Development of the digital suitability map toolbox

For IDP camp suitability in Borno, Adamawa and Yobe (BAY) states, Nigeria

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Executive summary

The digital suitability map toolbox aims to support data-driven decision-making for selecting suitable locations and prioritizing interventions in both current and new IDP camps. The toolbox consists of five thematic maps: Groundwater Availability, Groundwater Quality, Environmental Degradation, Flood Risk, and Terrain Characteristics. These maps collectively form an overall suitability map. The maps are integrated into a user-friendly web application, enabling IOM and other stakeholders to easily access the suitability maps from both office environments and field locations. This web application offers essential baseline information for identifying, prioritizing, and conducting site-specific studies, such as flood risk assessments with mitigation plans or water resource evaluations with groundwater development strategies.
This document describes the development of and the data underlying the digital suitability map toolbox.

Colophon

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1 Introduction

1.1 Aim of digital suitability map toolbox

Borno, Adamawa and Yobe (BAY) states in northeast Nigeria face recurrent seasonal floods due to its unique topography and soil characteristics. These floods significantly impact both the camps for internally displaced persons (IDPs) and surrounding host communities, leading to loss of life, property damage, and the spread of diseases. Among the most vulnerable populations are the IDPs, who are disproportionately affected by the consequences of flooding. In response to this ongoing challenge, the Borno State government has launched an initiative to alleviate overcrowding in IDP camps by resettling a portion of the population into newly identified sites.

To support this effort, the International Organization for Migration (IOM) is playing a key role in managing water resources in the affected areas. A crucial aspect of IOM's involvement is the application of digital tools to assess suitable drainage basins in the camps, while identifying and evaluating the effectiveness of potential flood mitigation measures. The current study aims to develop a comprehensive Suitability Map for the BAY states. This map classifies areas based on their suitability, with a color scale ranging from high (green) to low (red) suitability. The map has been developed based on five thematic layers: Groundwater Availability, Groundwater Quality, Environmental Degradation, Flood Risk, and Terrain Characteristics. These maps collectively form an Overall Suitability Map.

The maps of the Digital Suitability Map Toolbox are integrated into a user-friendly web application, available on https://iom.acaciadata.com/. The web application enables IOM and other stakeholders to easily access the suitability maps, and all background information, from both office environments and field locations, and to zoom in to specific sites. This IDP camp suitability map toolbox offers essential baseline information for identifying, prioritizing and conducting site-specific activities, such as flood risk assessments with mitigation plans, or water resource evaluations with groundwater development strategies. The insights generated aim to facilitate informed decision-making across the humanitarian sector and contribute to the wellbeing, development, and resilience of IDPs. This suitability map toolbox serves as a valuable tool for IOM and other stakeholders in emergency preparedness and sustainable crisis response, enabling quick assessments of flood risks and water security in existing IDP camps and to make well-informed and data-driven decisions regarding the selection and prioritization of new IDP resettlement sites.

1.2 Reading guide

This report provides a detailed description of the development of the suitability map toolbox. Chapter 1 presents the aim of the toolbox, Chapter 2 describes the methodology employed, and Chapter 3 to Chapter 7 presents the thematic suitability maps, followed by overall suitability in Chapter 8. Throughout the document, clickable hyperlinks are used to link the dataset described with the source used. The suitability maps are included in high resolution maps (A3 format) in Annex 1, and can be downloaded from the home-page of the web tool, together with the user manual for the web tool.

2 Development of the map toolbox

2.1 Overview

Five suitability maps have been created for the states of Borno, Adamawa, and Yobe. These maps are presented using a "Traffic Light Theme," where suitability levels are categorized into five classes (Figure 1). The colors range from green, indicating high suitability, to red, indicating low suitability.

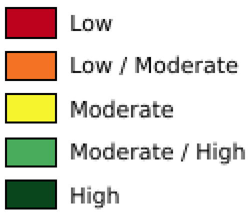

Figure 1 Five suitability classes

In this chapter, the development of the suitability map toolbox is discussed, describing the data underlying the suitability maps, the additional information layers and validation and use of the suitability maps.

2.2 Thematic maps

Each thematic map is composed of multiple input datasets, with the number of inputs varying depending on the availability of open-source data and the information provided by the IOM. When required, datasets underwent pre-processing to ensure they are compatible with the algorithms used to classify the data.

Suitability scores are determined based on expert judgment, and were discussed, adjusted and agreed together with the IOM, with all classification intervals thoroughly documented. After classification, weights have been assigned to reflect the importance of each dataset. Datasets with higher weights will have a greater influence on the resulting thematic suitability map. Figure 2 illustrates the workflow used to generate each thematic suitability map. The data sets and classifications are discussed in detail the following chapters.

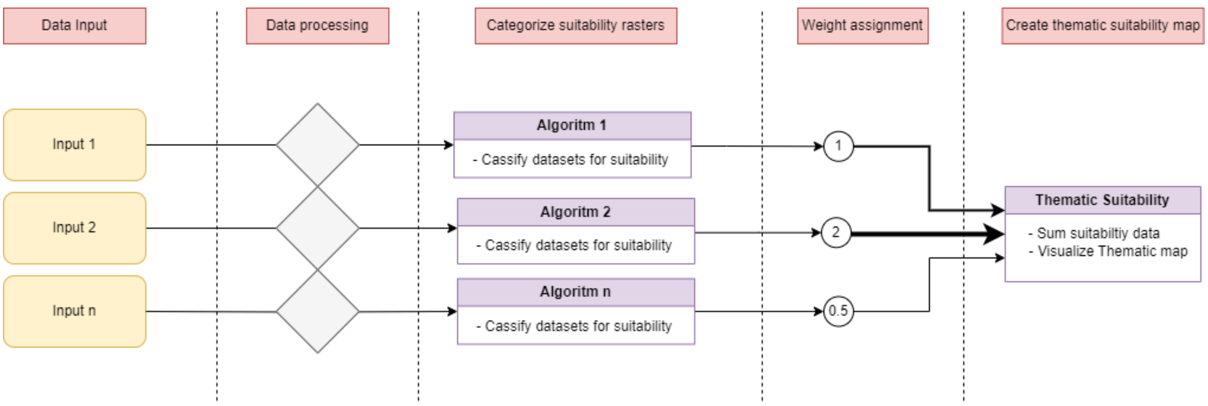

Figure 2 Illustration of the workflow to generate thematic suitability maps.

The following thematic suitability maps were created:

- Groundwater availability (chapter 3)
- Groundwater quality (chapter 4)
- Environmental degradation (chapter 5)
- Flood risk (chapter 6)
- Terrain characteristics (chapter 7)

The overall suitability was then derived by combining all five thematic suitability maps. The individual suitability maps have each been assigned a weight (Table 7), to make sure the overall suitability map (chapter 8) reflects the relative importance of each thematic map.

2.3 Additional information layers

Each thematic map also contains data sets that add information (and validation) of that particular theme, but has not been included in the suitability score itself. These additional information layers are presented as overlay layers on top of the suitability maps. For various reasons, these datasets could not be reclassified into a suitability score in a meaningful way.

For example, the spatial resolution of the borehole database is not adequate to extrapolate these datapoints and reclassify borehole yields or nitrate concentration into a groundwater availability respectively groundwater quality suitability score, since borehole data is scarce in most parts of Yobe and Adamawa state, and is not sufficiently considering the multi-layered aquifer system either. In addition, a point measurement of high nitrate concentration in one particular well does not necessarily mean that groundwater quality in the surrounding area is poor, but is rather a reflection of faecal contamination of a point source nearby the borehole. This makes the borehole database unsuitable for meaningful extrapolation and suitability reclassification. Nevertheless, these data points are extremely important, adding useful 'on the ground' information that can be used to 'validate' the groundwater availability and groundwater suitability maps.

Another example is the presence of protected nature reserves. It depends on the level of protection and the actual implementation of the protected status, if the presence of protected nature has a positive or negative implication for the suitability for an IDP camp. This could range from totally unfit (e.g. if an IDP camp is not allowed by law, or if the nature reserve relates to a permanently inundated marshland) to slightly unsuitable (if the presence of wild animals is a safety risk for IDP camp) to very suitable (if the protected nature implies low risk for environmental degradation and the nearby presence of vegetation and water). For this reason, the nature reserves are added to the terrain characteristics map, the environmental degradation map and the combined suitability map as an informative overlay, without effecting by the suitability score itself.

In addition, vector files have been added to the thematic maps to improve the orientation and use of the maps, such as major rivers, dams, roads, cities, IDP camps and State & LGA boundaries.

The table below displays the additional datasets used for the suitability maps, with a hyperlink to the data source used.

Table 1 The additional datasets used for the suitability maps, showing the name (underlined in blue when hyperlink is included), the provider of the data and the description.

Dataset	Provider	Description
State boundaries	Humanitarian data exchange (HDX)	Dataset showing the BAY states boundaries and labels
LGA boundaries	Humanitarian data exchange (HDX)	Dataset showing the LGA boundaries and labels
Major cities	OpenStreetMap (OSM)	Dataset showing the major cities
Borehole functionality	IOM, mWater database	Functionality of boreholes, based on borehole database provided by IOM and the North East Nigeria GW Dashboard (mWater)
Borehole yield	IOM, mWater database	Yield in m^3/h for boreholes, based on borehole database provided by IOM and the North East Nigeria GW Dashboard (mWater), supplemented with interpretation of ~40 Well Completion Reports provided by IOM
Dam	OpenStreetMap (OSM)	Dataset displaying the major dams
Flood wards 2022, 2024	OCHA	Dataset showing the wards in which flooding occurred in 2022 and 2024
IDP clusters	IOM	Dataset showing the IDP camps as clusters. Zoom in to identify individual camps and labels.
IGRAC fluoride	IGRAC	Dataset showing the probable areas of fluoride pollution on global scale
Main road	OpenStreetMap (OSM)	Dataset showing the main roads
Major river	HydroRivers	Dataset showing the major rivers
Protected nature	Protected Planet	Dataset showing the protected nature reserves
Recharge	British Geological Survey	Dataset showing the contour lines obtained from the Africa recharge map by the British Geological Survey.
Waterbody / wetland	ESA Worldcover 2021	Dataset showing the areas that are classified as Waterbody or Wetland
Fluoride / Nitrate concentration	IOM, mWater database	Fluoride and Nitrate concentration in mg/l for boreholes, based on borehole database provided by IOM and the North East Nigeria GW Dashboard (mWater), supplemented with interpretation of ~40 Well Completion Reports provided by IOM
Geology	British Geological Survey	Dataset showing the main geological units.

2.4 Validation

The underlying raw datasets have not been validated by the project team as part of this project. However, for many of the remote sensed datasets, previous validation and calibration efforts have been undertaken. Some examples of these efforts have been included in the reference list.

The suitability scoring of the thematic maps haven been checked and improved where possible, based on local point data (for example borehole yields for the groundwater availability map) and field information (for example a data set showing flooded LGA's in 2022 and 2024 has been use to improve the weights of the data sets that create the flood risk map). Moreover, the suitability maps have been discussed with local experts from the IOM team, and optimized where possible, to mimic local conditions as closely as possible.

2.5 Use of suitability maps

The five thematic maps and overall Suitability Map are designed to support decision-making by providing an indication of suitability based on available datasets combined with the latest remote sensing data and technology. However, it is not intended as a stand-alone decision tool. The maps should always be interpreted with expert judgment, using local experience and expertise, and should be updated as new information becomes available. We recommend incorporating field verification and ground-truthing to ensure accuracy and reliability.

