transparency, digital hydrological infrastructures can strengthen institutional coordination, enhance stakeholder participation, and improve evidence-based decision-making. In transboundary basins such as the Congo, these functions are particularly important because water governance depends on the ability of multiple actors to access shared information and develop common understandings of basin dynamics.

An important innovation of CB-CIS is the explicit integration of socio-hydrological and governance dimensions into the information architecture. Water management challenges in the CRB are closely linked to navigation, hydropower development, agriculture, mining, biodiversity conservation, urbanization, and climate adaptation. Consequently, hydrological processes cannot be analysed independently from the human systems that influence and depend upon them. Water management decisions in such areas frequently involve trade-offs among competing environmental, economic, and social objectives. The inclusion of socio-economic indicators, governance variables, and water-use information therefore extends the analytical scope of the platform beyond conventional hydrological databases. This broader perspective is increasingly recognized as necessary for supporting integrated water resources management and adaptive governance under conditions of environmental change and institutional fragmentation. More than 1,300 named rivers and historically recognized hydrographic systems were integrated into the catchment hierarchy, creating a bridge between scientific hydrography and local knowledge systems. Hydronyms frequently encode information related to environmental conditions, flood behaviour, navigation routes, ecosystem characteristics, and cultural relationships with water bodies. Their inclusion contributes to preserving indigenous and local knowledge while enhancing hydrographic databases and promoting more inclusive approaches to water governance. This integration reflects increasing recognition of the value of combining scientific and local knowledge systems in environmental management.

From an operational perspective, the application cases demonstrate the capacity of CB-CIS to support a wide range of management objectives, including water balance assessments, flood forecasting, navigation planning, peatland monitoring, hydropower development, climate adaptation, and water quality management. These applications illustrate how integrated hydrological information systems can contribute to climate resilience and sustainable development. By integrating hydrological, ecological, and socio-economic information, CB-CIS provides a platform for assessing ecosystem vulnerability and supporting conservation planning.

Despite these advances, several limitations remain. Significant observational gaps continue to affect hydrological analyses and model calibration across many parts of the basin. Although remote sensing products substantially improve spatial coverage, they cannot fully replace long-term ground observations. In addition, key processes such as wetland–river exchanges, groundwater interactions, peatland hydrodynamics, and biogeochemical feedbacks remain insufficiently represented in current modelling frameworks. Addressing these limitations will

require continued investment in monitoring networks, model development, and interdisciplinary research.
The long-term sustainability of CB-CIS will also depend on institutional cooperation, data-sharing mechanisms, technical capacity development, and sustainable financing arrangements. Experience from other transboundary river basins suggests that governance challenges often become more significant constraints than technological limitations. Future developments should therefore focus on strengthening interoperability among institutions, expanding real-time monitoring systems, integrating artificial intelligence and machine learning techniques, and developing digital twins for major sub-basins.
Overall, CB-CIS demonstrates how catchment classification, digital infrastructure, socio-hydrological integration, and adaptive governance can be combined to strengthen hydrological intelligence in one of the world's most complex and least monitored river basins. Beyond the CRB, the framework offers a transferable model for improving water governance and climate resilience in large tropical river basins facing similar challenges of environmental complexity, observational scarcity, and institutional fragmentation.

Funding statement

This work was supported by the Royal Society and the UK Foreign, Commonwealth & Development Office (FCDO) under the FLAIR and the Congo Rainforest Alliance for Forest Training for Sustainable Development grants.

Clinical trial number
Not applicable.

Ethics and consent
Not applicable.

Consent to publish
Not applicable.

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