MALI

COUNTRY REPORT

GIS Hydropower Resource Mapping and Climate Change Scenarios for the ECOWAS Region

ECOWAS Centre for Renewable Energy and Energy Efficiency
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Program Responsibility:

The ECOWAS Small-Scale Hydropower Program was approved by ECOWAS Energy Ministers in 2012. In the frame of this program ECREEE assigned Poyry Energy GmbH in 2015 for implementation of a GIS Hydro Resource Mapping and Climate Change Scenarios in ECOWAS countries with Hydropower potentials. One deliverable of this project are 14 country reports summarizing the GIS Hydro Resource mapping and climate change scenarios. The overall methodology background information and lessons learnt of these Country Reports are described in the final report *"GIS Hydropower Resource Mapping and Climate Change Scenarios for the ECOWAS Region - Methodology & Lessons Learnt."*
www.ecowrex.org/smallhydro

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PREFACE

The 15 countries of the Economic Community of West African States (ECOWAS) face a constant shortage of energy supply, which has negative impacts on social and economic development, including also strongly the quality of life of the population. In mid 2016 the region has about 50 operational hydropower plants and about 40 sites are under construction or refurbishment. The potential for hydropower development – especially for small-scale plants – is assumed to be large, but exact data were missing in the past.

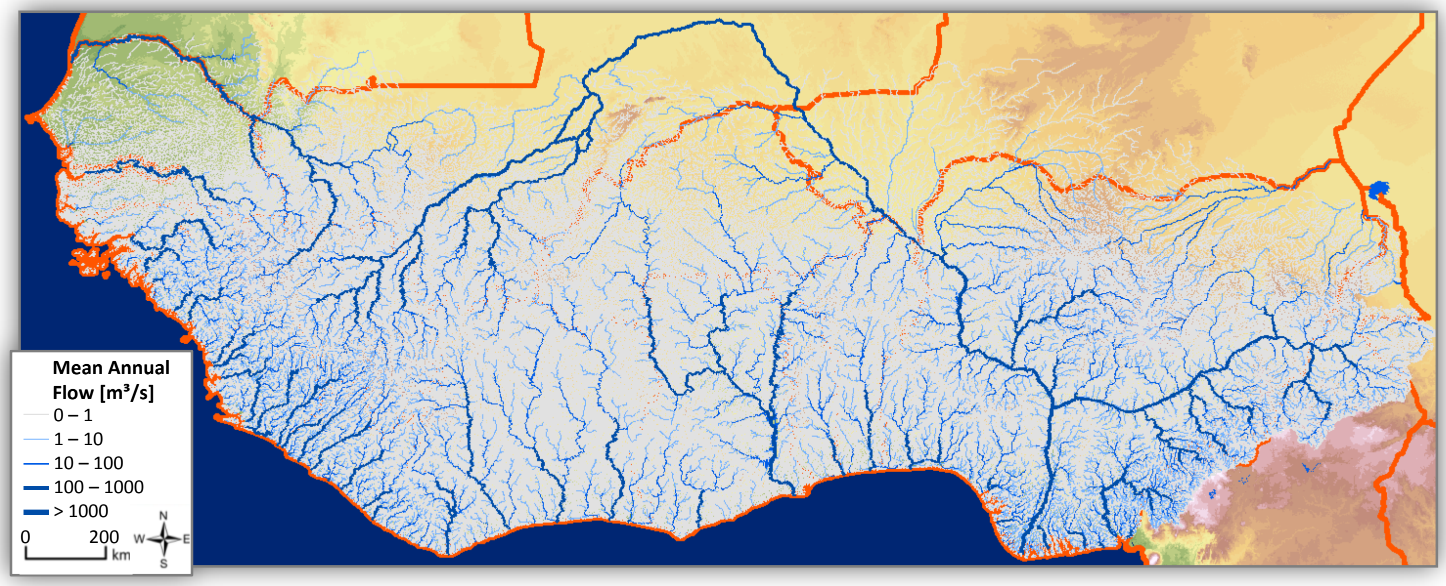
The ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE), founded in 2010 by ECOWAS, ADA, AECID and UNIDO, responded to these challenges and developed the ECOWAS Small-Scale Hydropower Program, which was approved by ECOWAS Energy Ministers in 2012. In the frame of this program ECREEE assigned Pöyry Energy GmbH in 2015 for implementation of a hydropower resource mapping by use of Geographic Information Systems (GIS) for 14 ECOWAS member countries (excluding Cabo Verde). The main deliverable of the project is a complete and comprehensive assessment of the hydro resources and computation of hydropower potentials as well as possible climate change impacts for West Africa. Main deliverables of the GIS mapping include:

- River network layer: GIS line layer showing the river network for about 500,000 river reaches (see river network map below) with attributes including river name (if available), theoretical hydropower potential, elevation at start and end of reach, mean annual discharge, mean monthly discharge, etc.
- Sub-catchment layer: GIS polygon layer showing about 1000 sub-catchments with a size of roughly 3000 km². This layer summarizes the data of all river reaches located within the sub-catchment.

Hydropower plants are investments with a lifetime of several decades. Therefore, possible impacts of climate change on future discharge were incorporated into the river network and sub-catchment GIS layers. The GIS layers are available in the ECREEE Observatory for Renewable Energy and Energy Efficiency (www.ecowrex.org).

This report summarizes the results of the GIS layers for Mali and includes:

- General information
- Climate
- Hydrology
- Hydropower potential
- Climate change



GENERAL INFORMATION

Mali covers an area of 1.2 Mio km² but has only 17 Mio inhabitants. Most of the population is concentrated around the capital Bamako in the south, whereas the northern part of the country extends into the Sahara desert. The neighboring countries of Mali are Senegal in the west, Mauritania in the north-west, Algeria in the north, Niger in the east, as well as Burkina Faso, Côte d'Ivoire and Guinea in the south (see map below).

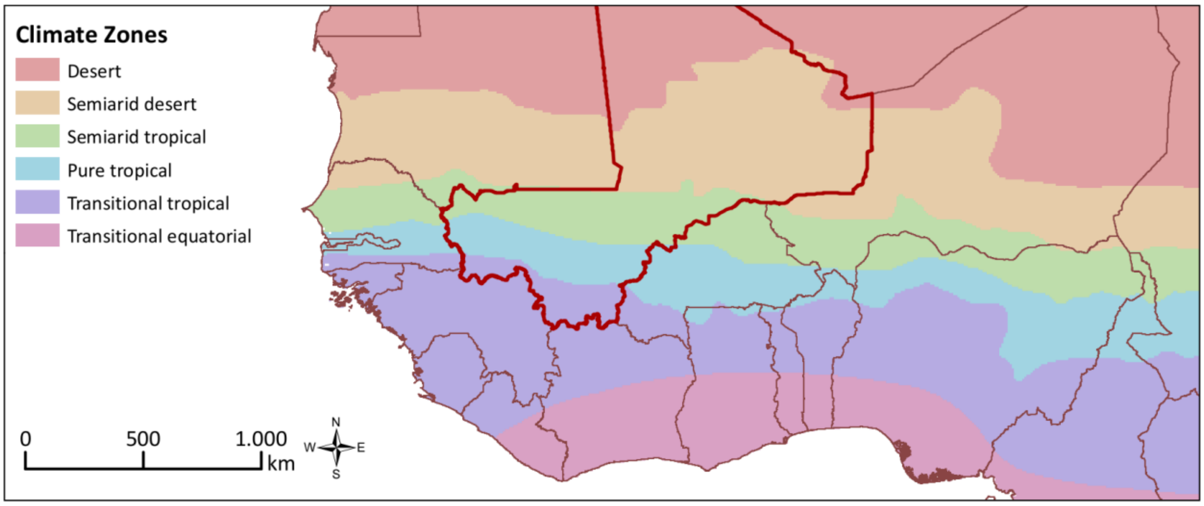
Hydropower plays an important role for energy generation in Mali, as hydropower contributes more than half of the total electricity generation in the country (see table below). There are nine hydropower plants operational or under construction, including small, medium and large hydropower plants.