3 Groundwater availability

The groundwater availability map represents the spatial distribution of groundwater resources across the BAY states, indicating where groundwater is more readily available at economically viable depths. Surface water in the BAY states is generally unreliable as potable water source, since it is more exposed to pollutants and waste, increasing the risk of waterborne diseases, and due to seasonal availability (dry up during long dry season) or inaccessibility (far away from IDP camps). Groundwater provides a safer, more reliable, and sustainable option for meeting the water needs for drinking, sanitation, and daily IDP camp needs. The groundwater availability map is invaluable for locating sites that can support the water demands of an IDP camp sustainably and cost-effectively, making it a key tool in planning for both short- and long-term IDP camp operations.

3.1 Suitability data input

First, the Africa Groundwater Atlas was used to assess the geology and hydrogeology of the BAY states in Nigeria. The Atlas contains shapefiles of the 1:5,000,000 scale hydrogeology (aquifer type and productivity) and geology (with particular relevance to hydrogeology) maps of Nigeria, which were used to identify the main hydrogeological units with categories that combine aquifer type and productivity.

The main geological units and its hydrogeological characteristics within the BAY states are:

- **Alluvial aquifer along the Benue River**, unconsolidated sediments of Quaternary age, containing unconfined aquifers of moderate to high productivity
    - Covering the central part of Adamawa State along the Benue River and its main tributaries
- **Chad Formation** (and Keri-Keri Formation), Chad Basin, unconsolidated and consolidated sedimentary deposits of Paleogene to Quaternary age, containing unconfined and confined aquifers of moderate to high productivity.
    - Chad Formation: lacustrine sediments, covering the entire northern and central parts of Yobe and Borno State
    - Keri Keri Formation: conglomerate, grit and sandstone, in the southwestern part of Chad Basin around Potiskum, Yobe State
- **Bima Sandstones**, Upper Benue Basin, consolidated sedimentary deposits of Paleogene age, typically confined aquifers of low to moderate productivity.
    - Covering southern parts of Yobe and Borno State
- **Sedimentary rocks**, Upper Benue Basin, Cretaceous age, low to moderate aquifer productivity.
    - Covering southern parts of Yobe and Borno State and central part of Adamawa State
- **Igneous volcanic rocks**, Upper Benue Basin, Paleogene age, typically unconfined aquifers of low to moderate productivity
    - Covering the southern part of Borno State (and a very small part of Yobe State), and the central southern part of Adamawa State
    - NB. In the most northwestern part of Yobe State, two small parts of igneous rocks of Jurassic age outcrop, with low aquifer productivity

- **Basement rocks**, Basement Complex, crystalline rocks, typically of low aquifer productivity, but can form local unconfined aquifers if the degree of weathering and/or fracturing is sufficient
    - Covering most of Adamawa State and the southeastern part of Borno State

In addition, the *Final Report of the North East Nigeria Groundwater Surveillance Project* (Action Against Hunger Nigeria – Groundwater Surveillance Project, 2021) as well as *Geology and Mineral Resources of Nigeria* (Obaje, 2009) were used for an improved understanding of the groundwater resources in the BAY states. This specifically helped identifying the characteristics of the multiple water bearing formations (aquifers) that can be found within the **Chad Formation**.

The Chad Formation is up to 840 m thick and consists of fluviatile and lacustrine thick bodies of clay, separating three major sand bodies. The sand is uncemented with angular and subangular quartz grains and contains lenses of diatomite (a siliceous sedimentary rock composed mainly of the fossilized skeletal remains of diatoms, which are single-celled organisms related to algae) up to a few meters thick. The clay is massive and locally gritty in texture. The three sand bodies correspond to the upper, middle and lower aquifers. Around Maiduguri (capital of Borno State), the water bearing formations within the Chad Formation are well demarcated (shown in Figure 3) and can be described as:

- **Chad Formation Upper Aquifer = shallow water table aquifer** - of Early Pleistocene (2.6-1.8 Ma) alluvial deposits that are often covered by recent sand dunes, varying in thickness from 15 to 100 m. It consists of interbedded sands, clays and silts, with discontinuous sandy clay lenses which give aquifer characteristics ranging from unconfined, semi-confined to confined type. The transmissivity ranges from 0.6 to 8.3 m^2/day and the aquifer which recharges from rainfall and run-off is mainly used for domestic water supply (hand dug wells and shallow boreholes), vegetable growing and livestock watering.
- **Aquitard** – Early Pliocene (5.3-3.6 Ma) grey to bluish-grey clays varying in thickness from few tens of meters to over 350m at the edge of the lake, separates the middle aquifer from the upper aquifer.
- **Chad Formation Middle Aquifer = deep confined (and still artesian?) aquifer** – Early Pliocene (5.3-3.6 Ma) lies at a depth of 240 and 380 m, and consists of 10-40m thick sand beds with interbedded clays and diatomite, hosting the confined aquifer. The aquifer geometry has a gentle northeast dip and does not outcrop in the Nigerian part of the Chad Basin. The average transmissivity is 360 m^2/day and the hydraulic gradient is 0.015% in the NE direction. The aquifer bears mineralized water comparing to the upper unit and 70% of the pumping wells are artesian (head pressure up to 21m above ground surface) or the water table rises up to shallow depth due to pressure release. Heavy pumping, to meet water demand, has lowered the water table of the shallow and deep artesian aquifers since the beginning of the 1980s (between 1.1 and 3m/year) and has provoked lose of artesian conditions in some wells.
- **Aquitard** – thick layer of clays separating the Lower Aquifer from the Middle Aquifer
- **Chad Formation Lower Aquifer** – at depths of 400-600m, sands and sandy clays (only known from Maiduguri area, not much explored)

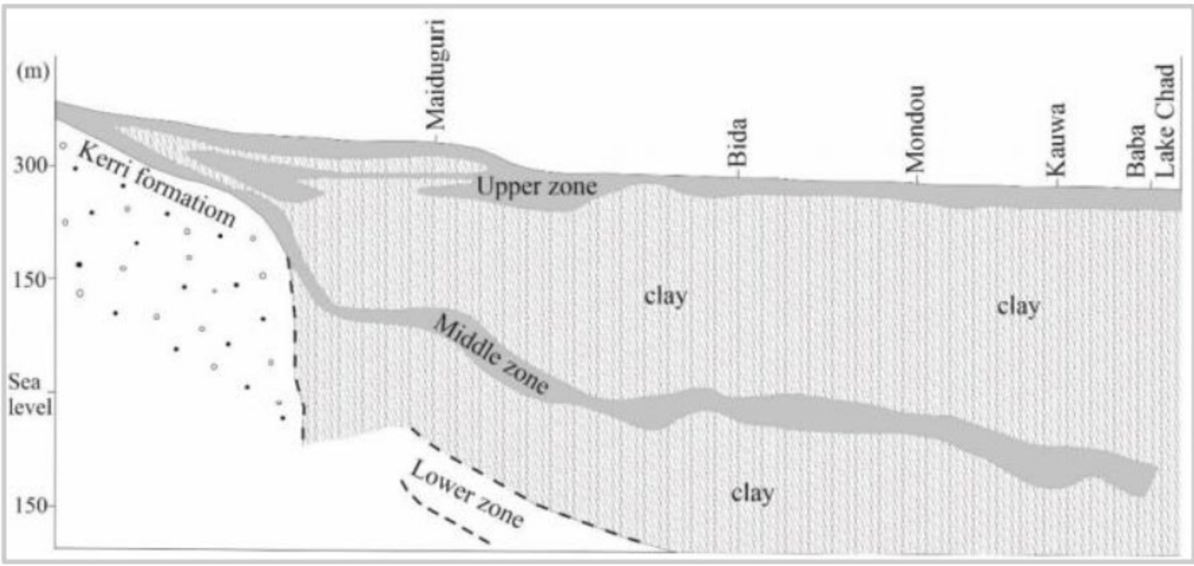

Figure 3 Cross-section showing the Upper Chad Aquifer and Middle Chad Aquifer, across Borno State from the north of Bama (left) along Maiduguri city to Lake Chad (right) (source: Groundwater Surveillance Project (2021) along with the studies they reference)

For validation of the groundwater availability map, the north east Nigeria borehole reporting dashboard was assessed and in addition, 44 borehole drilling reports (including some borehole rehabilitation and geophysical survey reports) of 2019-2023 were shared by IOM and analyzed by Acacia Water. Most reports refer to tube-boreholes (mostly machine drilled, some hand drilled) that were drilled for IOM in IDP Camps, located in Borno State (37) and Adamawa State (7); none in Yobe State:

- Most boreholes in Borno State are shallow, tapping in the upper phreatic aquifer of the Chad Formation, with a BH depth of 40-80 mbgl, BH yield ~1 l/s, Static Water Level is 15-20 mbgl
- A few boreholes in Borno State (in Kaga and Jere LGA) tap into the middle confined aquifer of the Chad Formation, with an average BH depth of 220 mbgl, BH yield = ~2.5 l/s, Static Water Level is 30-35 mbgl
- The boreholes in Adamawa state are, except one, drilled in the Bima sandstone aquifer

It can be concluded that the **shallow water table aquifer (Upper Chad aquifer)** is the main source of water for boreholes in the humanitarian sector in the BAY states. Since the depth of this aquifer is limited, boreholes are relatively easy and cheap to drill, and water seams easily available, although boreholes are not high yielding. It should be noted that this shallow water table aquifer is renewable (due to recharge from infiltrating rainfall) but can also be seasonally depleted, during long dry periods.
Lake Chad, the main permanent and seasonal rivers and various tributaries recharge a vast network of variably connected shallow water table aquifers. Away from the main water courses, the shallow water table aquifers are recharge by infiltrating rainfall. The rate of diffuse rainfall recharge rate for the Upper Chad Formation in Borno and Yobe States have been estimated at between 14 mm/yr and 60 mm/yr (Groundwater Surveillance Project (2021) along with the studies they reference). This corresponds to the groundwater contour lines obtained from the Africa recharge map by the British Geological Survey indicating a recharge of 25 mm/yr in the most northern part of Yobe and Borno state, which increases towards the south with a recharge of 150 mm/yr in the

most southern part of Adamawa state. These contour lines have been added as information layer (see chapter 2.3) to the groundwater availability map (Figure 5)

In contrast, the **confined Middle Chad aquifer** used to be artesian (with groundwater pressure around 20m above ground level), but due to over-use since its discovery in the 1950's, confined aquifer pressures have been continuously declining and in most deep wells artesian flow stopped decades ago. This is confirmed by the reported Static Water Level of 30-35 mbgl in the well completion reports of boreholes in this aquifer. According to Obaje (2009) heavy pumping, to meet water demand, has lowered the water table of the shallow and deep artesian aquifers since the beginning of the 1980s (between 1.1 and 3 m/year) and has provoked lose of artesian conditions in some wells. There is debate as to whether the Middle Chad Formation aquifer continues to receive modern recharge or whether it is 100% paleo water.

It should be noted that the geological and hydrogeology maps of the Africa Groundwater Atlas cover the **surface geology and surface hydrogeology**. It is important to consider the depth component, as in some areas a sedimentary succession containing multiple aquifers exist. Particularly in Chad Basin, where the Precambrian basement rocks are overlain by sedimentary cover of ~3500m thick. Deep geological formations, such as **the Gombe Formation** and **Congila Formation**, that could contain large aquifers with good quality water, are not considered in the groundwater availability map, due to its significant depth and associate high drilling costs. At present time, the groundwater development potential of the Lower Aquifer of the Chad Formation has not been very well characterized by researchers and investigators beneath Borno State. This has been due to the fact that the Middle Chad Formation proved to be so productive for many years, there was not the incentive to drill, explore and characterize the deeper formations of the Chad Basin.

Based on this information above, it was decided to combine the productivity of the Middle Chad aquifer with the estimated hydrogeological characteristics of the (surface) geological units into the overall suitability scoring of the groundwater availability map.

