The Sudan Flood Risk Profile

Assessment of flood socio-economic impacts for Sudan in current and projected climate scenarios.

ITALIAN AGENCY FOR DEVELOPMENT COOPERATION

cima RESEARCH FOUNDATION

The Sudan Flood Risk Profile is a result of the initiative *APIS - "Early Warning and Civil Protection for Floods and Droughts in Sudan"*, implemented by CIMA Research Foundation and funded by the Italian Agency for Development Cooperation (AICS).

DISCLAIMER

RIGHTS AND PERMISSIONS

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Acknowledgements

The scientific team conducted the risk assessment process with the collaboration of the technical members of the National Council for Civil Defense for local data collection, to whom the implementing organizations express their gratitude and acknowledge the valuable support.

At the time the production of the risk profile started, the primary objective was to support local authorities of Sudan with evidence-based information to orient polict making in disaster risk reduction. The conflict erupted in Sudan in April 2023, deeply modified the context requiring a reassessment of the target audience of the risk profile and on the use and interpretation of its results.

The information contained in this report can support International Donors and NGOs, providing a solid overview of the expected impact for natural hazards alone. A reliable baseline to identify priority sectors and regions for risk mitigation funding and actions in the current emergency context, with the ongoing conflict further exacerbating the natural disaster risk scenarios identified.

As science is first and foremost at the service of sound decision-making, we hope that this report facilitates the translation of knowledge into solutions to reduce the additional losses that the Sudanese population might suffer due to flood disasters impacting on the current fragile context.

The authors would also like to thank the Internal Displacement Monitoring Center (IDMC) for their financial and conceptual contributions in refining the displacement risk component. They also acknowledge that the Sudan displacement risk analysis was made possible through the financial support of the Habitable project, funded by the European Commission's Horizon 2020 programme.

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Key findings

1

The annual number of **people affected** from riverine floods grows from about 270 thousand in current climate conditions to more than 1,440 thousand in projected climate conditions SSP1-RCP2.6 considering socio-economic projections (SEP), and up to about 3,320 thousand considering SSP5-RCP8.5 & SEP.

2

At national level, the annual average direct economic loss to **built-up area** grows from almost USD 625 million in current climate conditions to more than USD 2,300 million in projected climate conditions SSP1-RCP2.6, and up to about USD 6,600 million considering SSP5-RCP8.5.

3

For **agriculture damages**, in current climate condition, up to 56,000 hectars of cropland, more than 6,300 hectars of grazing land and 56,000 livestocks could be damaged yearly on average. In projected climate conditions SSP5-RCP8.5 the damage to the agriculture sector is expected to be more from 5 to 10 times higher.

4

For **critical infrastructure damages**, in current climate condition, almost 145 km of transportation network, 2 education facilities and 2 health facilities could be damaged yearly on average. In projected climate conditions SSP5-RCP8.5 the number of the critical infrastructure damages more than 10 times higher.

At a glance

RISK METRICS

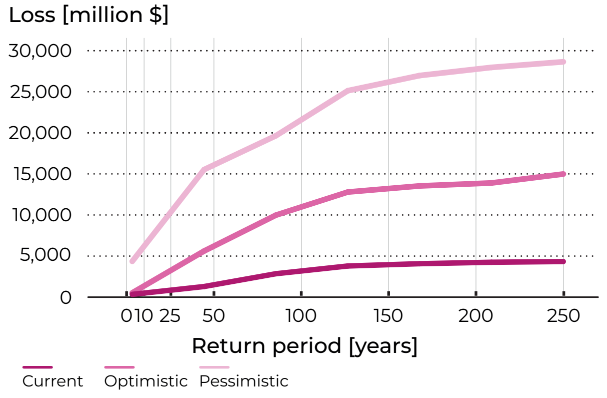
AAL – Average Annual Loss (AAL) is a compact metric that represents the annualised accumulated effect of small to medium and extreme events and predicts the likely displacement associated with them on a yearly basis.

AAD – Average Annual Displacement is the expected number of displacements per year, averaged over many years.

PML – Probable Maximum Loss metric shows the likelihood of a certain scenario producing an estimated amount of economic losess.

PMD – Probable Maximum Displacement metric shows the likelihood of a certain scenario producing an estimated amount of displacements. PMD at 100-year return period (100- yrp) expresses the number of displacements that can be exceeded in a disastrous event occurring on average once every 100 years.

Probable Maximum Loss curve of direct economic losses to built-up areas



CLIMATE SCENARIOS

To investigate how climate change may alter the future frequency and intensity of extreme events, two different scenarios are explored as reference:

OPTIMISTIC – the scenario closest to the 20th percentile, corresponding to an average temperature rise of about +1°C by 2100.

PESSIMISTIC – the scenario closest to the 80th percentile, corresponding to an average temperature rise of over +5°C by 2100.