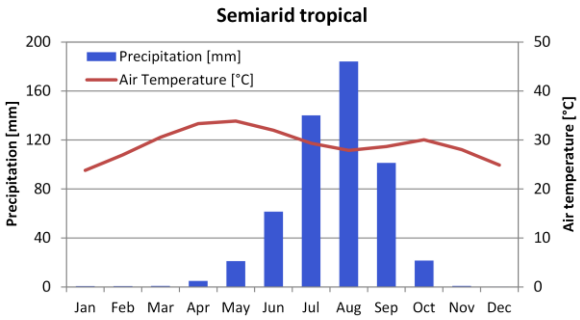
General Information for Mali	
Inhabitants (2014)	17.1 Mio.
Area (2014)	1,240,190 km²
GDP per capita (2014)	704 USD
Electrification rate total/urban/rural (2014/2012)	23/34/7 %
Hydro installed capacity (2014)	182.9 MW
Electricity generation (2014)	1,591 GWh
Electricity generation from hydropower (2014)	997.1 GWh
Number of existing hydropower plants with installed capacity > 1 MW (2016)	9
Number of existing small hydropower plants with installed capacity 1-30 MW (2016)	5
Number of existing medium hydropower plants with installed capacity 30-100 MW (2016)	2
Number of existing large hydropower plants with installed capacity >100 MW (2016)	2

Source: ECOWAS Country Profiles (www.ecowrex.org)
Reference year given in brackets.

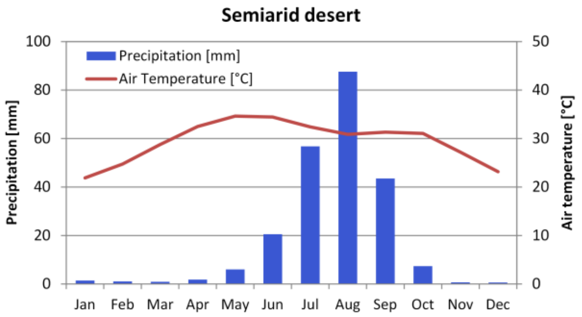
CLIMATE

The climate in West Africa can be grouped into six zones with distinctive seasonal rainfall patterns (L'Hôte et al., 1996). Mali covers a wide range of climate zones from "Transitional tropical" with high rainfall in the south to "Semiarid desert" and "Desert" in the north. The diagrams below summarize the mean monthly rainfall and air temperature in these climate zones.





Precipitation data source: Tropical Rainfall Measuring Mission (NASA/JAXA), TRMM 3B42, mean 1998-2014
Air temperature data source: Climate Research Unit (University of East Anglia), CRU TS 3.22, mean 1998-2013



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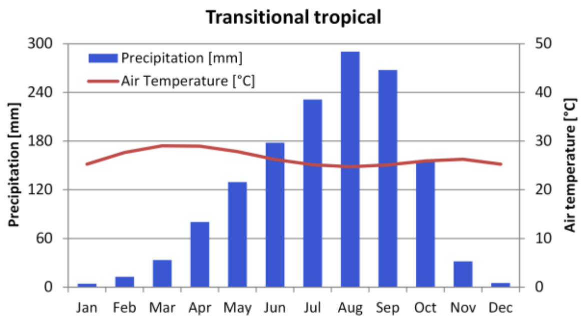
Air temperature data source: Climate Research Unit (University of East Anglia), CRU TS 3.22, mean 1998-2013



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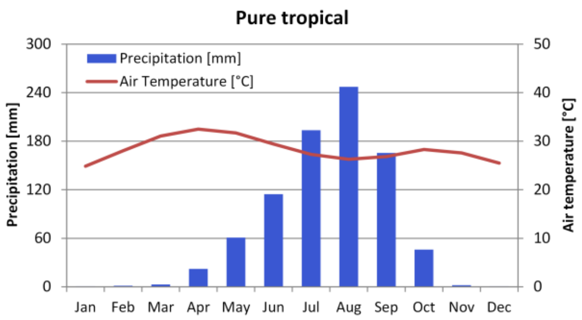


Precipitation data source: Tropical Rainfall Measuring Mission (NASA/JAXA), TRMM 3B42, mean 1998-2014
Air temperature data source: Climate Research Unit (University of East Anglia), CRU TS 3.22, mean 1998-2013

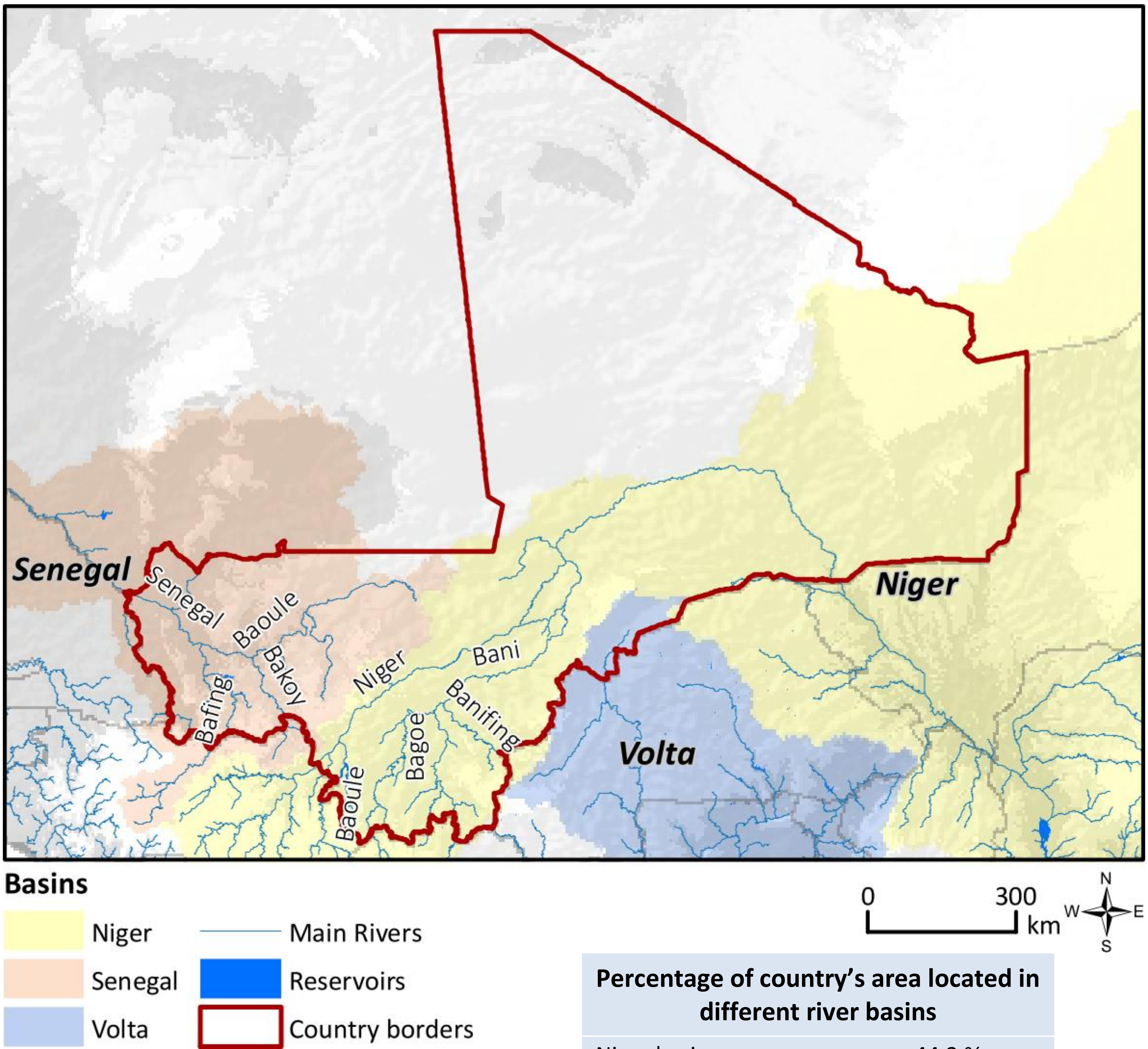
HYDROLOGY

The Niger River is the largest river in Mali. About 44 % of the country is located in the Niger basin. The Niger River enters Mali from Guinea and flows in north-westerly direction into the Inner Niger Delta near Mopti. A major tributary is the Bani basin (including the Bagoe River). At Diré the Niger River changes its course to east and finally south-east flowing into the Republic of Niger. The western part of Mali is situated in the Senegal basin, with the major tributaries Bafing and Bakoy (see map and tables below).