Main geological units and hydrogeological characteristics

The main geological units of the Africa Groundwater Atlas were used to classify the hydrogeological characteristics of the formations into five distinct suitability categories: low, low to moderate, moderate, moderate to high, and high.

Middle Chad formation

The Middle Chad Formation is classified in low, moderate and high according to the Zonification of the Middle Chad Formation, as presented in Figure 4 (source: Groundwater Surveillance Project (2021) along with the studies they reference). This zonification is based upon the original USGS-GSN investigations (Barber, 1965; Miller et al., 1968) the spatial variability in yield of Middle Chad was inferred and used to create a zonation map

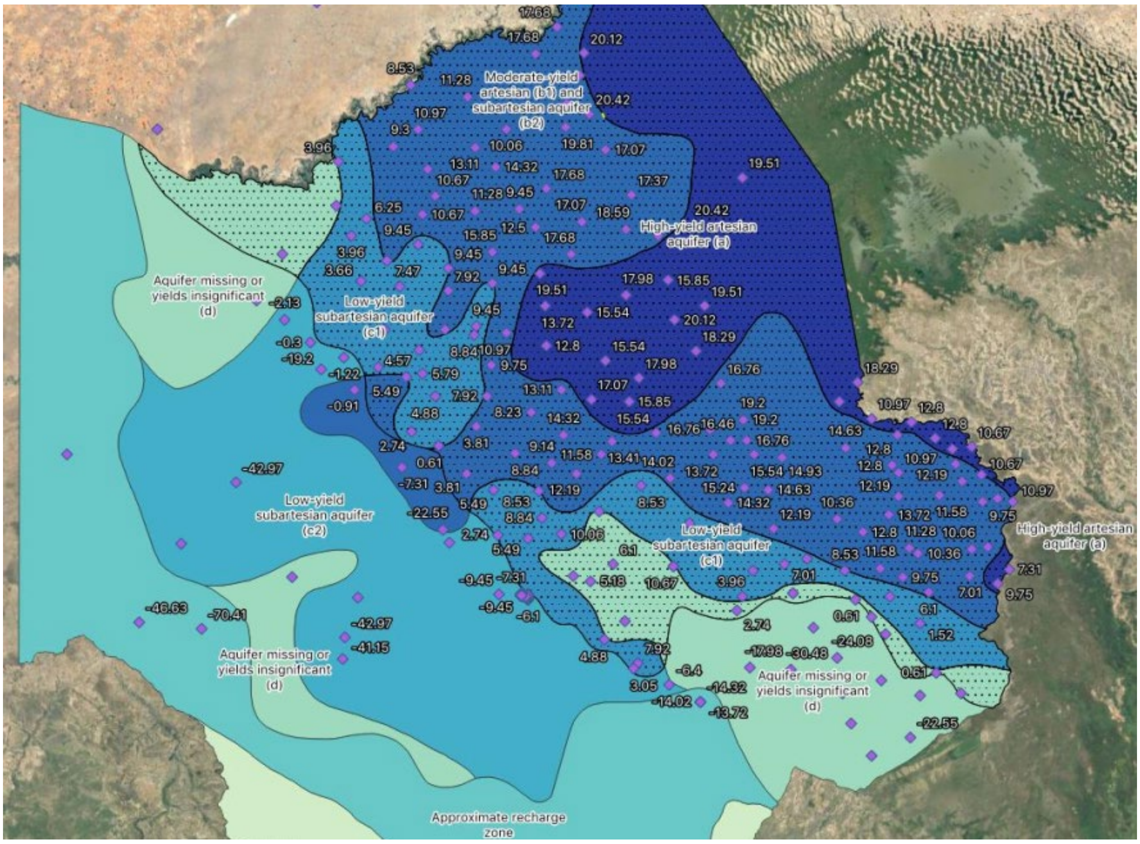

Figure 4: Zonification of the Middle Chad Formation (source: Groundwater Surveillance Project (2021) along with the studies they reference)

Borehole yield data

An overlay of point data with borehole yield in m^3/h, was used as additional information layer (chapter 2.3) for the groundwater suitability map. Borehole data provided by IOM and the North East Nigeria GW Dashboard (mWater database) was used, supplemented with the analysis and interpretation of ~40 Well Completion Reports provided by IOM. Borehole yields are also depicted in the groundwater availability map (Figure 5), indicating water yield and the aquifers from which the boreholes extract. The data reveal that boreholes tapping into the Upper Chad Aquifer generally have poor yields (0-5 m^3/h), while those accessing the Middle Chad Aquifer demonstrate higher yields (5-10 m^3/h and 10-15 m^3/h).

Reclassification

The reclassification of raw values to suitability values is done according to Table 2.

Table 2 Reclassification matrix for the Groundwater Availability thematic map

GROUNDWATER AVAILABILITY							
Suitability	Very unsuitable 1	2	Neutral 3	4	Very suitable 5	Unit	Weight
Hydrogeology	Low	Low / Moderate	Moderate	Moderate / High	High	-	1
Middle Chad Formation	Low	Low / Moderate	Moderate	Moderate / High	High	-	1

3.2 Groundwater availiblity map

The groundwater availability map (Figure 5, in A3 format included in Annex 1) assesses the suitability of IDP camp placement in the BAY states in relation to the availability of groundwater resources, based on key supporting data: the hydrogeology map and the presence of the Middle Chad Aquifer. The map includes several additional information overlays including groundwater recharge contour lines and borehole yields.

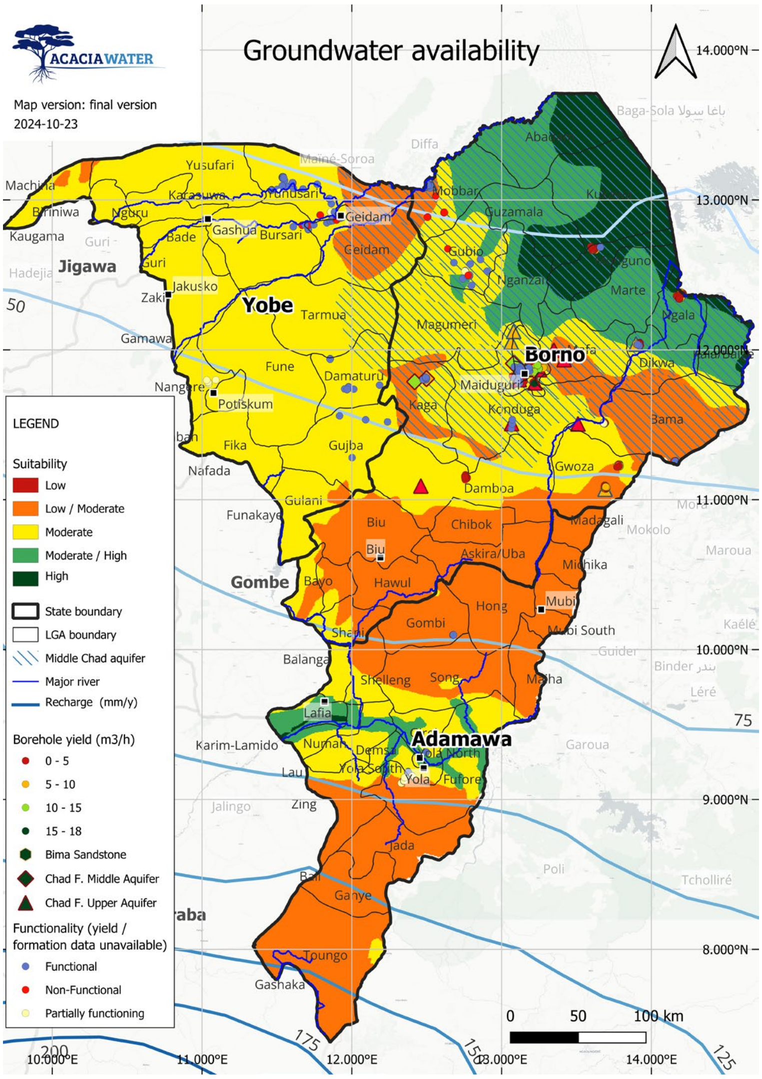

Figure 5 Groundwater availability suitability map.

The map indicates a higher suitability in areas closer to Lake Chad, particularly in the northeast, where the presence of the high productive Middle Chad Aquifer in addition to the shallow water table aquifers increase the groundwater availability suitability. Additionally, areas near rivers in Adamawa exhibit higher suitability. In contrast, the remainder of the states show low / moderate to moderate (orange / yellow) suitability, largely due low productive geological units.

4 Groundwater quality

The groundwater quality map represents the spatial distribution of groundwater quality across the BAY states, illustrating areas with varying groundwater quality characteristics and identifying regions where groundwater may or may not be suitable for potable use in IDP camp settings. It should be noted that even in areas with low groundwater quality suitability, groundwater can still be used for drinking if treated through appropriate methods. However, these treatments can be costly and may require significant investment in water treatment infrastructure.

4.1 Suitability data input

Groundwater quality in the BAY states is generally of good quality. Electrical Conductivity (EC) values reported in previous studies (e.g. the Groundwater Surveillance Project, 2021) and measured in wells (from borehole completion reports provided by IOM; described in chapter 3.1) are generally low (100-500 microS/cm), indicating that salinity is not a major groundwater quality issue. Sulphate, Iron and Manganese are sometimes reported to have concentrations above exceedance level, but this is mainly of aesthetic concern and possible clogging of wells and screens, and staining of clothes. Since they are not of direct health concern, they have not been included in the groundwater quality suitability score. Arsenic is another well known contaminant, but has not been mentioned in previous studies and is only been analysed in one well (very low concentration) of the ~40 boreholes completion reports provided by IOM. The IGRAC global groundwater quality maps do not indicate an area within the BAY states with a high risk for arsenic. This is different for fluoride, where in the central region of the BAY states a polygon is indicated with a high probability of occurrence of fluoride in groundwater. However, this high risk polygon is not reflected by the borehole data available for fluoride, provided by IOM and by mWater database, which indicate multiple boreholes scattered around the BAY states but not particularly in this polygon. For this reason, the Fluoride risk polygon has not been included in the suitability scoring but instead been added as an additional information layer (chapter 2.3) to the groundwater quality map. The laboratory results of water taps in IDP camps, provided by IOM, are not a good indicator of natural groundwater quality, since the distributed water is being treated.

The main water quality issues in the **shallow water table aquifer** are related to uncontrolled sewerage waste streams, as can be seen by elevated concentrations of Nitrate, E.coli bacteria and other faecal contaminants. Especially in Maiduguri city there are serious problems with shallow groundwater pollution.

Maiduguri city is built on shoreline sand barrier deposits of former Mega Lake Chad. Due to the porous soils, and the susceptibility to flooding, human waste streams percolate down to the water table, contaminating the source of drinking water for many residents. In a study of nitrate levels in the shallow aquifers beneath Maiduguri the nitrate concentration in groundwater was found to range between 1 and 700 mg/L, with 37 percent of the 128 samples had nitrate concentrations above the WHO limit of 50 mg/L (Groundwater Surveillance Project (2021) along with the studies they reference).

Uncontrolled sewerage waste streams, such as latrines and open defecation, but also percolation from landfills and inadequate waste management systems, and industrial activities, are often concentrated in urban areas with high population density and can contribute to the contamination of nearby shallow groundwater sources. For that reason, the nearby presence of build-up areas serve as a proxy for the probability and occurrence of contamination of the shallow (unconfined) water table aquifer.

Confined aquifers, such as the Chad Formation Middle Aquifer that is overlain by a thick and low permeable clay layer, are much better protected from surface-based contamination. Therefore, the areas where a deeper confined aquifer system exist is given a higher suitability score. However, geogenic contaminants such as Fluoride could be present in the Middle Chad Formation and other confined aquifers.