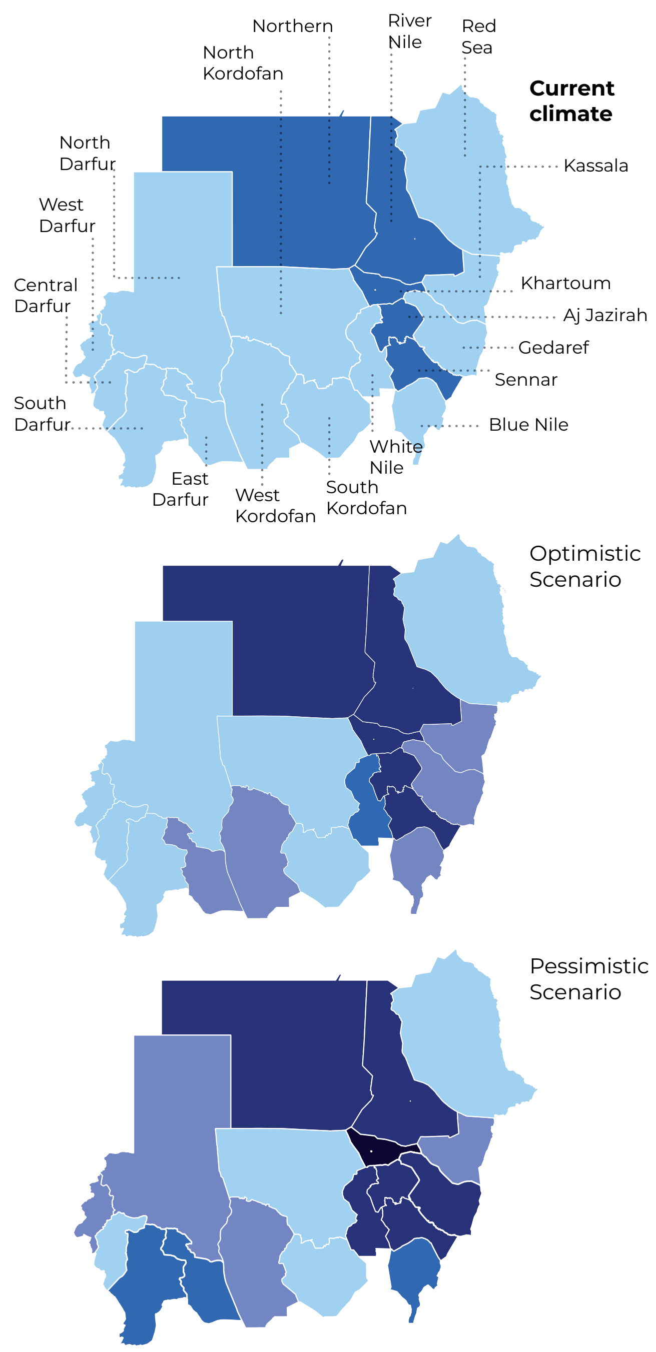
SOCIO-ECONOMIC PROJECTIONS

When considering climate scenarios, risk for population is evaluated by considering a distribution in line with UN projections for 2050.

AAL POPULATION
Current and projected climate conditions

nº of people: 0 – 5,000 – 30,000 – 100,000 – 500,000 – 1,150,000

	Current climate	Optimistic Scenario	Pessimistic Scenario
Aj Jazirah	**39,000** **0.94%**	300,000 3,87%	450,000 5.73%
Gedaref	**2,500** **0.15%**	20,500 0,66%	105,000 3.40%
Blue Nile	**4,700** **0.34%**	20,000 0,77%	44,000 1.65%
CentralDarfur	**150** **0.02%**	600 0,05%	3,000 0.27%
East Darfur	**350** **0.02%**	7,300 0,18%	40,000 1.00%
Kassala	**900** **0.04%**	6,800 0,15%	14,000 0.30%
Khartoum	**38,000** **0.50%**	350,000 2,41%	1,120,000 7.79%
North Darfur	**125** **<0.01%**	1,300 0,02%	6,000 0.09%
North Kordofan	**0** **0%**	<10 <0.01%	200 <0.01%
Northern	**75,000** **7.84%**	195,000 11,01%	280,000 15.83%
Red Sea	**0** **0%**	0 0%	0 0%
River Nile	**69,000** **4.40%**	335,000 11,39%	480,000 16.51%
Sennar	**37,000** **2.22%**	160,000 5,10%	425,000 13.48%
South Darfur	**350** **0.01%**	4,300 0,05%	30,000 0.32%
South Kordofan	**30** **<0.01%**	150 0,01%	1,900 0.11%
West Darfur	**250** **0.03%**	2,100 0,13%	6,000 0.38%
West Kordofan	**1,100** **0.06%**	7,800 0,23%	14,000 0.39%
White Nile	**4,500** **0.17%**	35,000 0,69%	300,000 5.86%



01

Introduction

Over the past few decades, natural disasters have frequently disrupted hard-earned development plans and progress, exacerbating poverty and hindering shared prosperity. The impacts of these disasters typically extend beyond physical damages to infrastructure and critical facilities, resulting in severe human, financial, cultural, and environmental losses. It is crucial to recognize the interconnectedness between disasters and development, as poorly-managed development itself can become a driver of risk, further perpetuating poverty.

Uninformed planning and urbanization processes can lead to unsustainable development, increasing the vulnerability of populations and existing economic systems. This vicious cycle not only depletes natural ecosystems but also intensifies the vulnerability of marginalized communities. Consequently, limited coping capacities and inadequate resources for investing in disaster risk reduction and recovery measures further amplify the challenges faced by impoverished populations.

In this context, post-disaster rehabilitation often necessitates international aid or diverts national funds originally allocated for development interventions, causing a significant setback to the overarching goal of poverty reduction and shared prosperity.

However, it is possible to significantly minimize the impact of disasters through rigorous scientific risk modeling, effective dissemination of risk information, and the establishment of robust institutional and community preparedness. By incorporating risk assessment as the foundation for disaster risk reduction and climate adaptation measures, it becomes feasible to anticipate and respond to the changing frequency and magnitude of natural hazard events resulting from climate change.

To achieve poverty reduction and shared prosperity, risk reduction processes must prioritize the effective communication and application of risk information. Strengthening institutional and human capacities is essential for informed decision-making that considers risks and builds resilience at all levels and within various socio-economic development sectors. This entails leveraging scientific risk information to hazards, exposures and assess vulnerabilities, and, enabling estimation of disaster impacts, population dynamics, economic losses, and other relevant indicators across different regions and sectors.

01. Introduction

Sudan is extremely vulnerable to a range of future hazards under climate change, particularly floods and droughts. About 15.6 million people live in poverty, being about 33% of the whole population in the country (World Bank Macro Poverty Outlook, 2023). The 2024 INFORM Risk Index (DRMKC, 2023) ranks Sudan 8th out of 191 countries due to high vulnerability. In 2020, Sudan was affected by the worst flooding in over three decades. The floods in the Nile basin and the heavy rainfall in the other regions affected over 875'000 people and caused about USD 4.4 billion of damage, mainly to the housing sector (Sudan Rapid Post Disaster Needs and Recovery Assessment, 2021). Disasters are expected to increase in frequency, intensity, and severity due to climate change. Sudan is projected to experience the average maximum daily temperature rise of around 2°C and 4.6°C toward the mid and end of the 21st century (World Banks' Climate Change Knowledge Portal). The country's major hazards are projected to worsen with the number of exposed persons to extreme riverine flooding and drought expected to rise.

The climate risk profile of Sudan is rapidly evolving as increasing urbanization, land-use changes, and infrastructure development, together with climate change, alter the spatial and temporal patterns of natural hazards. These changes are further exacerbated by the ongoing conflict erupted in April 2023, to be further investigated in future updates of the present report.

The present national disaster risk profile for Sudan relates information on natural hazards, specifically riverine floods, with the latest climate and socioeconomic data. The risk assessment methodologies are based on hydro-meteorological/hydraulic modeling including updated climate projection, and risk quantification using catastrophe risk modelling combining exposure and vulnerability information. Furthermore, the effectiveness of climate adaptation options is evaluated quantifying the spatial and temporal patters of benefit of climate change adaption in terms of averted flood damage and losses at varying levels of return periods.

02

Probabilistic risk assessment: methodology

Understanding disaster risk is essential for sustainable development. Many different and complementary methods and tools are available for analyzing risk. These range from qualitative to semi-quantitative and quantitative methods: probabilistic risk analysis, deterministic or scenario analysis, historical analysis, and expert elicitation. Often there is not a better or worse methodology, but they are intimately linked with the application they are intended to be used for. However, some methodologies have a higher information content and allow for more flexibility in their practical use. One of these is the probabilistic risk assessment approach, which was used to develop this disaster risk profile for floods in Sudan.