The figures on the following page illustrate the annual and seasonal variations in discharge for the Niger, Bagoe and Senegal rivers.

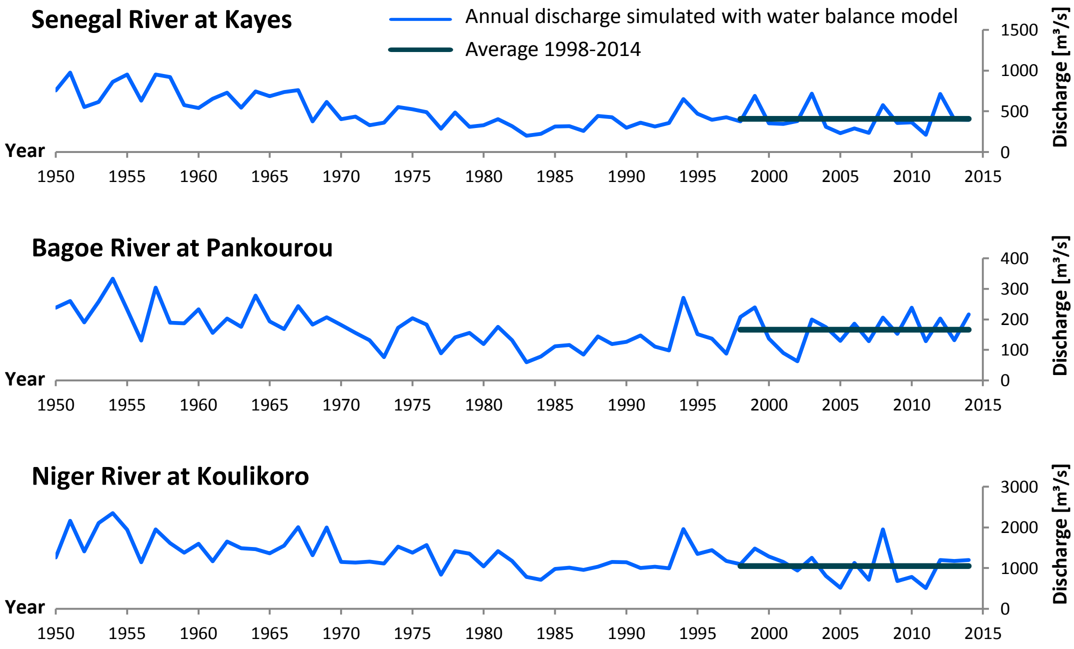
All three rivers show strong variations in annual discharge over the last 60 years. The 1950s and 1960s were the wettest decades, whereas the period 1998-2014 represents moderately wet conditions in the historic context.

There is strong seasonality in discharge, with high flows from August to October. Some of the rivers (e.g. Bagoe) may fall dry between February and April.

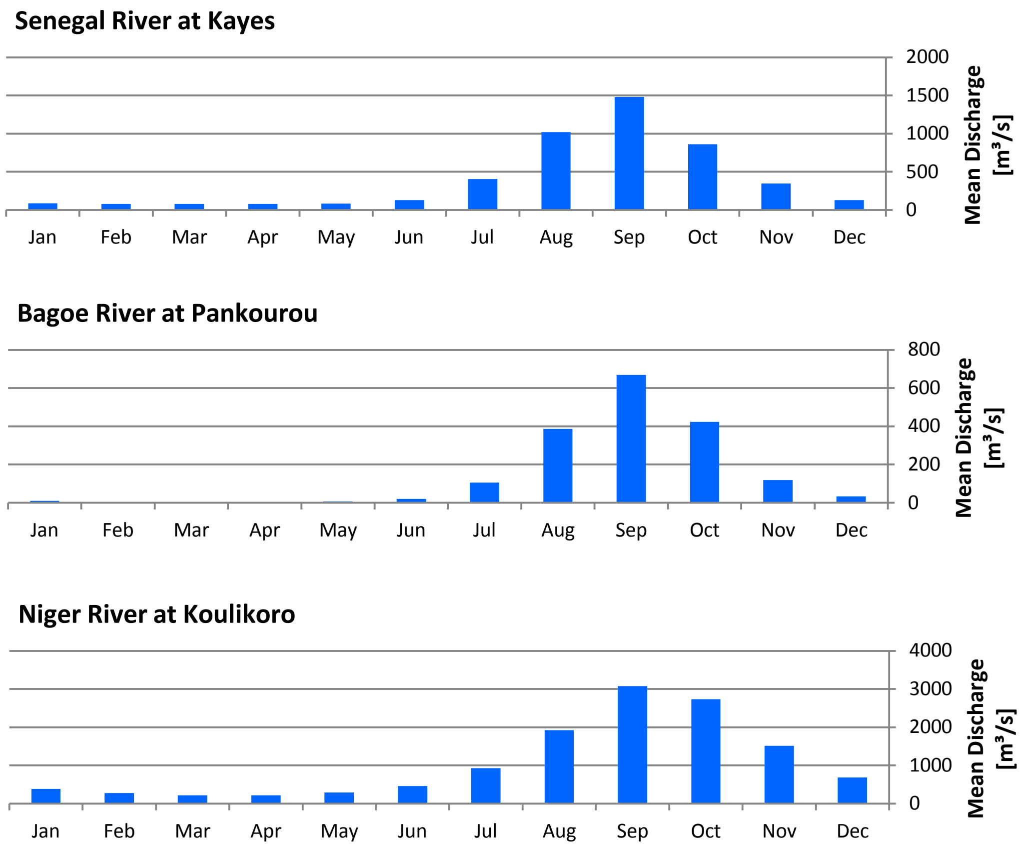


Percentage of country's area located in different river basins	
Niger basin	44.3 %
Senegal basin	13.7 %
Volta basin	1.4 %