Build-up areas

We obtained a build-up areas dataset from the ESA landcover dataset (discussed in more detail in Chapter 7), by selecting only the build-up areas from it. Then, the distance to the closest build-up pixel was computed for each grid cell. Based on expert judgement, all zones within 50m of a build-up pixel has been classified as very unsuitable, while all other zones have been classified as neutral.

Middle Chad aquifer

In areas where the Middle Chad aquifer is present (see Chapter 3), groundwater is much better protected from surface-based contamination and therefore tends to be relatively good. This region was therefore assigned a higher suitability.

Borehole water quality data

The IOM provided water quality data from several borehole completion reports as well as samples taken at IDP camp water points. These data are provided in the web application, but since they were variable in time, and sparse in spacing, they were not included in the suitability classification.

Reclassification

The reclassification of raw values to suitability values was done according to Table 3.

Table 3 Reclassification matrix for the Groundwater Quality thematic map

WATER QUALITY										
Suitability	Very unsuitable	1	2	Neutral	3	4	Very suitable	5	Unit	Weight
ESA Buildup	Buildup (pixelvalue = 50)			Other categories						1
Middle Chad aquifer						Areas where this aquifer is present.				1

4.2 Groundwater quality map

The groundwater quality map (Figure 6, in A3 format included in Annex 1) evaluates the suitability of IDP camp placement in relation to groundwater quality. The groundwater suitability is based on supporting data from the build-up dataset and the presence of the

Middle Chad Aquifer (chapter 3.1). Overall, the map displays a neutral classification (yellow) in most non-urban regions since there are no indications for poor groundwater quality.

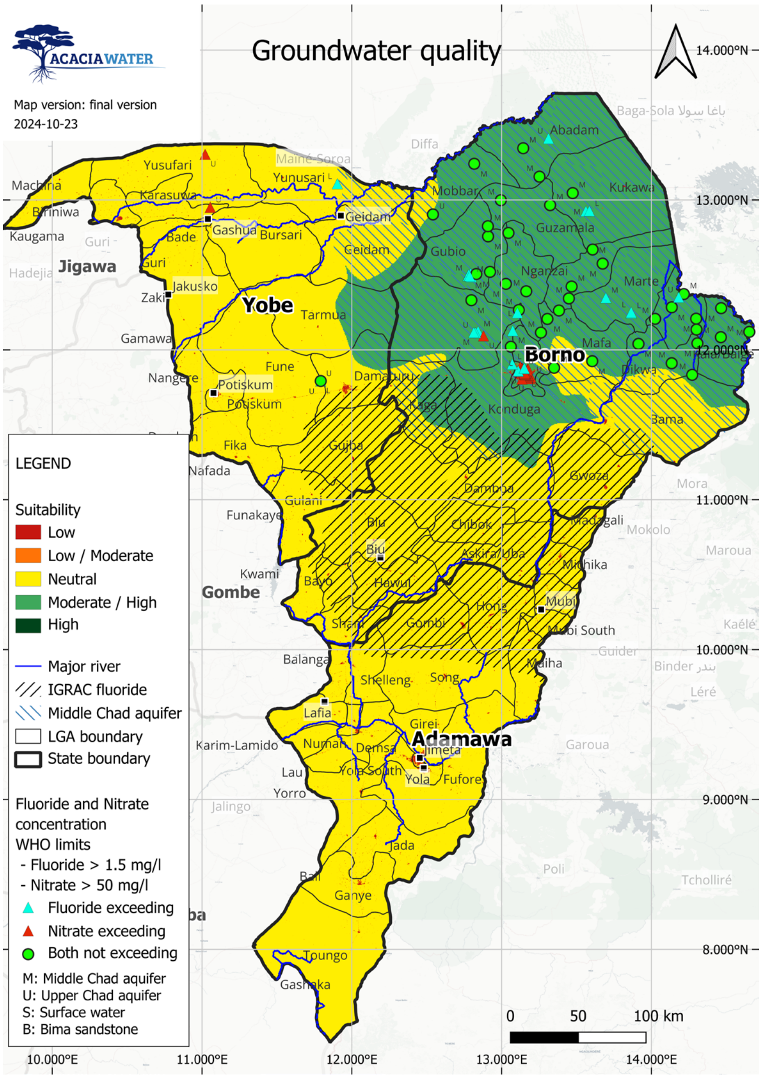

Figure 6 Groundwater quality suitability map.

Areas classified as low suitability for IDP camp placement correspond to pixels identified as urban build-up in the land use map. In these locations, the risk of human waste and other pollution percolate down to the water table is high. These areas are better visible when zooming in on groundwater quality map in the online web tool. The Middle Chad Aquifer, located in the northeastern part of the Yobe and Borno States, demonstrates higher suitability regarding groundwater quality, since this confined aquifer is better protected by an overlaying clay layer.

Additionally, the map illustrates concentrations of fluoride and nitrate in groundwater from boreholes. Most boreholes do not exceed the WHO limits for fluoride and nitrate, indicated by green dots. However, there are some boreholes that exceed the fluoride limit (represented by light blue triangles) and the nitrate limit (represented by red triangles). Notably, the spatial distribution of nitrate exceedances is primarily in or around urban areas, likely due to anthropogenic contamination.

5 Environmental degradation

The environmental degradation map represents areas where natural resources or ecosystem health have a high(er) likelihood to be, or already have been, compromised due to factors such as deforestation, soil erosion, or loss of biodiversity. These maps are essential for assessing the feasibility and potential impacts of establishing an IDP camp in a particular area. The environmental degradation map is a valuable tool for making informed, sustainable decisions in IDP camp planning, as it helps balance immediate humanitarian needs with environmental stewardship and the resilience of local resources.

5.1 Suitability data input

Erosion

The modified Erosion Potential Model (mEPM) was developed for global soil erosion assessments. The model calculates erosion rates considering processes like sheet, rill, gully erosion, and soil slumps, unlike USLE-type models that focus mainly on sheet and rill erosion (Bezak et al., 2024). The resulting dataset displays global erosion potential in six classes. These classes were adjusted to fit our 5-class classification (Table 4).

Soil permeability

An Acacia Water model was used to estimate the soil permeability based on soil textures obtained from ISRIC soilgrids (Hengl et al., 2017). Soil permeability is a measure that reflects the ability of soil to transmit water through its profile. Hence, a permeable soil will have higher infiltration rates than a soil with lower permeability. Low permeability soils will thus have a higher chance of superficial runoff and high erosion rates.

Depth to bedrock

The Depth to Bedrock Map created by the International Soil Reference and Information Centre (ISRIC) provides a global estimate of the distance from the ground surface to bedrock. This dataset is based on more than 1.6 million borehole logs and 130,000 soil profile observations. To predict bedrock depth, the map uses machine learning techniques such as Random Forest and Gradient Boosting Tree, incorporating various environmental factors like DEM-based hydrological data, lithology, and MODIS land products. With a resolution of 250 meters, the map is extensively used in fields like hydrology, agriculture, and environmental modeling (Shangguan et al., 2017). Shallow soils generally reflect a poor infiltration capacity and unstable layers, indicating a higher chance of environmental degradation.

Reclassification

The reclassification of raw values to suitability values was done according to Table 4.

Table 4 Reclassification matrix for the Environmental Degradation thematic map

ENVIRONMENTAL DEGRADATION							
Suitability	Very unsuitable 1	2	Neutral 3	4	Very suitable 5	Unit	Weight
Erosion	20+	10-20	5-10	3-5	0-3	T/h/y	3
Soil permeabili ty	10	25	35	50	50+	Mm/d	2
depth to bedrock	<85	85-107	107-130	130-152	>152	cm	1

5.2 Environmental degradation map

The environmental degradation map (Figure 7, in A3 format included in Annex 1) assesses the suitability for IDP camp placement in the states of Borno, Yobe, and Adamawa, based on factors such as erosion potential, soil permeability, and depth to bedrock. Note that a low suitability means there is a high risk of environmental degradation.

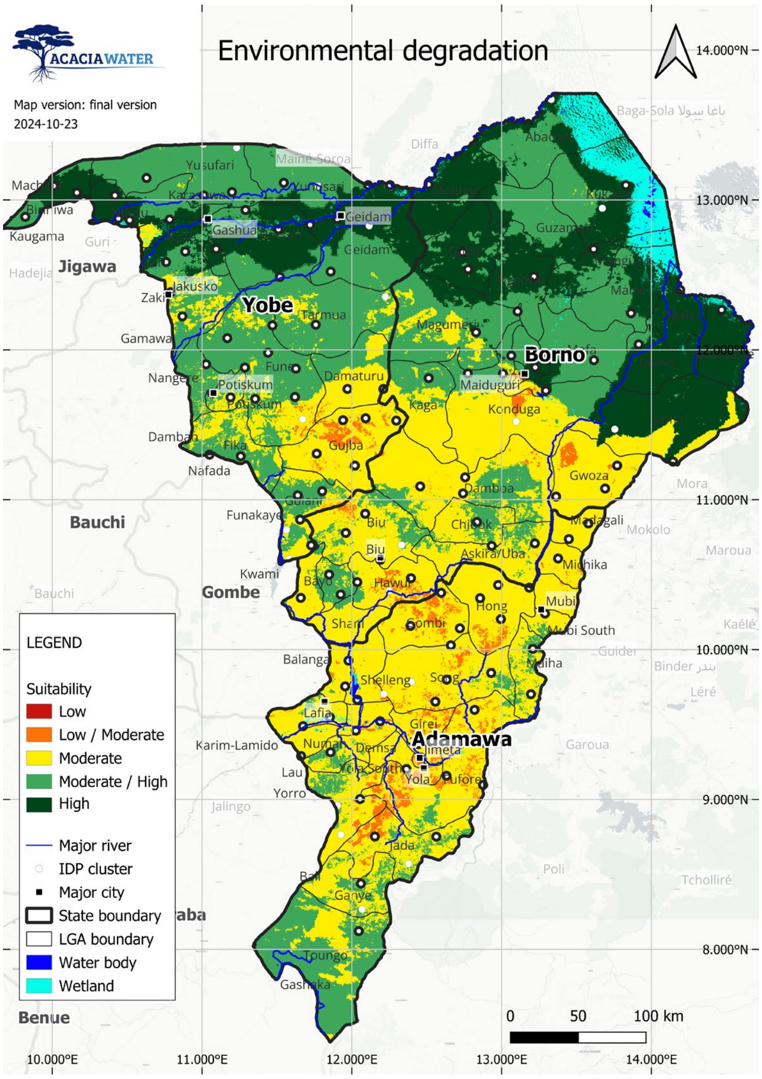

Figure 7 Environmental degradation suitability map. Note that a low suitability means there is a high risk of environmental degradation.

It highlights that northern parts of Yobe and Borno are the most suitable for camp placement. In contrast, the southern regions of Borno and Yobe, along with much of Adamawa, are less suitable, though still classified as moderately suitable (indicated by yellow). Areas shaded in orange show low to moderate suitability, with higher erosion potential, making them more prone to environmental degradation. Importantly, very few areas are classified as unsuitable, suggesting that environmental degradation is not a primary challenge in the BAY states.

6 Flood risk

The flood risk map represents areas susceptible to flooding based on factors such as topography, rainfall patterns, river systems, and historical flood data. It illustrates zones with varying flood probabilities, identifying regions that are more or less vulnerable to flooding events. The flood risk map is essential in IDP camp planning, as it identifies zones that are at higher risk of flooding, which may not be suitable for establishing IDP camps.