The probabilistic risk assessment is based on a modelling approach to predict possible present and future scenarios, taking into consideration the spatial and temporal uncertainties involved in the analyzed process. Probabilistic disaster risk profiles consider all possible risk scenarios in a certain geographical area. A realistic set of all possible hazardous events (scenarios) that may occur in a given region, including very rare, catastrophic events, is simulated. This means that both low frequency, high loss impact events, as well as high frequency, lower loss impact events are calculated, meaning that their probability of occurrence is included in the assessment. Events which have never been historically recorded but might occur in projected climate conditions are also considered in the risk analysis. This feature is particularly useful in the context of climate change which is dramatically increasing uncertainty about future hazard patterns. Thus, societies need to calculate the possible impacts of those uncertain patterns in order to be prepared. Under this lens, there is no valid alternative to a probabilistic analysis to address this uncertainty in a usable, quantitative way.

For each event, defined through the probability of occurrence of the event magnitude, potential impacts are computed in terms of number of people, assets affected or economic losses, considering publicly available information on Hazard, Exposure, and Vulnerability.

Finally, statistics of losses are computed and summarized through proper quantitative risk metrics, such as: the Annual Average Loss (AAL) and the Probable Maximum Loss (PML).

ANNUAL AVERAGE LOSS (AAL)	PROBABLE MAXIMUM LOSS (PML)
The expected loss per year, averaged many years.	The likelihood of a certain scenario producing an estimated amount of losses

While there may actually be little or no loss over a short period of time, the AAL also accounts for much larger losses that occur less frequently. As such, AAL can represent the annual average disaster loss over a long period of time. On the other hand, the PML describes the maximum loss that could be expected corresponding to a given likelihood, expressed in terms of annual probability of exceedance or its reciprocal, the return period. Typically, when referred to economic losses, PML is relevant to define the size of resources needed to restore damaged capital assets from individual events.

In computing the final metrics (PML, AAL), the uncertainties that permeate the different steps of the computations are explicitly quantified and taken into account, namely: uncertainties in the hazard forcing, uncertainties in the exposure values and their vulnerabilities.

These risk metrics can be calculated both at a regional and national scale, as well as by sector and by administrative unit, which allows for a geographic and quantitative comparison of disaster losses, both within a country and/or between countries. These analyses and comparison exercises are an important step of the risk awareness processes, key in pushing for risk reduction, risk adaptation and risk management mechanisms to be put in place.

A probabilistic disaster risk profile should be seen as a risk diagnosis instrument, as it provides indications on possible hazardous events and their impacts. Both past and probable future events have been taken into consideration in a comprehensive risk assessment exercise.

02. Probabilistic risk assessment: methodology

Probabilistic risk assessment: risk scenarios

The Disaster Risk Profile for Sudan provides a comprehensive view of hazard, risk and uncertainties for floods in a changing climate, with projections for the period 2017-2100. The risk assessment considers a large number of possible scenarios, their likelihood, and associated impacts. A significant amount of scientific information on hazard, exposure, and vulnerabilities has been used to simulate disaster risk.

In this risk profile three different climate scenarios were considered:

- **under current climate conditions**
  with disaster risk assessed using the observed climate conditions in the 1979 - 2016 period;

- **under projected climate conditions, optimistic scenario**
  with disaster risk being assessed under projected climate conditions between 2061-2100, considering the IPCC SSP1-RCP2.6 scenario, designed with the aim of simulating a development that is compatible with the global 2°C target, assuming climate mitigation measures being taken.

- **under projected climate conditions, pessimistic scenario**
  with disaster risk being assessed under projected climate conditions between 2061-2100, considering the IPCC SSP5-RCP8.5 scenario, which foresees high radiative forcing by the end of century, driven by the economic success of industrialized and emerging economies, coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world.

Probabilistic risk assessment: risk components

HAZARD

process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.

In order to predict possible riverine flood scenarios, a modelling chain composed of climate, hydrological, and hydraulic models combined with available information on rainfall, temperature, humidity, wind and solar radiation, has been used.

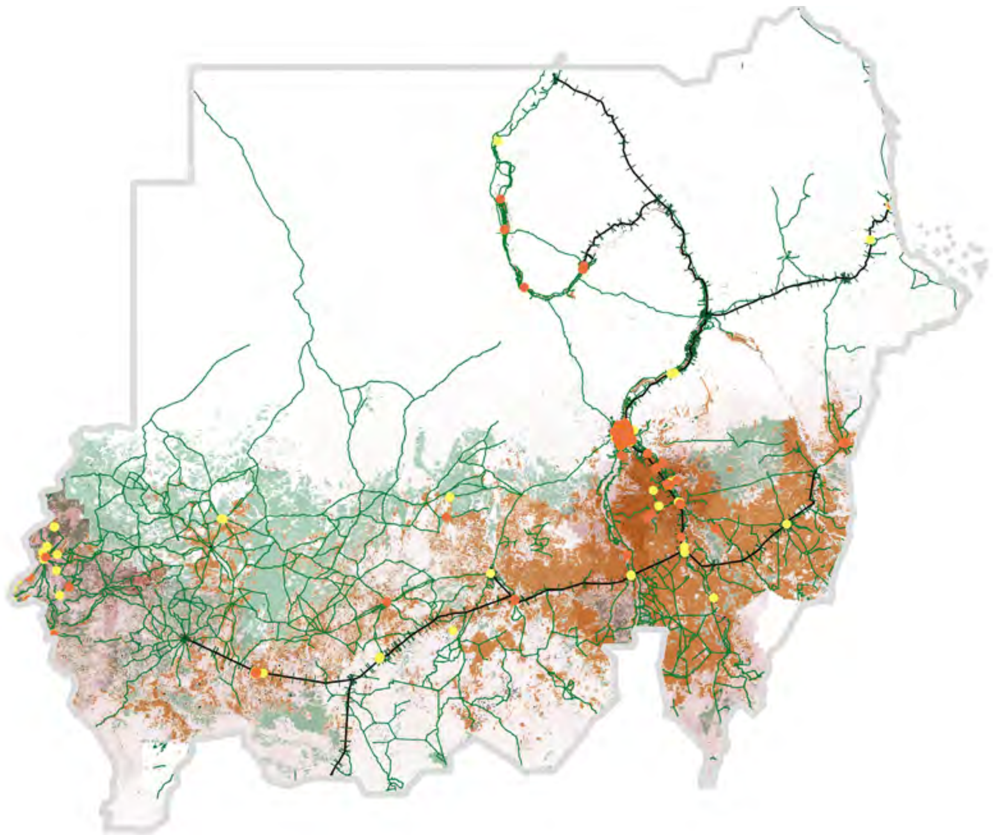
A set of mutually exclusive and collectively exhaustive possible hazard scenarios that may occur in the country, including the most catastrophic ones, is generated and expressed in terms of frequency, extent of the affected area and intensity in different locations.