Historic Variation in Annual Discharge



Seasonality in Discharge



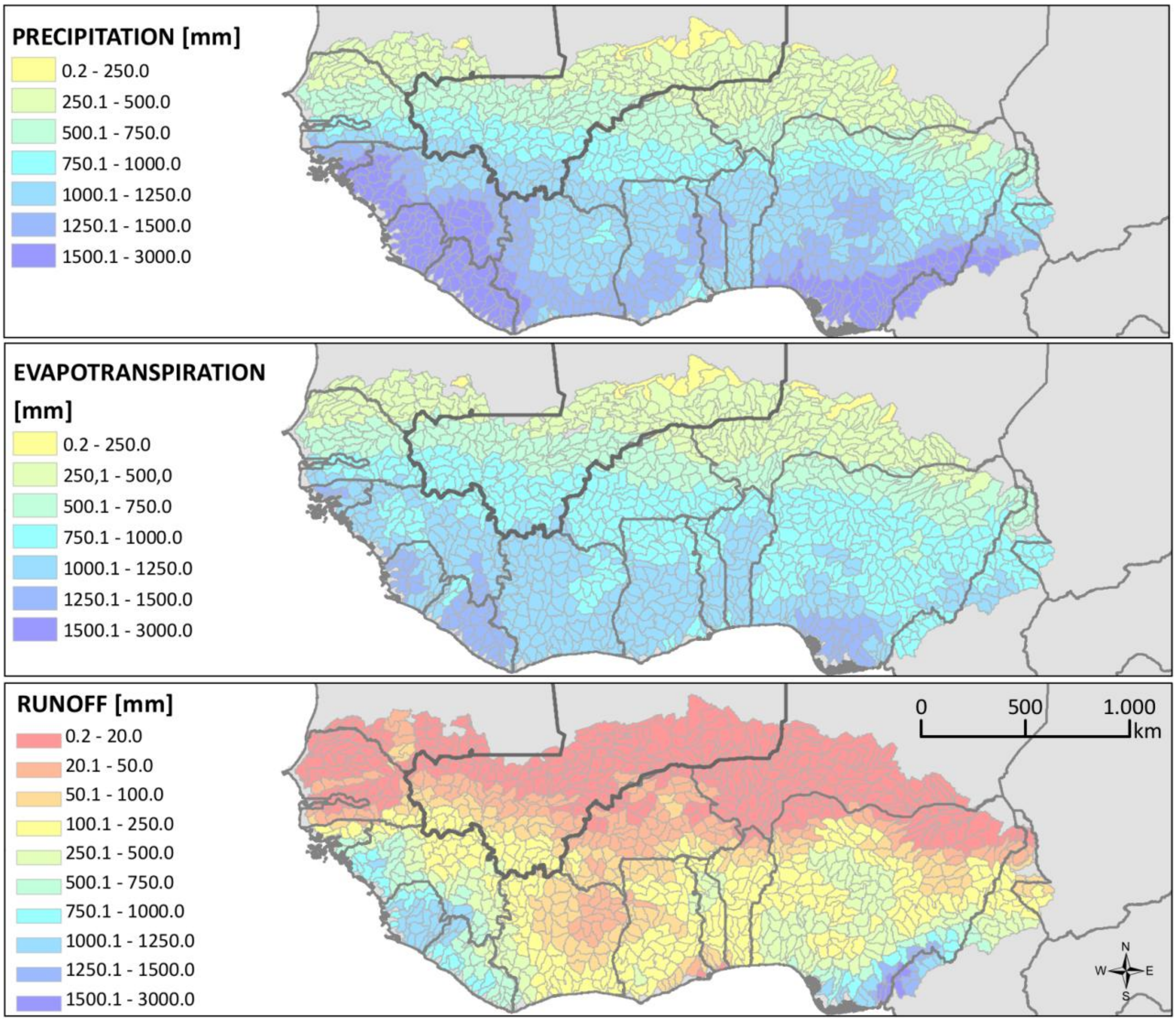
Annual Water Balance

The long-term mean annual water balance describes the partitioning of precipitation (rainfall) into actual evapotranspiration (transpiration by plants, evaporation from soil) and runoff, as over long time periods the change in storage (soil moisture, ground water) can be assumed to be negligible for the mean annual water balance.

The regional distribution of the water balance components in West Africa is strongly controlled by spatial variations in mean annual precipitation. An annual water balance model calibrated with observed discharge data of 400 gauges was used to determine mean annual actual evapotranspiration and runoff for the period 1998-2014, as shown in the maps below. In most parts of West Africa mean annual actual evapotranspiration is considerably larger than mean annual runoff.

This is also the case for the mean annual water balance in Mali. In the southern parts of the country about 85 % of rainfall is lost via evapotranspiration and only about 15 % of rainfall generates runoff. This relationship becomes more extreme in the central and northern parts of the country, where almost all of the rainfall is lost via evapotranspiration and mean annual runoff is below 20 mm.

Mean annual discharge is computed by aggregating runoff along the river network, which together with channel slope determines the hydropower potential (see next section).

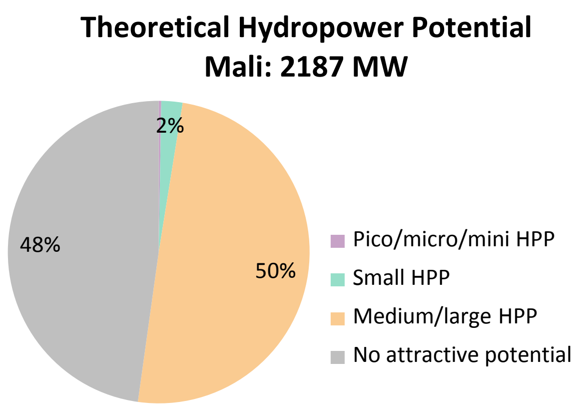


HYDROPOWER POTENTIAL

The theoretical hydropower potential of a river is defined as the amount of power that would be produced if the full head of the river was used and if 100 % of the mean annual discharge was turbinated (i.e. no spillway losses or environmental flow constraints). In this study overall plant efficiency (turbines, hydraulic losses) is assumed with 87 %.

The theoretical hydropower potential for Mali is estimated to be 2187 MW (reference period 1998-2014), which is the total of all rivers in the country.

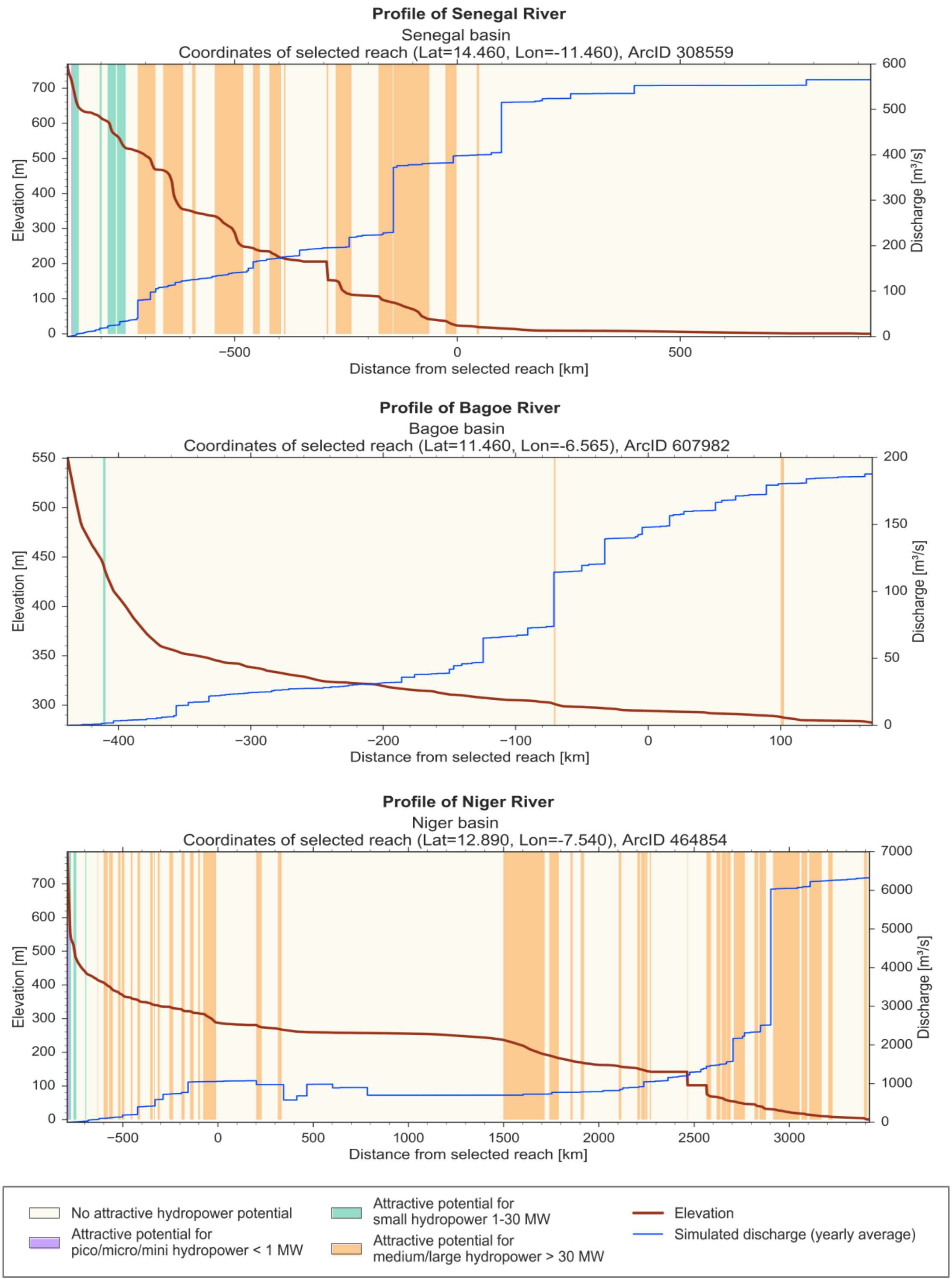
The following table and figure show how the total potential of the country is subdivided into theoretical potential for hydropower plants (HPP) of different plant size. A classification scheme based on mean annual discharge (m^3/s) and specific hydropower potential (MW/km) was applied to determine the preferred plant size for river reaches with a typical length of 1-10 km. Four classes were considered for the preferred plant size, including pico/micro/mini HPP (< 1 MW installed capacity), small HPP (1-30 MW installed capacity), medium/large HPP (> 30 MW installed capacity), and "No attractive potential" for river reaches with too low specific hydropower potential. For the latter in some cases it may still be worthwhile to utilize this potential in e.g. multi-purpose schemes. Almost all of the attractive theoretical potential in Mali is classified as medium/large HPP. The technical potential was not assessed in this study.