6.1 Suitability data input

Peak precipitation

Peak precipitation is a good indicator for the possibility of flooding to occur. To compute the peak precipitation, the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) dataset was used (Funk et al., 2015). CHIRPS offers global daily precipitation data with high spatial resolution, making it well-suited for long-term climate analysis. From this precipitation dataset, the maximum daily precipitation over a 20-year period (2004-2024) was computed for the study area.

Topographic Wetness Index (TWI)

To identify flood prone areas, the topographic wetness index (TWI) was calculated using several processing steps available in the R library WhiteBoxTools (Wu & Brown, 2022). First, the flow accumulation and slope in radians were derived from a digital elevation model (the SRTM data). Flow accumulation measures the amount of upstream area draining into each cell, while the slope indicates the steepness of the terrain. Then TWI was computed with the following formula:

$$TWI = \ln\left(\frac{A}{\tan(S)}\right),$$

where: A is the flow accumulation and S is the slope in radians. The resulting TWI displays the spatial wetness distribution, indicating areas with higher or lower water accumulation potential. As such, the TWI can provide an indication of flood risk.

Soil permeability

The soil permeability map as described in chapter 5.1 was used to classify the flood risk map as well. A high permeability indicates high infiltration rates, decreasing the chance of flooding and vice versa.

Flooding areas

The flood vulnerability mapping of Nigeria BAY States in May 2024 and of May 2023 were used to identifyregions susceptible to flooding. These include areas that are modeled to be flood-prone, as well as the LGA's that are known to have previously suffered from flooding in 2022 and 2024. These datasets have been combined to create an overview of flood vulnerability. Given their known susceptibility to flooding, these regions were utilized as a mask that categorizes very unsuitable areas.

Reclassification

The reclassification of raw values to suitability values was done according to Table 5.

Table 5 Reclassification matrix for the Flood Risk thematic map

FLOOD RISK							
Suitability	Very unsuitable 1	2	Neutral 3	4	Very suitable 5	Unit	Weight
Peak precipitation	>80	70-80	50-70	40-50	<40	mm/d	1
Topographic Wetness Index	>1.6	0-1.6	-0.87-0	-1.7--0.87	<-1.7	-	2
Permeability	>10	10-25	25-35	25-50	50+	Cm/d	2
Flood prone areas	Polygon				Rest	-	Mask

6.2 Flood risk map

The flood risk map (Figure 8, in A3 format included in Annex 1) evaluates the suitability of IDP camp placement in the states of Borno, Yobe, and Adamawa, using the following supporting data: actual and modeled flood-prone areas, infiltration capacity, CHIRPS maximum precipitation over the last 30 years, and topographic wetness index. Note that a low suitability means there is a high risk of flooding.

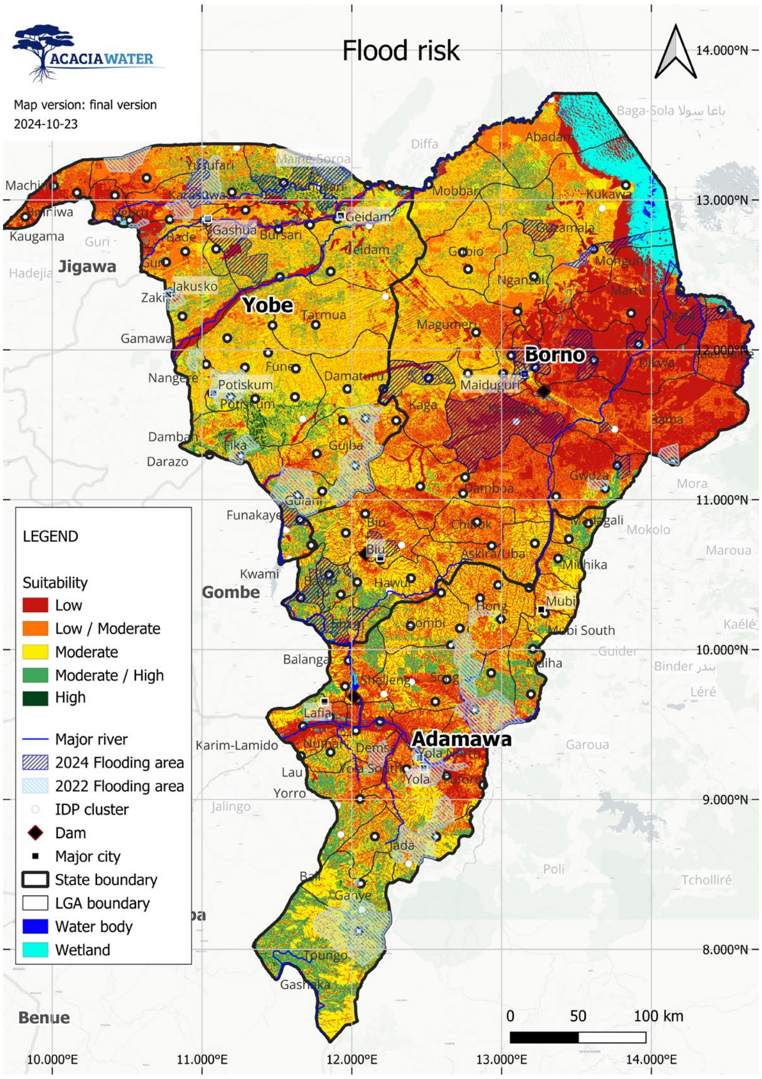

Figure 8 Flood risk suitability map. Note that a low suitability means there is a high risk of flooding.

The first observation is the low suitability along major river networks, which are masked as flood-prone areas, indicating high vulnerability to flooding. In northern Yobe and the central and eastern parts of Borno, low suitability is also evident, largely due to low infiltration capacity and high topographic wetness. These areas are prone to water accumulation, as indicated by calculated flow patterns and contributing areas. To highlight vulnerability towards floods the wards in which flooding have occurred in 2022 and 2024 have been added to the map. It is visible that these areas have lower suitability values, although these areas have not been incorporated in the suitability calculations, confirming the accuracy of the flood risk map. In contrast, Adamawa shows higher suitability for IDP camp placement regarding flood risk, thanks to its higher elevations, steeper slopes, and less water flow accumulation, except near rivers. Overall, flood risk is a significant factor to consider when selecting locations for IDP camps.

7 Terrain characteristics

The terrain characteristics map represents the physical features of the landscape, including slope, land cover and vegetation health, that are critical in identifying safe, accessible, and stable locations for IDP camps. Knowing the terrain helps to select sites where construction and development of facilities, such as shelters, latrines, and community spaces, are more feasible and cost-effective. The terrain characteristics map is critical in supporting decisions that enhance both the safety and well-being of camp residents while reducing infrastructure challenges.

7.1 Suitability data input

Slope

The slope data are derived from the globally available SRTM Digital Elevation model (DEM) dataset. This elevation dataset was produced through a collaboration between NASA, the German Aerospace Center (DLR), and the Italian Space Agency (ASI), during a mission that took place in February 2000. The result of this endeavor is a 30 x 30 meter elevation grid, providing detailed topographic information for use in various applications (Farr et al., 2007). This DEM grid was used to compute the rate of elevation change between adjacent cells. The slope for each grid cell was calculated as the steepest angle of descent or ascent across the grid, typically expressed in degrees. We applied trigonometric formulas to determine the slope based on differences in elevation and horizontal distance, providing a measure of terrain steepness at each grid cell (Hijmans, 2024). The final slope map was translated to percentages to ease interpretation.

Land cover

The European Space Agency (ESA) Land Cover 10m dataset is a high-resolution global land cover map, produced by the ESA as part of its Copernicus program. Derived from Sentinel-2 satellite imagery, the map provides detailed land cover classifications at a 10 m spatial resolution. This dataset offers valuable insights into various land cover types such as forests, grasslands, urban areas, and water bodies, making it a key resource for environmental monitoring, land management, and many other applications (Zanaga et al., 2022). For this thematic map, the landcover dataset was used together with three derived landcover products: Distance to tree cover, distance to buildup, and distance to Water bodies. These three datasets were created by Acacia Water using the proximity (raster distance) tool in the QGIS model designer since the distance to these landcover classes are of main importance.

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) was derived from Sentinel-2 Surface Reflectance images ((ESA), 2024), that provide high-resolution (10 m) observations with atmospheric corrections. The NDVI is a remote sensing index used to assess vegetation health and density. It was computed using the following formula:

$$NDVI = \frac{NIR+RED}{NIR-RED},$$

where NIR (Near-Infrared) and RED refer to specific spectral bands in satellite imagery (Pettorelli, 2013). For Sentinel-2 data, this is band 8 for NIR data and band 4 for red data. The resulting dataset represents the median NDVI value for a specified region over a 20-year period (January 1, 2004, to January 1, 2024). It provides insights into long-term vegetation health and density trends within the selected area, and can therefore be used as a proxy for water availability.

Reclassification

The reclassification of raw values to suitability values was done according to Table 6. These suitability scores were discussed and agreed with the IOM.

Table 6 Reclassification matrix for the Terrain Characteristics thematic map

TERRAIN MAP							
Suitability	Very unsuitable 1	2	Neutral 3	4	Very suitable 5	Unit	Weight
Slope	>15 & <1	10-15	6-10	4-6	1-4	%	2
Distance to tree cover	>8000 & <50	4000-8000	2000-4000	1000-2000	<1000 & >50	m	1
Distance to buildup	>8000 & <50	4000-8000	2000-4000	1000-2000	<1000 & >50	m	3
Distance to water body	>8000 & <50	4000-8000	2000-4000	1000-2000	<1000 & >50	m	1
Land cover suitability	○ Water body ○ Trees ○ Herbaceous wetland ○ Snow and ice ○ Mangroves ○ Bare / Sparse ○ Buildup		○ Tree cover ○ Cropland ○ Moss / Lichen	grassland		-	1
NDVI	<0.05	0.05-0.1	0.1-0.2	0.2-0.3	>0.3	-	2

7.2 Terrain characteristics map

The terrain characteristics map (Figure 9, in A3 format included in Annex 1) assesses the suitability of IDP camp placement in the states of Borno, Yobe, and Adamawa, making use of the following supporting datasets: distance to urban buildup, tree cover, and water bodies, the ESA land cover map, median NDVI values over multiple years, and the slope in degrees.