VULNERABILITY
conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.

Direct losses on different elements at risk are evaluated by applying vulnerability functions. This links hazard intensity to the expected loss (economic loss or number of affected people) while counting for associated uncertainty. Vulnerability functions are differentiated by the typology of exposed elements, and also take into account local factors, such as typical constructive typologies for infrastructures or crop seasonality for agricultural production. In the case of floods, vulnerability is a function of water depth.

EXPOSURE
people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.

Losses caused by floods are assessed in relation to population, GDP and a series of critical sectors (education, health, transport, housing, and the productive and agricultural sectors). Publicly available global and national data, properly generated, enables the location of these elements at high resolution, for the whole country. The total number of people and the national GDP (in USD) are considered in both current (2020) and projected climate (2050) scenarios. The critical sectors are characterized in terms of their economic value (in USD), using the most updated information available.



04. Probabilistic risk assessment: risk components

05

Risk indicators

Several indicators can be used to quantify the impacts of floods and droughts under current and project climate and socio-economic conditions. The choice of indicators can be influenced by several factors: relevance for the country and the context, availability of data and coherency with international policies such as Sendai framework. The indicators selected for Sudan for Floods and Droughts reflect the following needs and constraints:

- Availability of homogeneous and reliable exposure data to be used for the risk indicators definition
- Availability of homogeneous and reliable impact data to calibrate the risk estimation method
- Relevance of the exposure layers and related risk indicators for DRM
- Feasibility of deriving reliable metrics

The following set of risks were therefore selected for floods

PEOPLE LIKELY TO BE AFFECTED

Number of people likely to be affected based on flood extent and magnitude.

PEOPLE LIKELY TO BE DISPLACED

Number of people expected to be displaced as a result of riverine flood events was evaluated considering potential loss of housing and livelihoods, and with the latter income.

ECONOMIC LOSS

Direct economic loss based on flood extent and magnitude, divided into sector classes categories reported in the Sendai Framework Indicators:

To Built-up Area	To Critical Infrastructures
Productive sector (Industrial sector)	Transportation systems (Roads)
Service sector	Education facilities
Housing sector	Health facilities

06

Socio-economic outlook

Sudan is a country located in the Horn of Africa and borders with Egypt, Libya, Chad, Central African Republic, South Sudan, Eritrea, Ethiopia and the Red Sea. Khartoum is the capital where White Nile and Blue Nile meet to form River Nile flowing then to the north reaching Egypt and the Mediterranean Sea. The desert region in the far north is opposed to fertile lands along Nile valleys and Gezira region; agriculture and livestock are widely practiced in the other southern regions (World Bank). The country is affected by seasonal rains in different ways: in the north side, with dry semi-desert climate, the rainy season lasts almost three months (July to September), while in the south and east (Red Sea State) five months from June to October. Sudan is regularly affected by climate related disasters such as floods and droughts with evidence showing increased frequency and intensity of the

POPULATION

46.9 Million People
2022

84.0 Million People
2050 (UNDESA)

OVERVIEW OF THE COUNTRY

Area: **1,878,000** km2 (WB 2021)
Population density: **24** people/km2 (WB 2021)
HDI - Human Development Index: **0.508** (UNDP 2021)
GDP: **51.55** US$ billion (WB 2022)
Median age: **18.6** years (UNDESA 2023)
Life Expectancy at birth: **65** (WB 2021)
Unemployment: **18.7%** (WB 2022)
Employment in agriculture: **41%** (WB 2021)
Employment in industry: **15%** (WB 2021)
Employment in services: **44%** (WB 2021)

06. Socio-economic outlook

hazard with high impact on living conditions and economic growth, determined also by the lack of robust framework to prepare and respond to disasters (IFRC, 2019).

The country has a strategic position in terms of socio-economic relationships in East Africa, with huge potential in several economic sectors such as agriculture and mining (AfDB, 2023). GDP per Capita in Sudan (total population of 48 million) was $1,685 in 2022, a decrease of $62 from $1,746 in 2021 representing a change of -3.5% in GDP per capita (World Bank and UNFPA). The political instability and the conflict started in April 2023 are severely affecting the entire region with more than 6 million individuals internally displaced and over 1 million cross-border movements been made into neighbouring countries (IOM, August 2023). The current humanitarian crisis is causing tremendous consequences to the population, following years of economic instability and never ended conflict situations in some regions, making the future of the country uncertain (OCHA, revised HRP 2023).

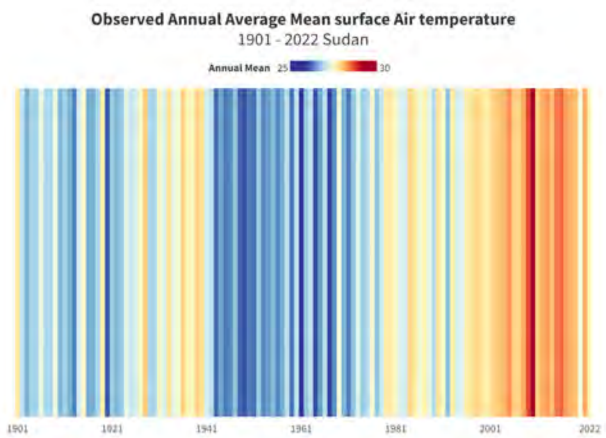
07

Climate outlook

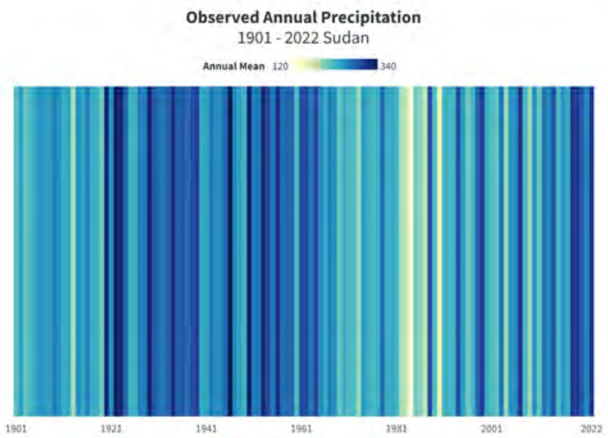
The climate of the country ranges from hot desert in the north to tropical savanna in limited portions of the south. The country experiences generally high temperatures in all regions, while rainfall is more erratic, with higher rates in the southern regions and almost no rain in the northern regions. Most rainfall occurs during the rainy season from April to October (World Banks' Climate Change Knowledge Portal, CCKP). Sudan suffers extreme seasonal and year-to-year variations in the total amount, intensity and localisation of rainfall. The precipitation variability is linked to global conditions, in particular the combination of El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). The concurrence of positive IOD with East Pacific El Niño tipically results in wetter conditions, while the presence of negative IOD with East Pacific La Niña result in drier ones (Palmer et al, 2023).