Theoretical Hydropower Potential of Rivers in Mali	
Pico/micro/mini HPP	6 MW
Small HPP	50 MW
Medium/large HPP	1086 MW
No attractive potential	1045 MW
Total of all rivers in country	2187 MW
Total of rivers with attractive theoretical potential for pico/micro/mini, small, or medium/large HPP	1142 MW

Longitudinal Profiles of Selected Rivers

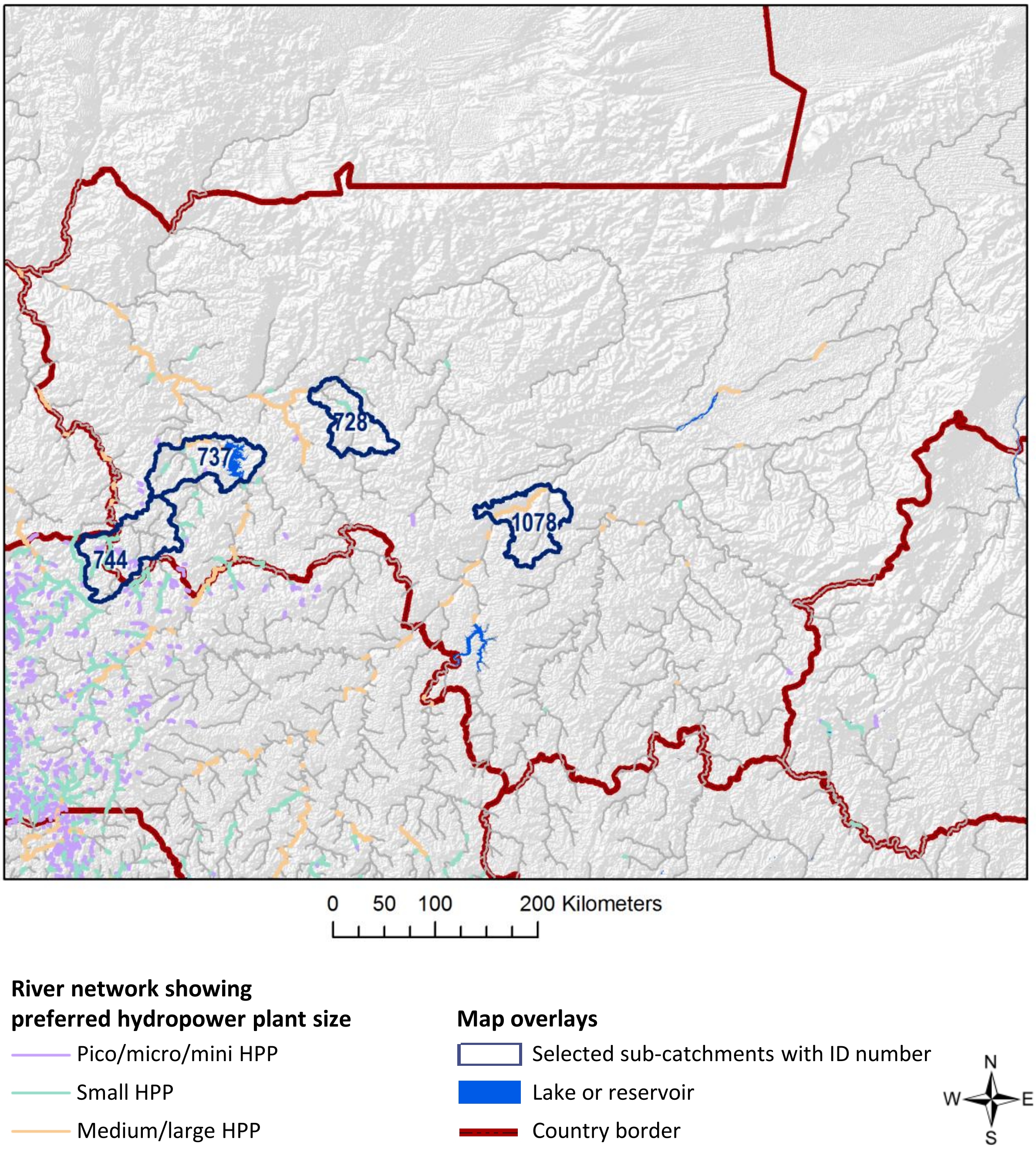
The following graphs show longitudinal profiles of the Senegal, Bagoe and Niger rivers, plotting elevation (red) and mean annual discharge (blue) from the source to the mouth of the river. Inflow from tributaries is clearly identifiable as sudden increase in river discharge. Reservoirs are identifiable by constant elevation in the reservoir lake and sudden drop of elevation at the dam site. Diversions and floodplain losses cause a decrease of discharge in some sections of the Niger River. The background color indicates if a river reach has an attractive theoretical hydropower potential for pico/micro/mini HPP (< 1 MW installed capacity), small HPP (1-30 MW installed capacity), or medium/large HPP (> 30 MW installed capacity).

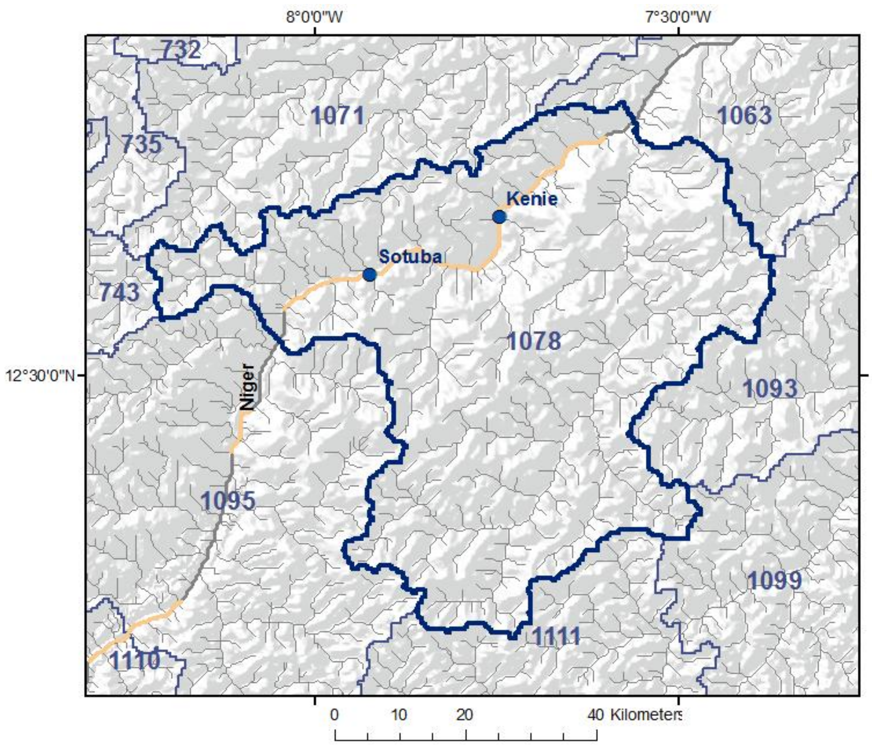


Hydropower Potential in Selected Sub-catchments

The following maps and tables give information about the theoretical hydropower potential of selected sub-catchments in Mali. The selected sub-catchments are located in the central and western parts of Mali.