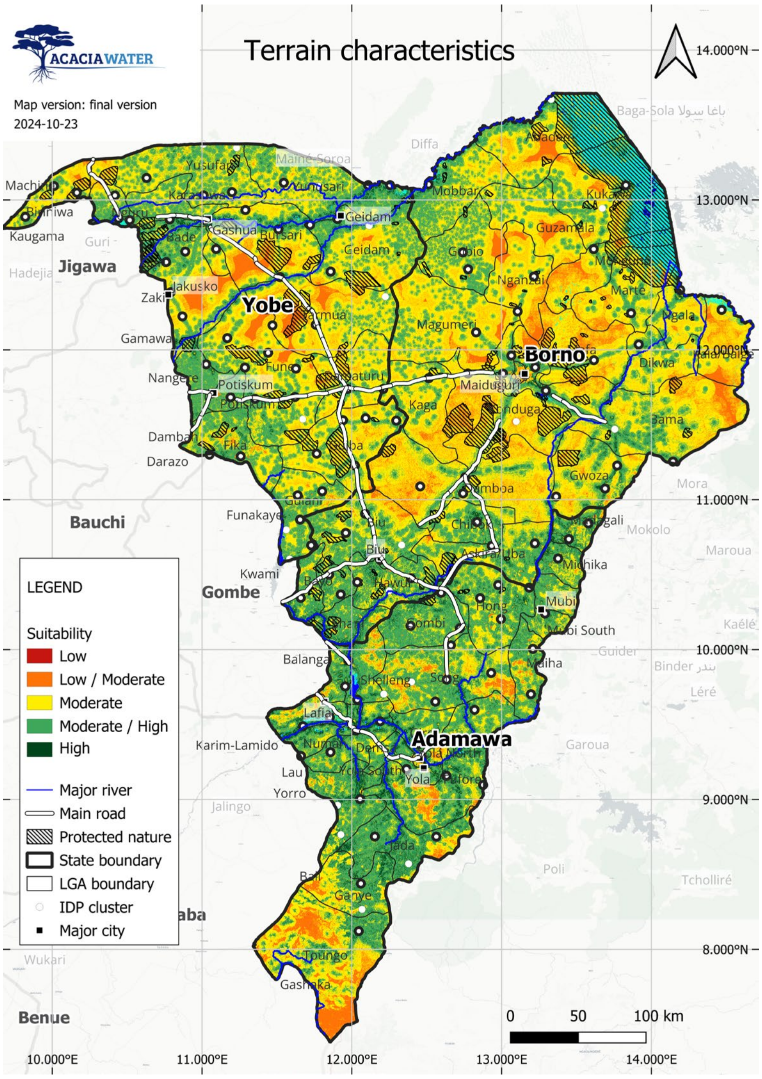

Figure 9 Terrain characteristics suitability map

The suitability for IDP camp placement based on terrain is primarily informed by the land cover products, as reflected in the terrain characteristics map. Generally, suitability is higher near urban areas, roads, and rivers, and decreases with increasing distance from these features. Areas with limited access to water, urban facilities, or tree cover tend to exhibit lower suitability values. The weight of the urban buildup layer is particularly pronounced, highlighting the importance of accessibility in evaluating potential camp locations. In regions with steep slopes or very gentle terrain, suitability also tends to be low to moderate. To aid in decision-making for camp placement, additional overlays have been included on the map, such as protected nature areas and major roads, providing critical context for selecting suitable locations.

8 Overall suitability

The overall suitability map represents the biophysical suitability for IDP camps in the BAY states, considering terrain characteristics, groundwater availability, groundwater quality, environmental degradation and flood risk combined.

8.1 Suitability data input

The five thematic maps that were each derived from raw data as presented in chapter 3-7, were combined to produce an overall suitability assessment for the location of IDP camps. For this purpose, weights were assigned to reflect the relative importance of each thematic map. The weighted average, presented in Table 7, were assigned based on the judgement of IOM and Acacia Water experts.

Table 7 Weighting of the thematic maps to create the overall suitability map

Overall suitability	
THEMATIC MAP	FINAL WEIGHTING
Terrain charateristics	0.1
Groundwater quality	0.2
Groundwater availability	0.25
Enviornmental degradation	0.1
Flood risk	0.35

8.2 Overall suitability map

The overall suitability map (Figure 10, in A3 format included in Annex 1) is a weighted composite derived from the previous thematic maps. As shown in the figure below, the color palette balances out, with a prominent presence of orange and yellow, reflecting the potential contradictions among datasets from different thematic maps.

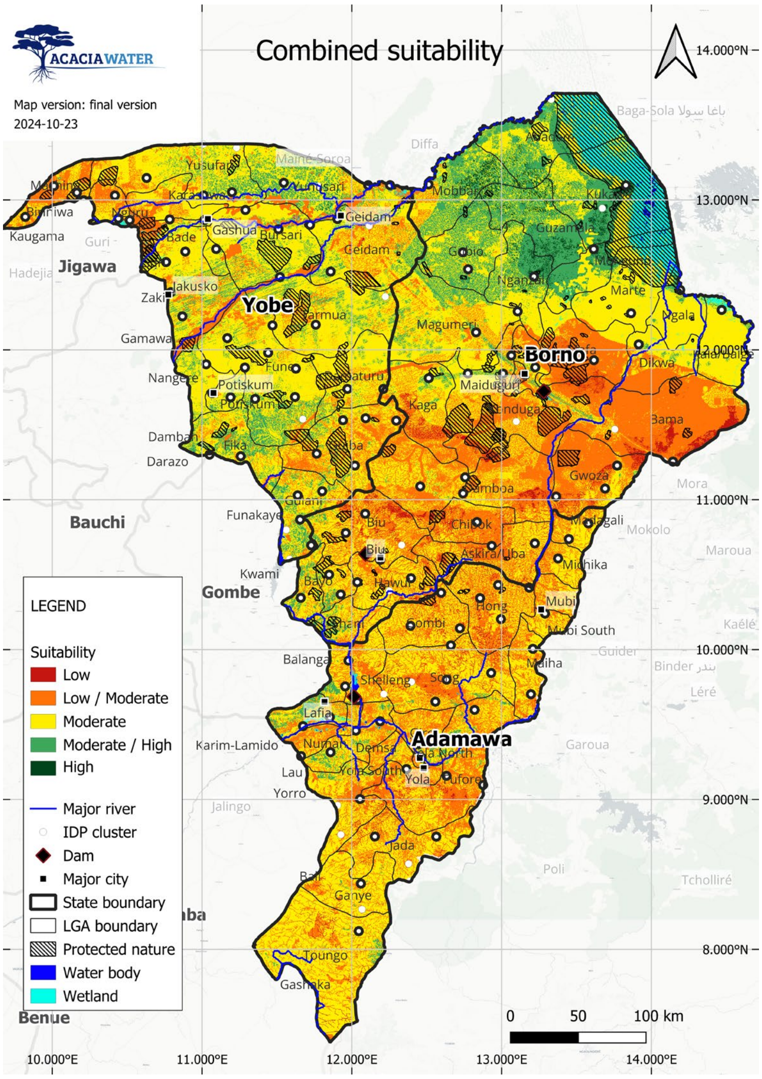

Figure 10 Combined suitability map.

Notably, the northern region of Borno state exhibits higher suitability values (classified as high and moderate/high) compared to the other two states, indicating that these areas are the most favorable for IDP camp placement based on the available data. Additional areas of moderate/high suitability are located in central northern and southern parts of Yobe state, as well as in the most western part of Adamawa near the Gombe state border.

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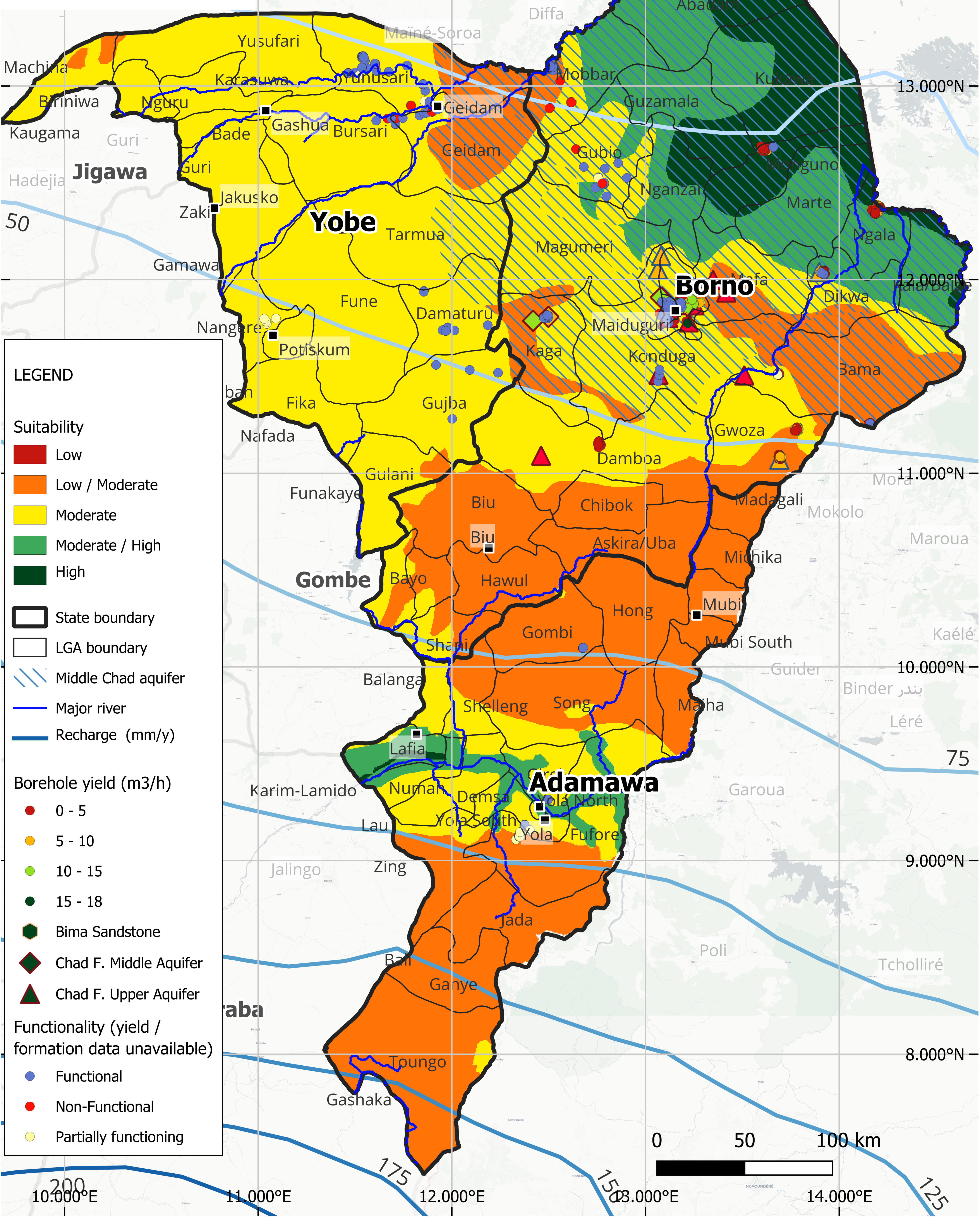
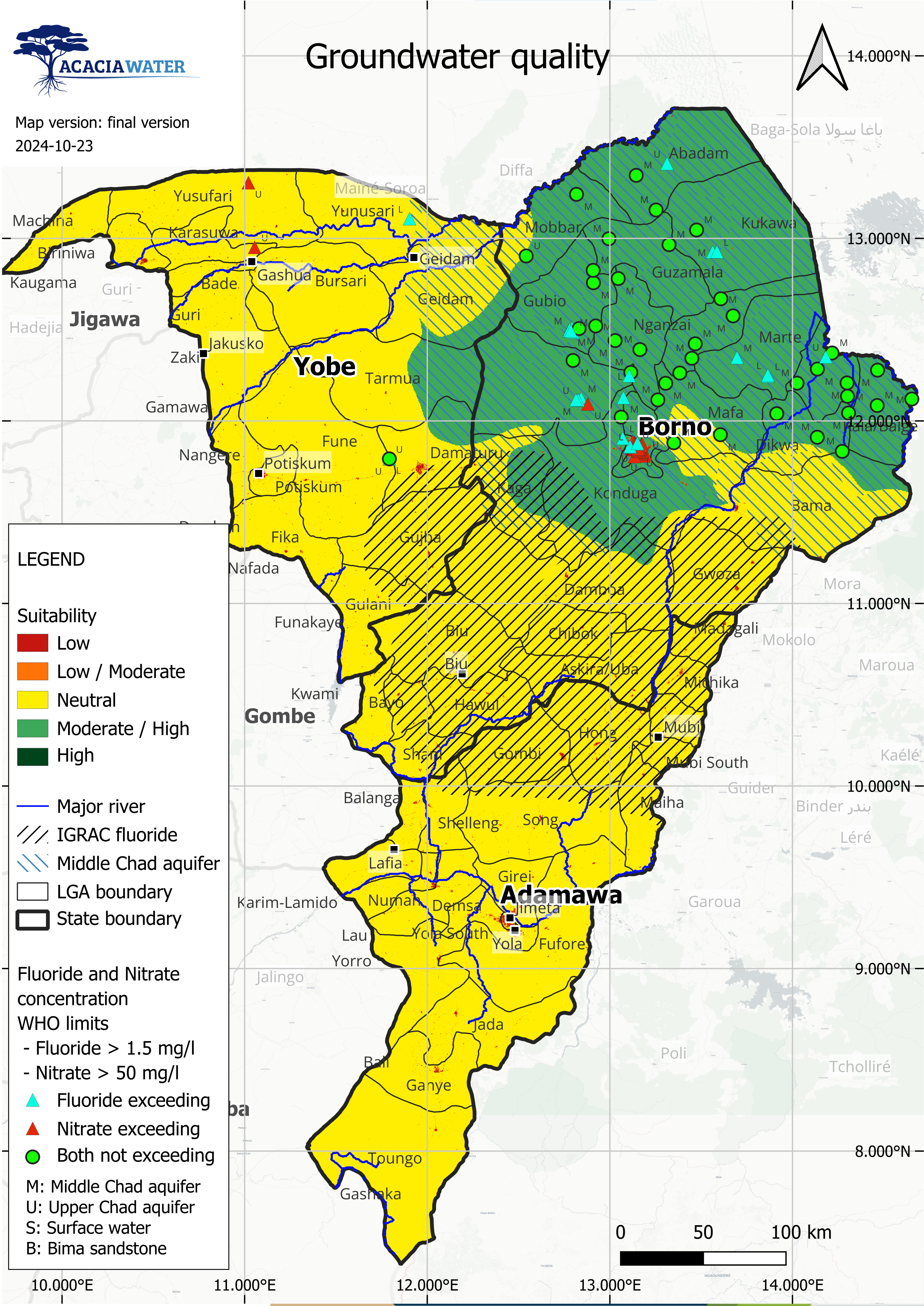
Annex 1 - Thematic suitability maps (A3)