Key trends

Temperatures are generally high, with mean anuual values between 26°C and 32°C. The average maximum temperatures can reach 40°C in April, while average minimum temperatures reach 13°C in January. Temperature increases have been observed, approximately of 0.37°C per decade since the 1970s.



Rainfall varies widely across the country. In the norther regions annual rainfall is less of 50 mm, while in the central regions ranges from 200 to 700 mm and in the southern ones it can exceed 1,500 mm. Generally, no statistically significant changes in the total amount of mean annual rainfall (250 mm) have been detected in the last century.



Climate projections

Climate projection studies are abundant for multiple different time spans and with various scales. Climate models are tools that the scientific community uses to assess trends in weather conditions over long periods. The main data source for the World Banks' CCKP is the Coupled Model Inter-comparison Project Phase 6 (CMIP6), utilized within the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), providing estimates of future temperature and precipitation. To capture the spread of possible climate scenarios, 15 models are compared from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) - which provides bias-corrected CMIP6 climate scenarios for pre-industrial, historical, SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 conditions - in terms of temperature and precipitation rise with respect to 2016.

In this analysis RCP2.6 and RCP8.5, the extremes of low and high emissions pathways, are the primary focus. RCP2.6 represents a very strong mitigation scenario, whereas RCP8.5 represents an increased GHG emissions scenario:

- SSP1-RCP2.6, the scenario closest to the 20th percentile, corresponding to an average temperature rise about +0.30°C by 2100 relative to 2020 for Sudan;
- SSP5-RCP8.5, the scenario closest to the 80th percentile, corresponding to an average temperature rise of over +5°C by 2100 relative to 2020 for Sudan.

These models show in Sudan a trend of continued, consistent warming, varying by emissions scenario. The projections in rainfall are less certain. However, the trends show a likely increase in the total annual amount and in the frequency and intensity of heavy rainfall events. (CCKP)