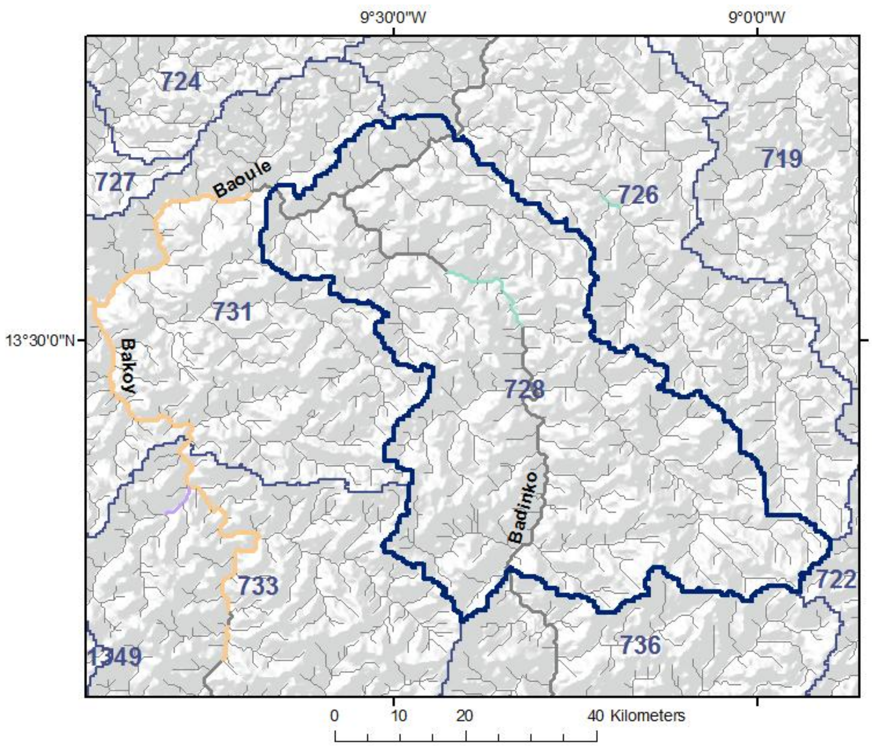
The table data summarizes the total theoretical hydropower potential of all river reaches within the sub-catchment. River reaches were grouped according to preferred plant size for pico/micro/mini HPP (< 1 MW installed capacity), small HPP (1-30 MW installed capacity), or medium/large HPP (> 30 MW installed capacity). Similarly, the color code of the river network displayed in the maps indicates the preferred plant size. A grey color indicates no attractive potential for hydropower development.





Theoretical Hydropower Potential of Rivers in Sub-Catchment #1078	
Pico/micro/mini HPP	0 MW
Small HPP	0 MW
Medium/large HPP	223.4 MW

In this section of the Niger River near Bamako there is considerable potential for medium/large HPP. This section of the Niger River also includes the Sotuba HPP (operational) and the Kenie HPP (under construction).



Theoretical Hydropower Potential of Rivers in Sub-Catchment #728	
Pico/micro/mini HPP	0 MW
Small HPP	9.1 MW
Medium/large HPP	0 MW

This sub-catchment of the Baoule River includes the lower sections of the Badinko River. There is a short section of the Badinko River that has some potential for small HPP. It is located in the Reserve du Badinko.

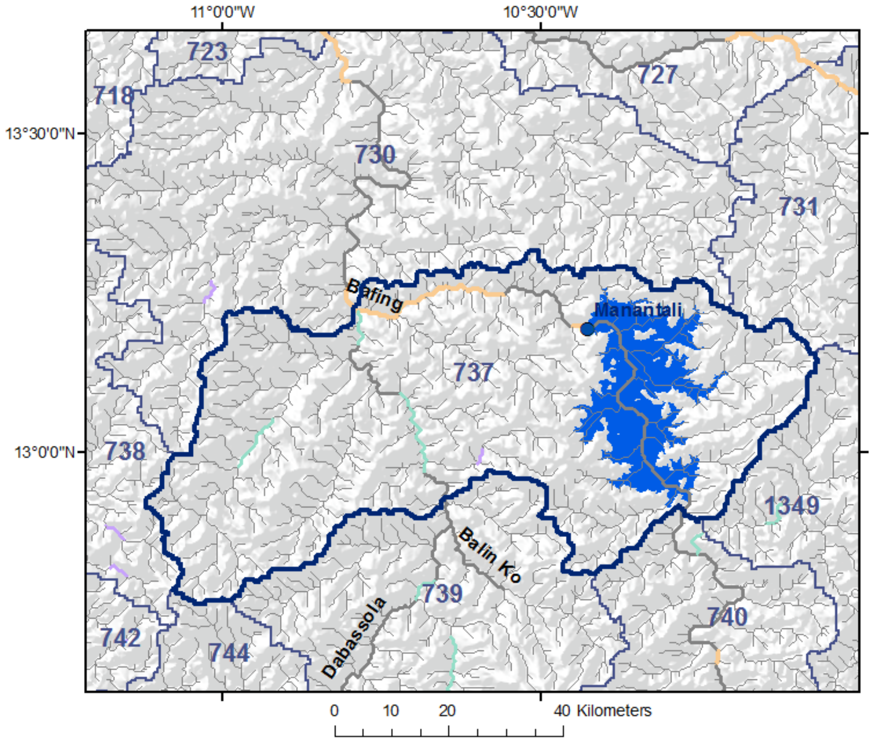
River network showing preferred hydropower plant size

- Pico/micro/mini HPP
- Small HPP
- Medium/large HPP
- No attractive potential

Map overlays

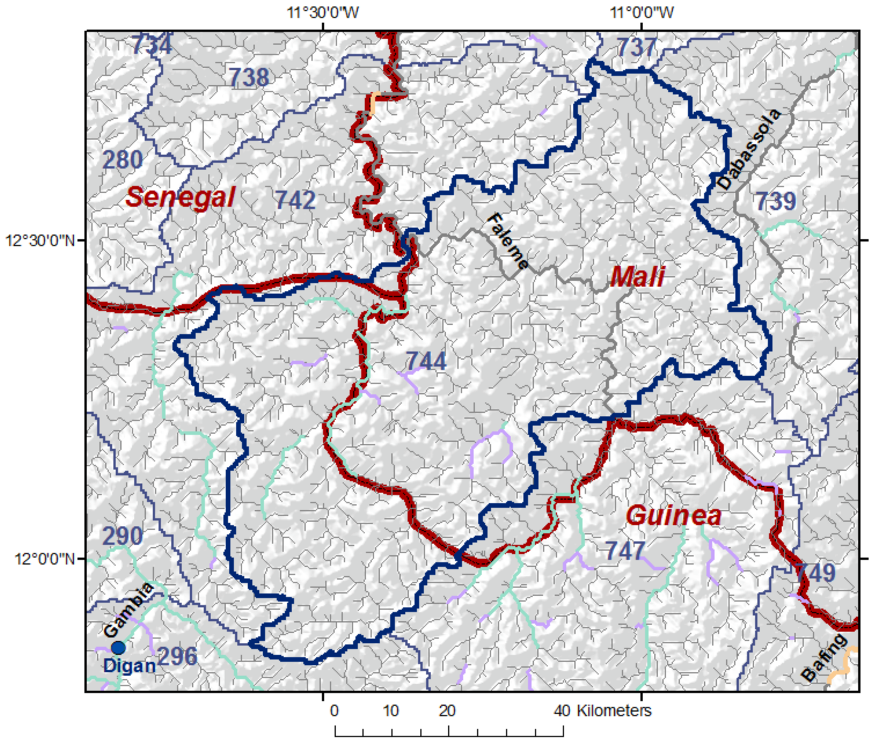
- Existing hydropower plant
- Lake or reservoir
- Sub-catchment boundary
- Country border

N W E S



Theoretical Hydropower Potential of Rivers in Sub-Catchment #737	
Pico/micro/mini HPP	0.2 MW
Small HPP	7.6 MW
Medium/large HPP	152.7 MW

This sub-catchment of the Bafing River includes the existing Manantali HPP, which already utilizes about half of the potential of the sub-catchment. The remaining potential for medium/large HPP is located at the Bafing River downstream of the reservoir. The potential for small HPP is mainly located at the Balin Ko River.



Theoretical Hydropower Potential of Rivers in Sub-Catchment #744	
Pico/micro/mini HPP	3.0 MW
Small HPP	19.0 MW
Medium/large HPP	0 MW

This sub-catchment of the Faleme River is located in the south-western corner of Mali and extends into Guinea. In Mali there are a few streams that have some potential for pico/micro/mini HPP. A tributary to the Faleme River forms the international border between Mali and Guinea. This tributary has considerable potential for small HPP.