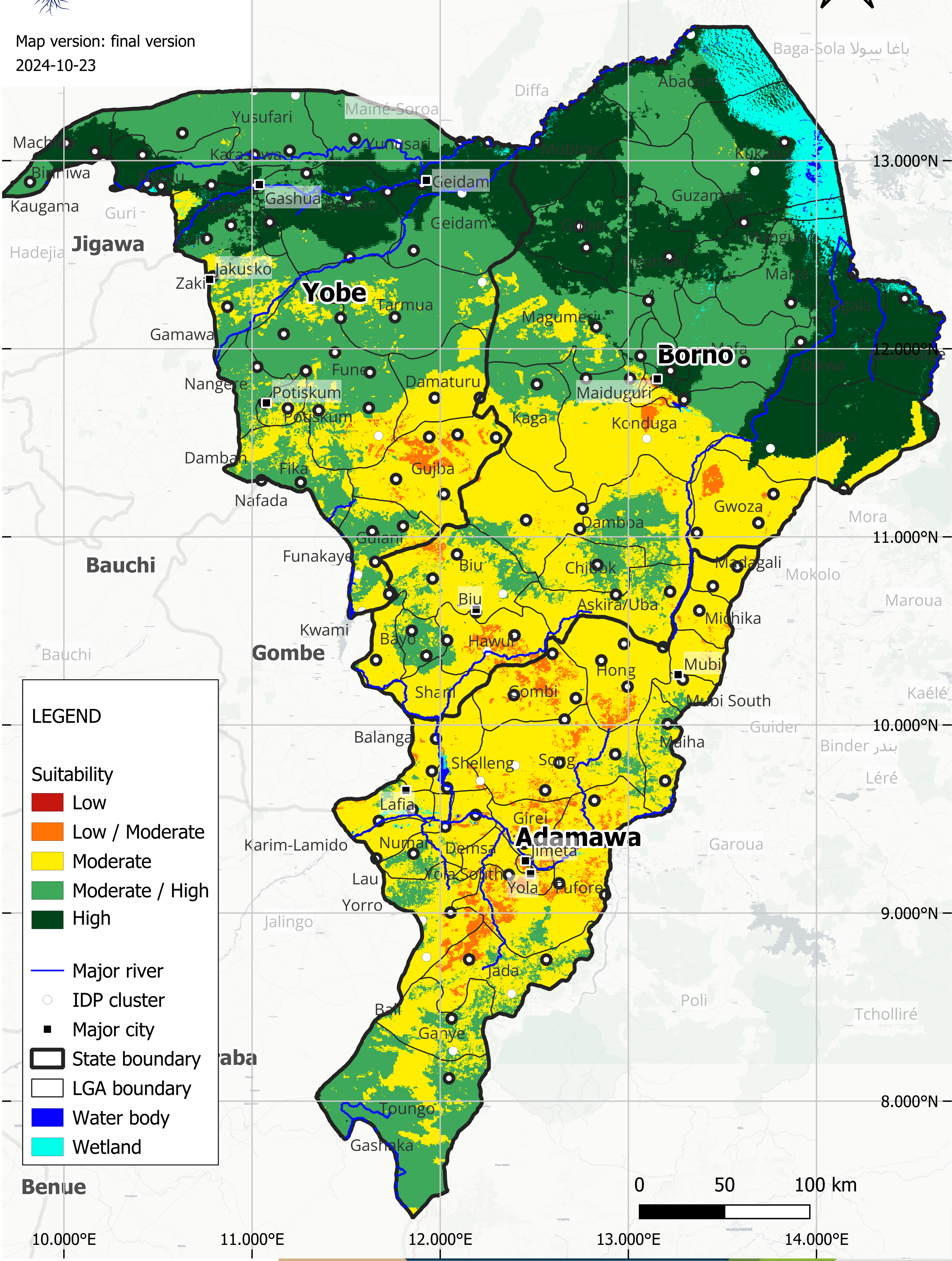
2024-10-23

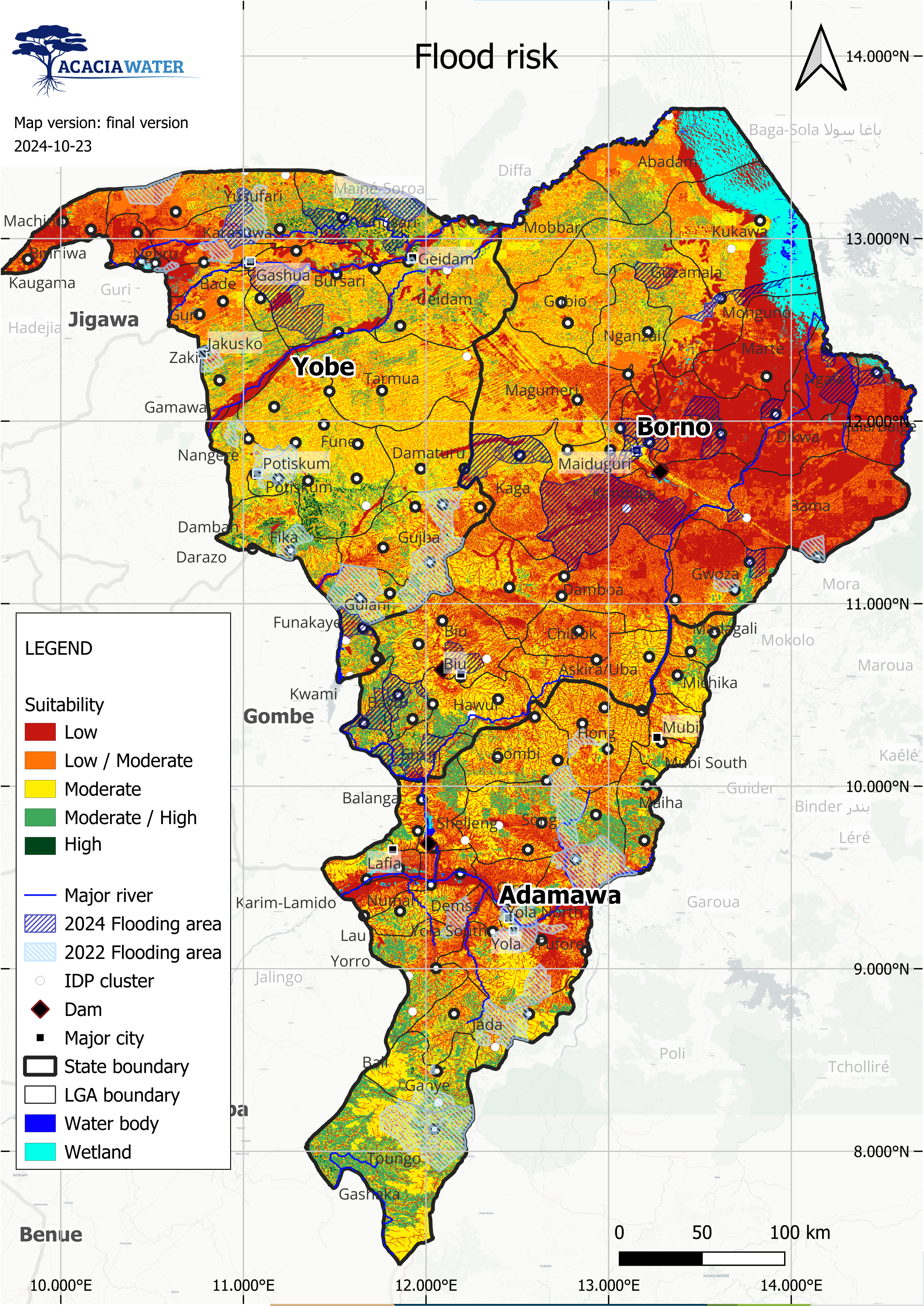

Yobe
Borno
Adamawa
Jigawa
Gombe
Yusufari
Machina
Karasuwa
Yunusari
Briniwa
Nguru
Geidam
Kaugama
Gashua
Bursari
Bade
Guri
Hadejia
Jakusko
Zaki
Tarmua
Gamawa
Fune
Damaturu
Nangere
Potiskum
Fika
Gujba
Nafada
Gulani
Funakaye
Diffa
Maïné-Soroa
Abadam
Mobbar
Guzamala
Gubio
Nganzai
Magumeri
Marte
Ngala
Dikwa
Maiduguri
Kaga
Konduga
Bama
Gwoza
Damboa
Madagali
Mokolo
Maroua
Biu
Chibok
Askira/Uba
Michika
Hawul
Bayo
Hong
Mubi
Gombi
Mubi South
Shani
Balanga
Guider
Binder بندر
Léré
Shelleng
Song
Maiha
Lafia
Karim-Lamido
Numan
Demsa
Yola North
Yola South
Yola
Fufore
Lau
Garoua
Kaélé
Jalingo
Zing
Jada
Poli
Tchollire
Ganye
Toungo
Gashaka
50
75
125
150
175
200
13.000°N
12.000°N
11.000°N
10.000°N
9.000°N
8.000°N
10.000°E
11.000°E
12.000°E
13.000°E
14.000°E
0
50
100 km
LEGEND
Suitability
Low
Low / Moderate
Moderate
Moderate / High
High
State boundary
LGA boundary
Middle Chad aquifer
Major river
Recharge (mm/y)
Borehole yield (m3/h)
0 - 5
5 - 10
10 - 15
15 - 18
Bima Sandstone
Chad F. Middle Aquifer
Chad F. Upper Aquifer
Functionality (yield / formation data unavailable)
Functional
Non-Functional
Partially functioning