LOW EMISSIONS SCENARIO

Substantial and sustained reduction in greenhouse gas emissions

RCP 2.6

INTERMEDIATE EMISSIONS SCENARIO

Some stabilisation in emissions

RCP 4.5

HIGH EMISSIONS SCENARIO

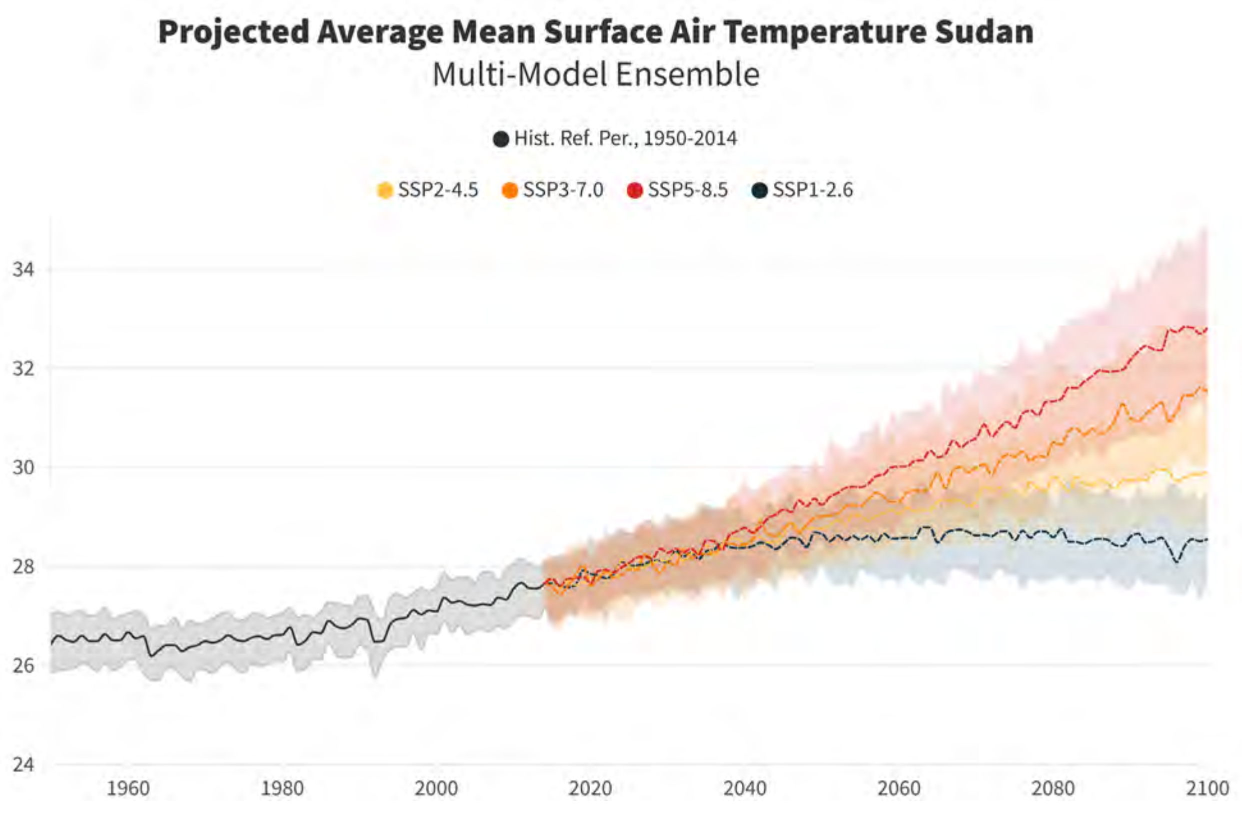
Continued high emissions

RCP 8.5

TEMPERATURE

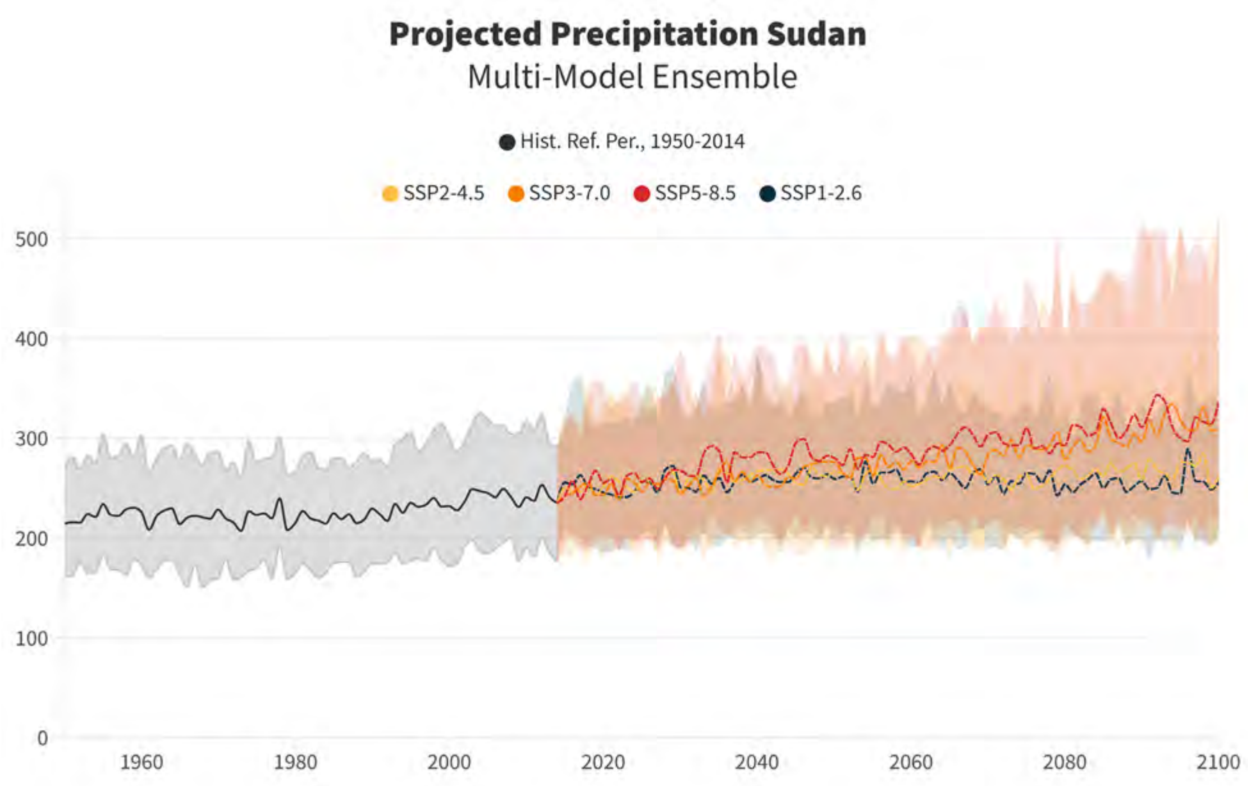
Comparing the highest emissions pathway (RCP8.5) and the 19956–2014 baseline, the average temperature in the country rises of up to 4.9°C by the end of the 21st century. In case of aggressive global emissions reductions (RCP2.6), the projected warming expected for Sudan is of 1.2°C, below the global average of 2°C, evaluated through the lower emissions pathways. The central months (May to July) show temperature changes slightly higher.

Geographically, according to the global model ensemble, the increases will be stronger (above 5°C by 2100) in the northern portions of the country (Northern, Red Sea, Nile and Northern Darfur States). Trends of the maximum and minimum temperatures are similar to the average one. Increase in temperature will likely intensify the impacts of drought events, through increased evapotranspiration and reduced soil moisture (CCKP and USAID).



PRECIPITATION

The local long-term future precipitation projections are characterised by a considerable uncertainty. Globally there is evidence that the intensity of sub-daily extreme rainfall events, causing flash flooding, increases with temperature (Westra, 2014), however this trend should be further investiged in the African continent. According to model ensemble, the seasonal rainfall between May and October should expect an increase in the total amount, especially in the second part of the season.
Considering the highest emissions pathway (RCP8.5), the average annual precipitation in the country rises of 55 mm by the end of 21st century. In case of low emissions scenario (RCP2.6), the increase expected is limited to 10 mm. Geographically, according to the global model ensemble, the increases will be stronger (above 100 mm) in the southern portions of the country (Gedaref, Al Jazeera, Sennar, Blue Nile, Southern Kordofan, Southern Darfur and Western Darfur States), while in the northern region limited to no increase is expected.