River network showing preferred hydropower plant size

- Pico/micro/mini HPP
- Small HPP
- Medium/large HPP
- No attractive potential

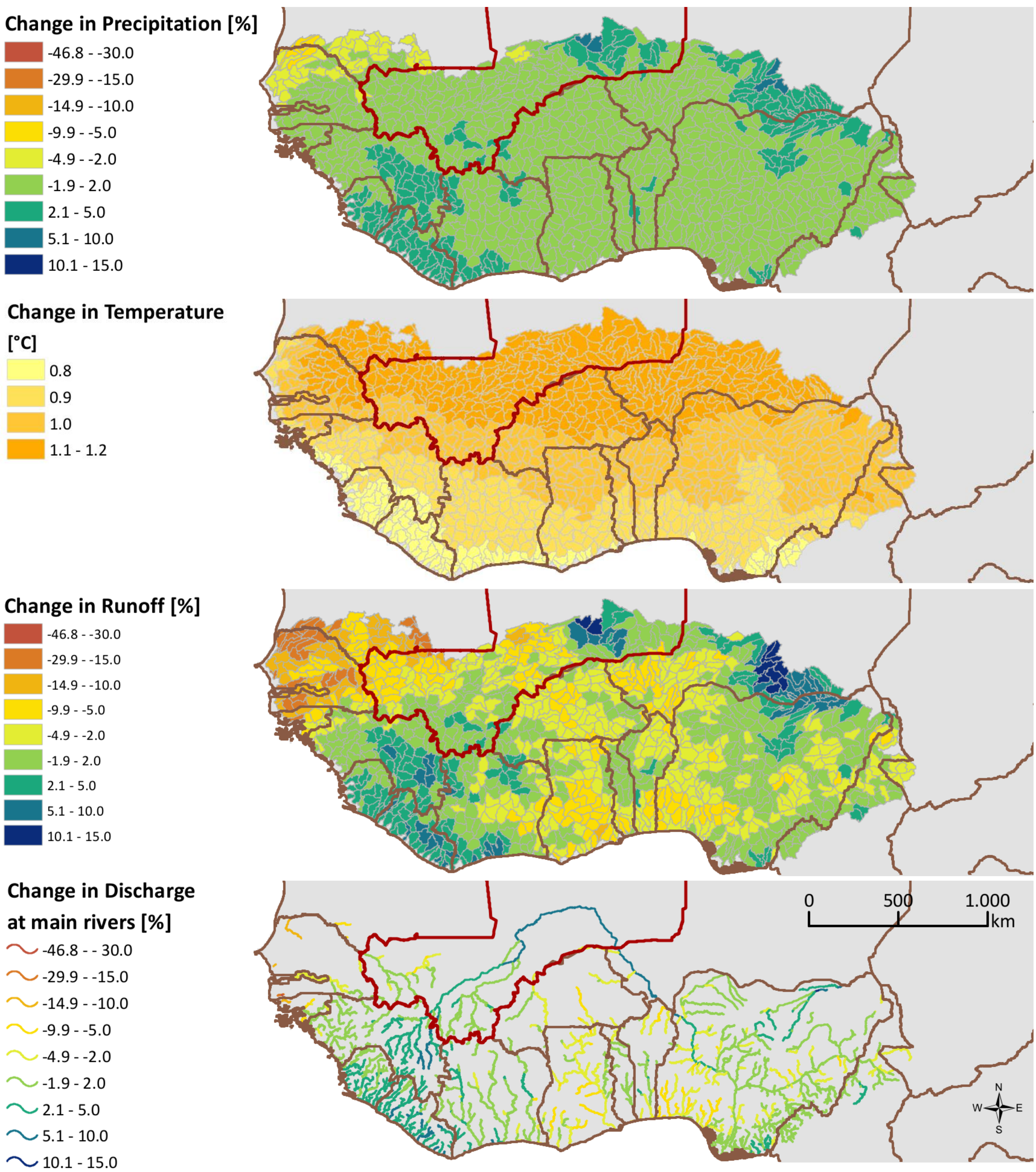
Map overlays

- Existing hydropower plant
- Lake or reservoir
- Sub-catchment boundary
- Country border

CLIMATE CHANGE

Climate change may have considerable impact on future water resources and thus hydropower generation. The following figures show an assessment of climate change projections for West Africa based on 15 Regional Climate Models of the CORDEX-Africa ensemble. Two Representative Concentration Pathways (RCP4.5 and RCP8.5) were considered, thus yielding a total of 30 climate model runs. Future runoff was simulated by driving a water balance model with precipitation and temperature climate change signals with respect to the reference period 1998-2014.

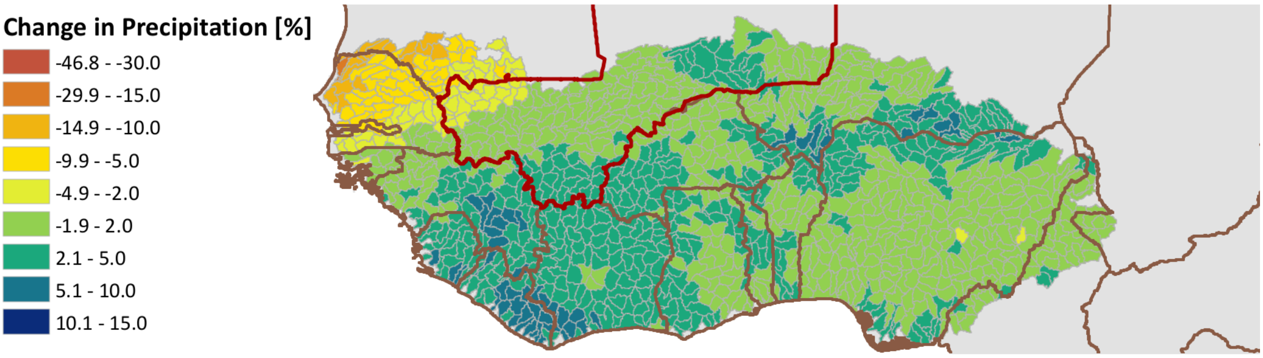
Projections for the Near Future 2026-2045

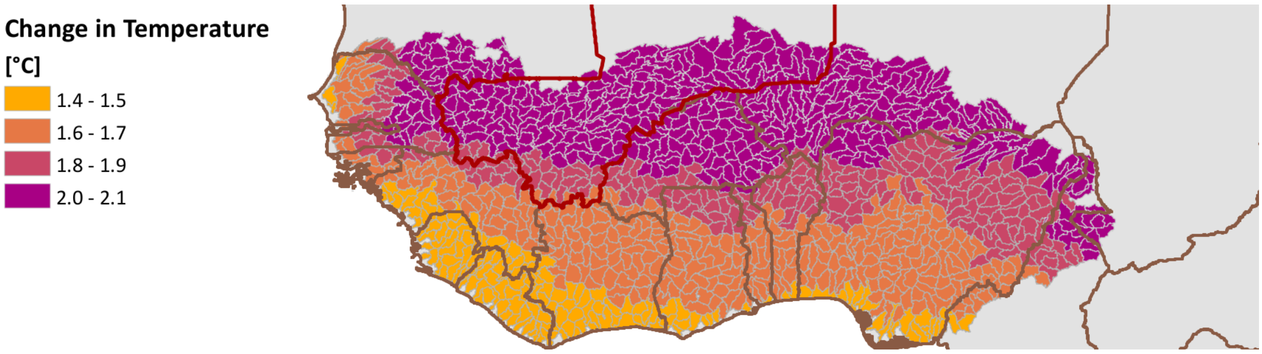


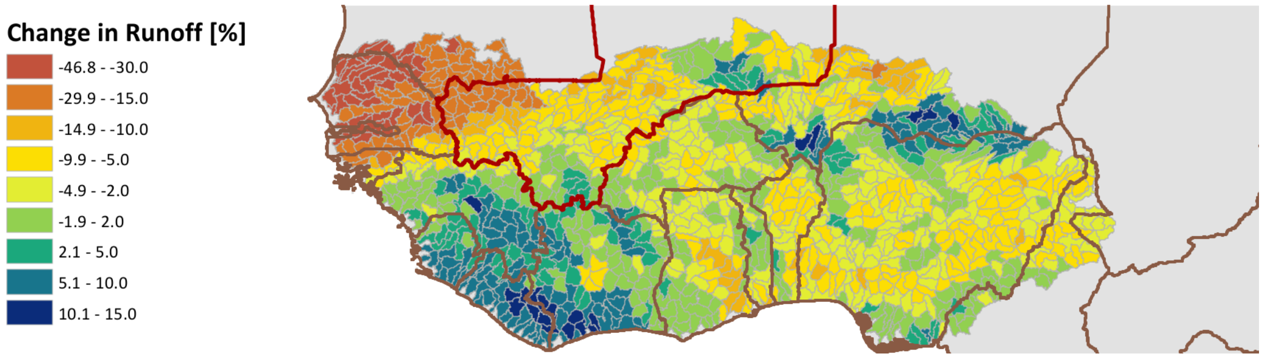
Projections for the Far Future 2046-2065