Groundwater quality
ACACIA WATER
Map version: final version
2024-10-23
LEGEND
Suitability
Low
Low / Moderate
Neutral
Moderate / High
High
Major river
IGRAC fluoride
Middle Chad aquifer
LGA boundary
State boundary
Fluoride and Nitrate concentration
WHO limits
- Fluoride > 1.5 mg/l
- Nitrate > 50 mg/l
Fluoride exceeding
Nitrate exceeding
Both not exceeding
M: Middle Chad aquifer
U: Upper Chad aquifer
S: Surface water
B: Bima sandstone
0
50
100 km
14.000°N
13.000°N
12.000°N
11.000°N
10.000°N
9.000°N
8.000°N
10.000°E
11.000°E
12.000°E
13.000°E
14.000°E
Jigawa
Yobe
Borno
Gombe
Adamawa
Baga-Sola باغا سولا
Diffa
Mainé-Soroa
Abadam
Yusufari
Yunusari
Machina
Karasuwa
Mobbar
Kukawa
Biriniwa
Kaugama
Guri
Bade
Gashua
Bursari
Geidam
Guzamala
Gubio
Hadejia
Nganzai
Marte
Jakusko
Zaki
Tarmua
Gamawa
Mafa
Dikwa
Fune
Nangere
Potiskum
Damaturu
Kaga
Konduga
Bama
Fika
Gujba
Nafada
Damboa
Gwoza
Mora
Gulani
Funakaye
Biu
Chibok
Madagali
Mokolo
Maroua
Askira/Uba
Michika
Kwami
Bayo
Hawul
Hong
Mubi
Shani
Gombi
Mubi South
Kaélé
Balanga
Guider
Maiha
Binder بندر
Shelleng
Song
Léré
Lafia
Girei
Karim-Lamido
Numan
Demsa
Jimeta
Garoua
Lau
Yola South
Yola
Fufore
Yorro
Jalingo
Jada
Poli
Bali
Tcholliré
Ganye
Toungo
Gashaka

Environmental degradation

Map version: final version
2024-10-23

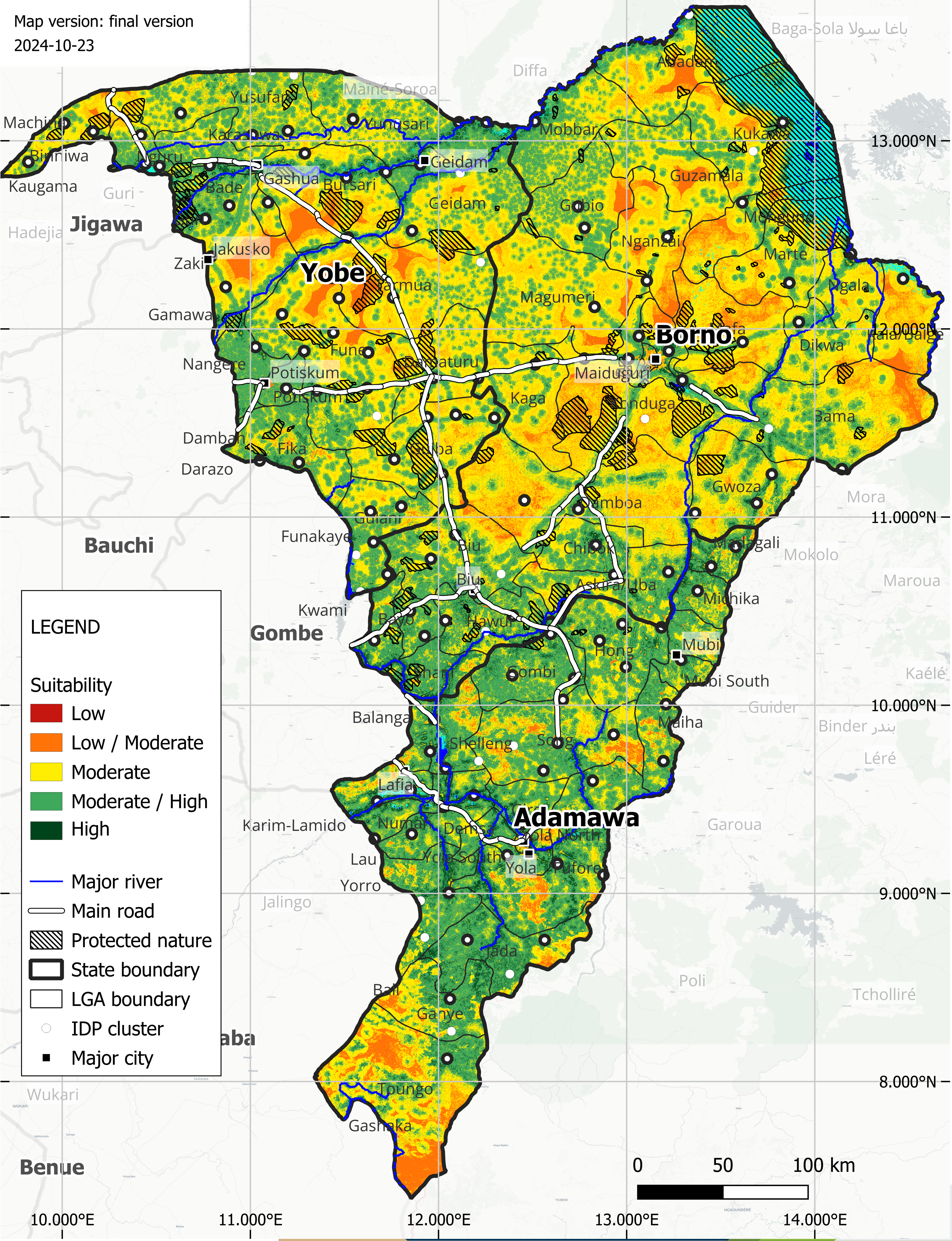


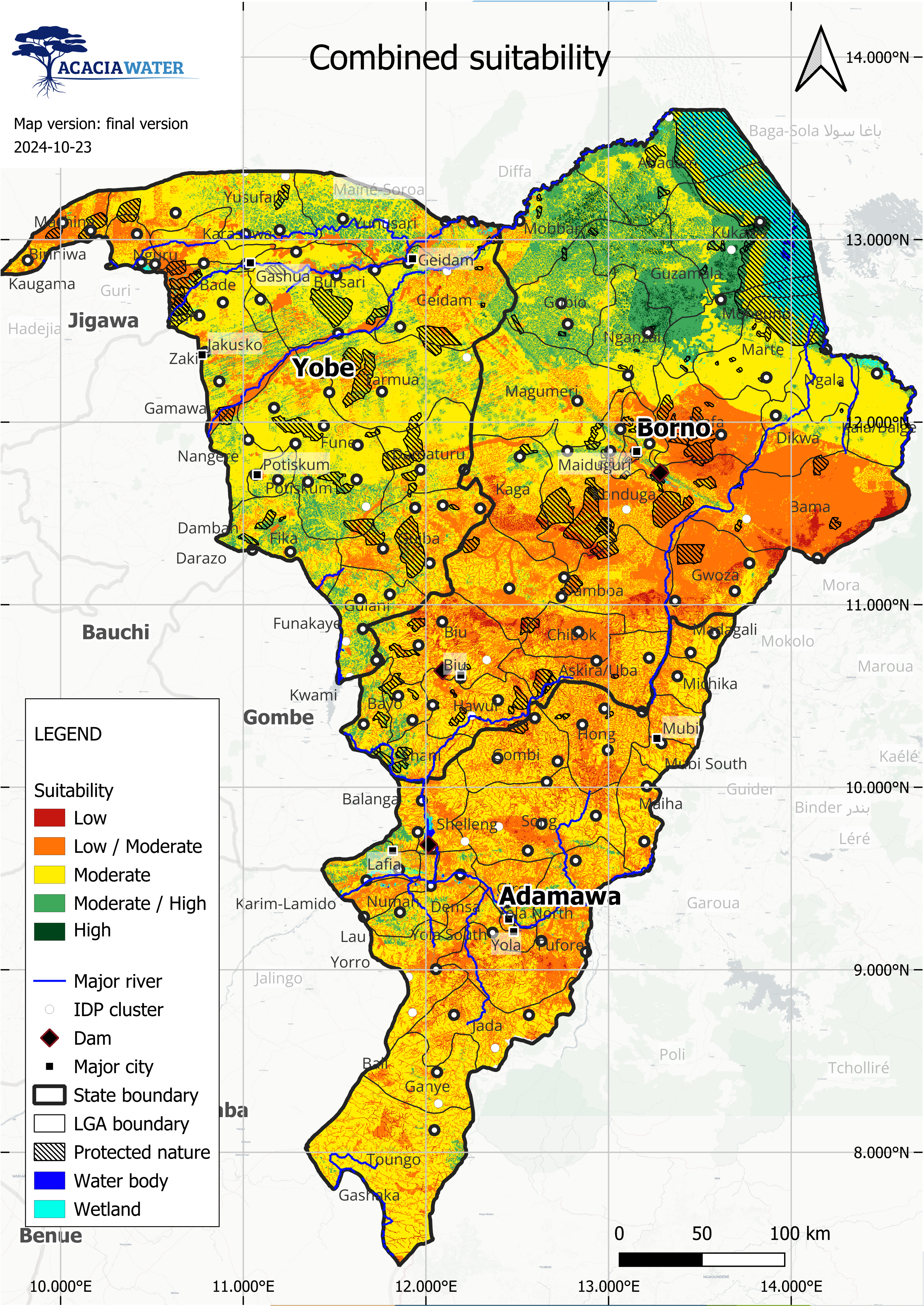


ACACIAWATER
Flood risk
Map version: final version
2024-10-23
LEGEND
Suitability
Low
Low / Moderate
Moderate
Moderate / High
High
Major river
2024 Flooding area
2022 Flooding area
IDP cluster
Dam
Major city
State boundary
LGA boundary
Water body
Wetland
Jigawa
Yobe
Borno
Gombe
Adamawa
Benue
14.000°N
13.000°N
12.000°N
11.000°N
10.000°N
9.000°N
8.000°N
10.000°E
11.000°E
12.000°E
13.000°E
14.000°E
0
50
100 km

Terrain characteristics

Map version: final version
2024-10-23




Combined suitability
ACACIAWATER
Map version: final version
2024-10-23
LEGEND
Suitability
Low
Low / Moderate
Moderate
Moderate / High
High
Major river
IDP cluster
Dam
Major city
State boundary
LGA boundary
Protected nature
Water body
Wetland
Jigawa
Yobe
Borno
Bauchi
Gombe
Adamawa
Benue
Maiduguri
Potiskum
Damaturu
Geidam
Gashua
Nguru
Bade
Bursari
Yusufari
Yunusari
Karasuwa
Machina
Jakusko
Tarmua
Fune
Fika
Nangere
Gujba
Gulani
Biu
Bayo
Hawul
Kwami
Shani
Gombi
Hong
Mubi
Mubi North
Mubi South
Michika
Madagali
Askira/Uba
Chibok
Damboa
Gwoza
Bama
Konduga
Kaga
Magumeri
Ngala
Marte
Dikwa
Monguno
Guzamala
Kukawa
Abadam
Mobbar
Gubio
Nganzai
Maiha
Song
Shelleng
Lamurde
Numan
Demsa
Yola North
Yola South
Fufore
Jada
Ganye
Toungo
Gashaka
Mayo-Belwa
Guyuk
Diffa
Mainé-Soroa
Baga-Sola باغا سولا
Kaugama
Guri
Hadejia
Birniniwa
Zaki
Gamawa
Damban
Darazo
Funakaye
Balanga
Karim-Lamido
Lau
Yorro
Jalingo
Bali
Mora
Mokolo
Maroua
Kaélé
Guider
Binder بندر
Léré
Garoua
Poli
Tchollíré
Kala/Balge
14.000°N
13.000°N
12.000°N
11.000°N
10.000°N
9.000°N
8.000°N
10.000°E
11.000°E
12.000°E
13.000°E
14.000°E
0
50
100 km

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