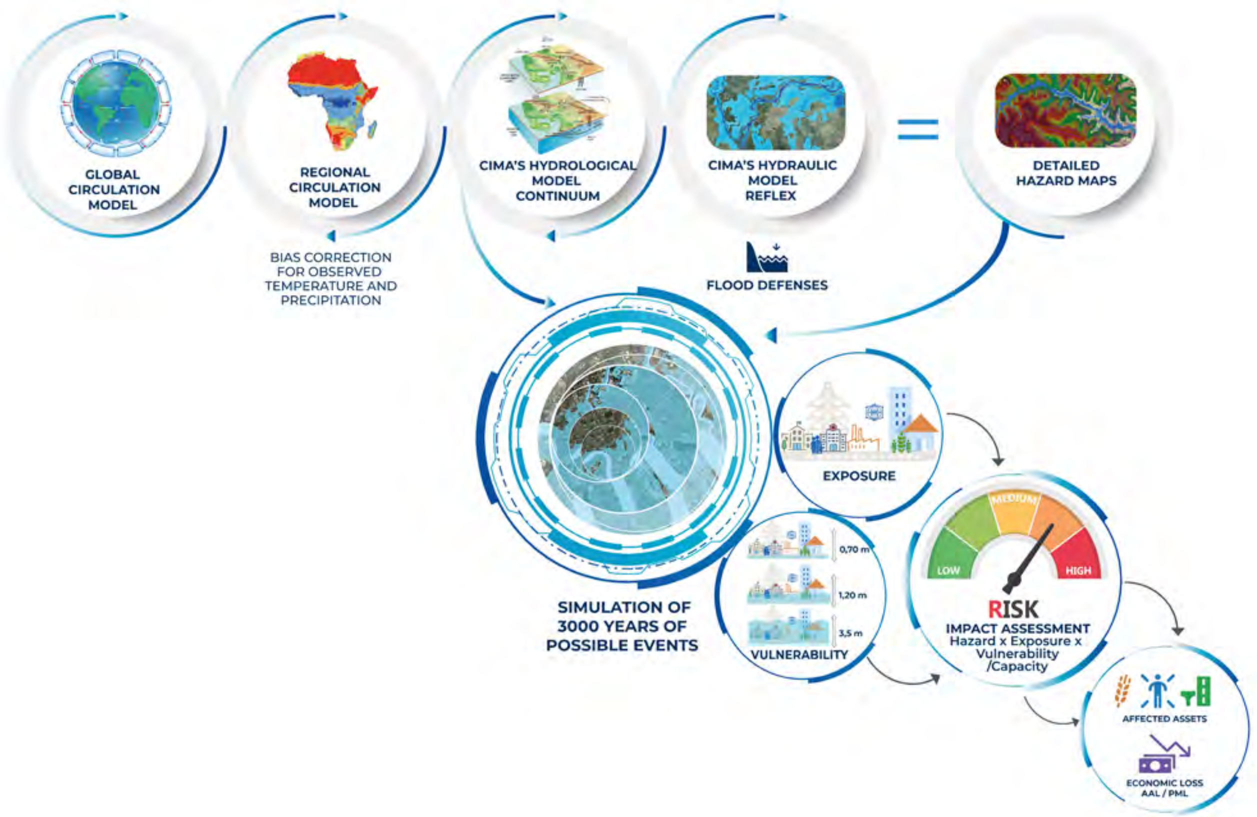
07. Climate outlook

08

Floods risk analysis

The flood risk assessment aims at understanding the probability that different magnitudes of damaging flood characteristics will occur over an extended period of time. These estimates can be calculated both in current and projected climate conditions, resulting in detailed hazard maps, to be then combined with the reproduction of past events patterns and the modelling of projected future events. Information on the performance capacity of flood protection measures is finally added to the analysis. This workflow allows for the estimation of the "expected" water depth for a certain location and/or individual infrastructures, for a set of reference scenarios.

From this step on, it is possible to explore the full frequency distribution of events and the consequent damage to exposed assets, taking into consideration their different levels of vulnerability (UNDRR, 2019).



Flood risk results are calculated in terms of annual average loss (AAL) and probable maximum loss (PML) curves for several indicators at different spatial levels of aggregation: national and subnational (administrative level 1). The study expresses also the metrics of displacement risk through annual average displacement (AAD) and probable maximum displacement (PMD), developed – with the support of the IDMC – under Work Package 3 of the Habitable project, aims to provide calibrated estimations of future human mobility, supporting the formulation of effective policies.
Their spatial distribution has been computed in current and projected climate conditions using the SSP1-RCP2.6 and SSP5-RCP8.5 scenarios in Sudan.

Within this articulated process, access to data is of vital importance to achieve an accurate risk evaluation. Not only is it necessary to feed information to the modelling chain for the identification of possible hazards in specific locations, such as historical series of observed temperature, rainfall, and discharges volumes, but it is also crucial to feed the damage models with detailed data on population and assets' levels of exposure and vulnerability. It is only possible to fully understand the economic, social, and environmental impacts of past and future possible events with this data. To this end, the present risk profile considers seven categories of potentially exposed values. Information about those values were provided by local institutions whenever available. Regional and global datasets were used both as substitutes, when local data was not available, and as data validators, to cross check the consistency of different data sources.

Flood Hazard Assessment

The aim of flood hazard assessment is to systematically analyze the likelihood and magnitude of flooding occurrences, considering factors such as topography, hydrology, climate patterns, and land use. This multidisciplinary process incorporates geospatial data, hydrological modeling, and historical flood records to generate accurate and comprehensive flood hazard maps that serve as essential tools for promoting resilience and minimizing the adverse effects of flooding events.

To best predict possible flood scenarios, we used a chain of climate, hydrological and hydraulic models. We applied the "Continuum" hydrological model (Silvestro et al. 2013 and 2015) to all basins in Sudan vuat a four kilometers resolution to obtain streamflow series for each pixel in current and projected climate conditions. We then used this information as input for a simplified hydro-morphological model, based on the Manning's equation, to create hazard maps at 90-metre resolution for different return periods. Return periods of T=2, T=5, T=10, T=50, T=100, T=200 and T=250 years in current and projected climate conditions were selected to represent the different frequency and intensity of possible events in each basin.

On this basis we developed hazard maps for each country under current, optimistic and pessimistic projected climate conditions, with long-term time horizon.
To assess risk in large domains, a set of mutually exclusive and collectively exhaustive possible hazard scenarios that may occur in the country, including the rarest and most catastrophic ones, is synthetically generated, keeping the historical spatial correlation of events.

Data Collection

Within this articulated process, access to data is of vital importance to achieve an accurate risk evaluation. Not only is it necessary to feed information to the modelling chain for the identification of possible hazards in specific locations, such as historical series of observed temperature, rainfall, and discharges volumes, but it is also crucial to feed the damage models with detailed data on population and assets' levels of exposure and vulnerability. It is only possible to fully understand the economic, social, and environmental impacts of past and future possible events with this data. To this end, the present risk profile considers four categories of potentially exposed values. Information about those values were provided by local institutions whenever available. Regional and global datasets were used both as substitutes, when local data was not available, and as data validators, to cross check the consistency of different data sources.

POPULATION

Population estimates were obtained from global datasets, which provides spatial binary information (population/no-population at any point in space) or information on the relative distribution of population inside a given area. This study considered population according to its density, meaning the spatial distribution of population across the country. In particular, WorldPop product 100-meter resolution (Bondarenko et al. 2020) has been adopted in the analysis.

Projections for future population were produced starting from UN 2050 projections, based on all available sources of data on population size and levels of fertility, mortality, and international migration.

For displacements assessment, the populations have been divided into three sector classes, according to the exposure categories reported in the Sendai Framework Indicators: housing sector distribution, service sector distribution and industrial sector distribution. The spatial resolution of such information has been improved through a proper downscaling procedure, guaranteeing coherence among the distributions of population and residential areas.

BUILT-UP

Information on the built-up area refers to two main aspects: to the description of the physical exposure of buildings, in terms of their economic value and their spatial location inside or outside flood-prone areas; the elements which might influence its vulnerability - such as its occupancy characteristics, the existence of basements, and the typology of its constructive materials.

The built-up data used for the present risk profile were obtained from the Global Exposure Socio-Economic and Building Layer (GESEBL), derived from the Global Infrastructure Risk Model and Resilience Index (GIRI) project, led by the Coalition for Disaster Resilient Infrastructure (CDRI[1]). Data were curated by UNEP-GRID-Geneva through the Internal Displacement Monitoring Centre funding. This global dataset on exposure includes country-specific building typology, usage, and value in both urban and rural settings. The dataset utilizes the count of individuals categorized by socio-economic class residing within a specific construction style in a defined geographic area as a foundation for distributing the exposed economic value of the building stock.

Built-up, as people, have been divided into three sector classes: housing sector distribution, service sector distribution and industrial sector distribution. All the data (socio-economic, building type and capital stock) are provided through a uniform geographical unit that are the reference grid at 1x1 km at equator. The resolution of 1x1 km needs to be improved through a proper downscaling procedure to match the increased resolution for the hazard proposed in this study at 90 m resolution.