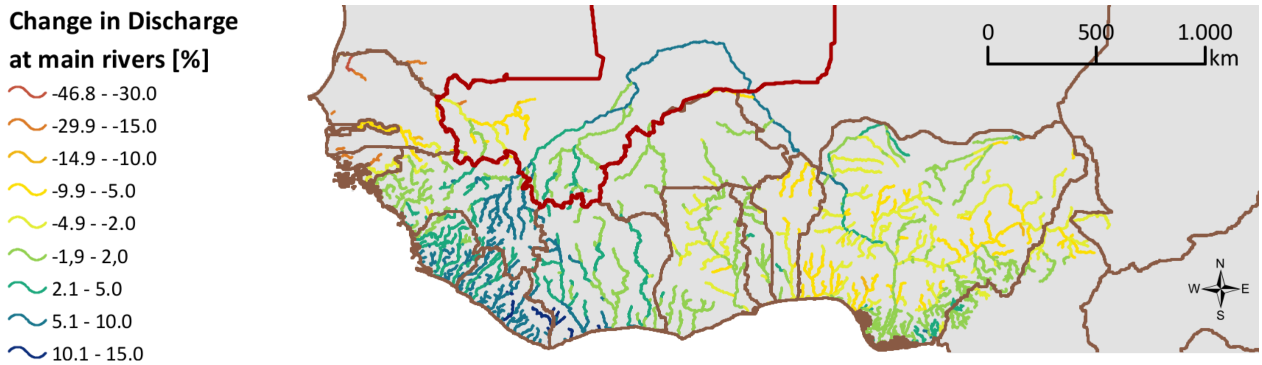
The maps below show the expected impact of climate change on future mean annual water resources. From the 30 climate model runs the median result was computed to generate the maps, which show change signals comparing the future periods 2026-2045 (previous page) and 2046-2065 (this page) vs. the reference period 1998-2014.

In large parts of West Africa increase or almost no change is projected for future precipitation. This is also the case for Mali. The combined effects of future precipitation and considerable warming (which affects evapotranspiration) were simulated with a water balance model to compute future runoff. In most regions of Mali a decrease is projected for future runoff (median of 30 model runs). However, this does not apply to discharge of the Niger River, as the river has its source in Guinea where runoff is projected to increase.









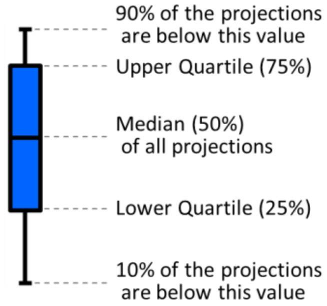
Projected Change in Discharge for Selected Gauges

Future mean annual discharge was estimated with data from 30 different climate model runs. Boxplots are presented to summarize the spread in the simulation results (see explanation at right).

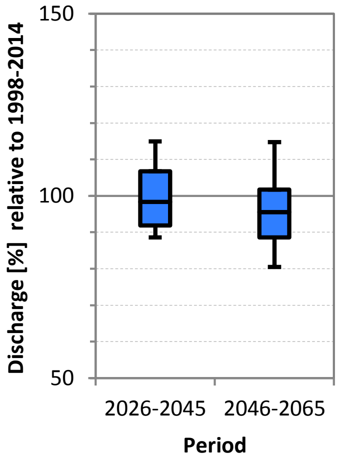
For the Senegal River there is a tendency of climate models to project a decrease in future discharge, with a median decrease of -5 % in the far future. In contrast, discharge of the Niger River is projected to increase by about +5 %, whereas for the Bagoe River projections with individual climate models do not agree if there will be an increase or decrease in future discharge.

Overall the climate change impact assessment shows that given the projections with the most detailed climate models currently available (CORDEX-Africa) there is no clear signal for pronounced changes in future discharge, apart from a few percent. This means that climate change is not a 'worst-case' scenario for hydropower development in Mali.

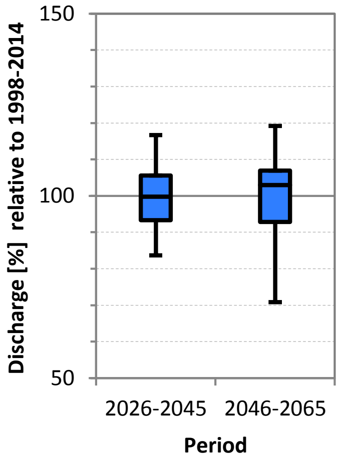
Boxplot summarizing projections with 30 climate model runs



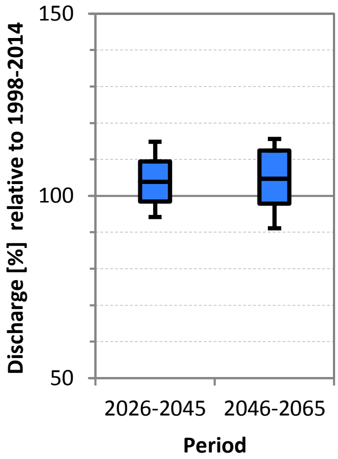
Senegal River at Kayes



Bagoe River at Pankourou



Niger River at Koulikoro



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This study was conducted by Pöyry Energy GmbH (Vienna, Austria) for the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE, Praia, Cabo Verde). This is a contribution to the ECOWAS Small-Scale Hydro Power Program, which aims to develop the small-scale hydropower sector in West Africa and is funded by the Austrian Development Agency (ADA) and the Spanish Agency for International Development Cooperation (AECID).

Observed discharge data were used for hydrological model calibration and were obtained from the following sources: Global Runoff Data Centre (GRDC), Volta Basin Authority, Niger Basin Authority, Senegal & Gambia Basin Authorities (OMVS, OMVG), Liberia National Hydrological Service, Sierra Leone National Hydrological Service, Japan International Cooperation Agency (JICA).

Precipitation data 1998-2014 are based on Tropical Rainfall Measurement Mission (TRMM 3B42 v7). Additional precipitation data 1950-2010 for model calibration were obtained from the Global Precipitation Climatology Centre (GPCC). Air temperature and potential evapotranspiration data were obtained from the Climatic Research Unit (CRU, Univ. East Anglia), with additional data from the CLIMWAT database of FAO. River network and elevation data were derived from the Hydrosheds dataset (USGS). Climate model data were obtained from the Coordinated Regional Downscaling Experiment for Africa (CORDEX-Africa), which is a project of the World Climate Research Program.

The delineation of climate zones is based on: L`Hôte Y, Dubreuil P, Lerique J. 1996. *Carte des types de climats en Afrique Noire à l'ouest du Congo. Rappels, et extension aux régimes hydrologiques*. In: L'hydrologie tropicale: géoscience et outil pour le développement (Actes de la conférence de Paris, mai 1995). IAHS Publ. no. 238, p. 55-65

More information about the general methodology for the GIS hydropower resource mapping is available in: Kling H, Stanzel P, Fuchs M. 2016. *Regional assessment of the hydropower potential of rivers in West Africa*. Energy Procedia, Elsevier, Special Issue of ERE, 8 pp.