CRITICAL INFRASTRUCTURES

Critical infrastructures data refer to the description of the physical exposure in terms of spatial location of educational and health facilities, as well as the transport network combined with their economic values related to the rehabilitation cost. Their location were derived from OpenStreetMap global datasets combined with the best national datasets possibly available. Due to the lack of local information on recovery costs, no economic losses could be derived from the potential impact on critical infrastructure.

AGRICULTURE

The agricultural exposure was obtained from the JRC's Anomaly hot Spots of Agricultural Production (ASAP), to determine the cropland and grassland area (Pérez-Hoyos, 2018). Furthermore, cattle population in the GHA Region has been considered, this dataset presents the cattle population count at the pixel level. The data is from Harvard dataverse 2010.

1. www.cdri.world/biennial-report-on-global-infrastructure-resilience

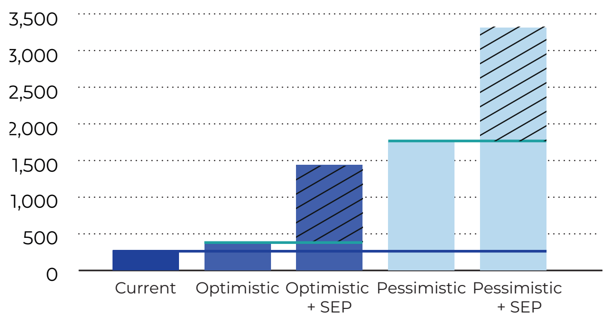
09

Results

Population

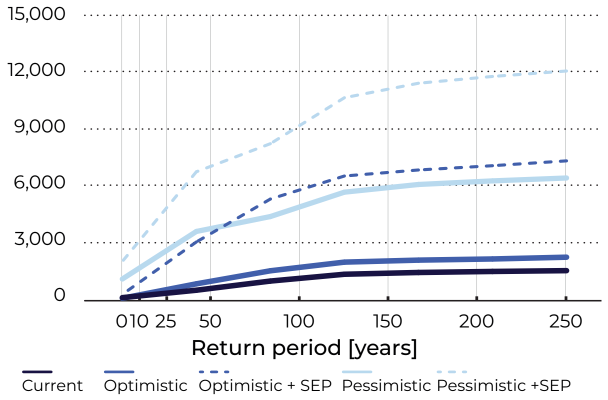
- At national level, the annual number of people affected from riverine floods grows from about **270 thousand in current climate conditions** to more than **1,440 thousand in projected climate conditions SSP1-RCP2.6** considering socio-economic projections (SEP), and up to about **3,320 thousand considering SSP5-RCP8.5 & SEP.**

Comparison of AAL of affected population
[Thousands of people / year]



- The PML curves show that a 100-year return period loss generates in current climate conditions 1.45 million people affected (which corresponds to more than 5 times the annual average affected population); the figure could increases up to 11.7 million in projected climate conditions SSP5-RCP8.5 & SEP.

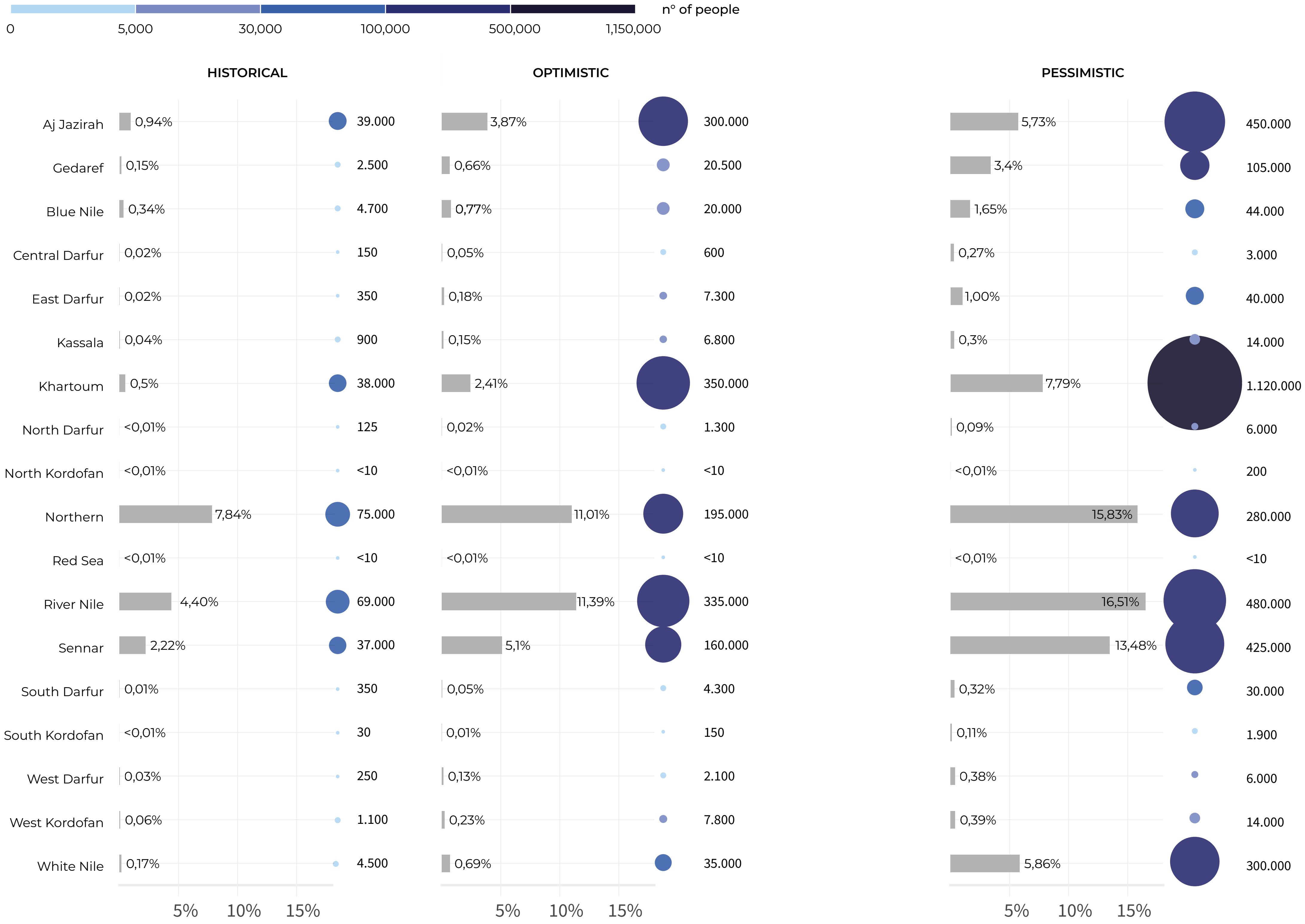
PML of affected population
Thousands of people affected

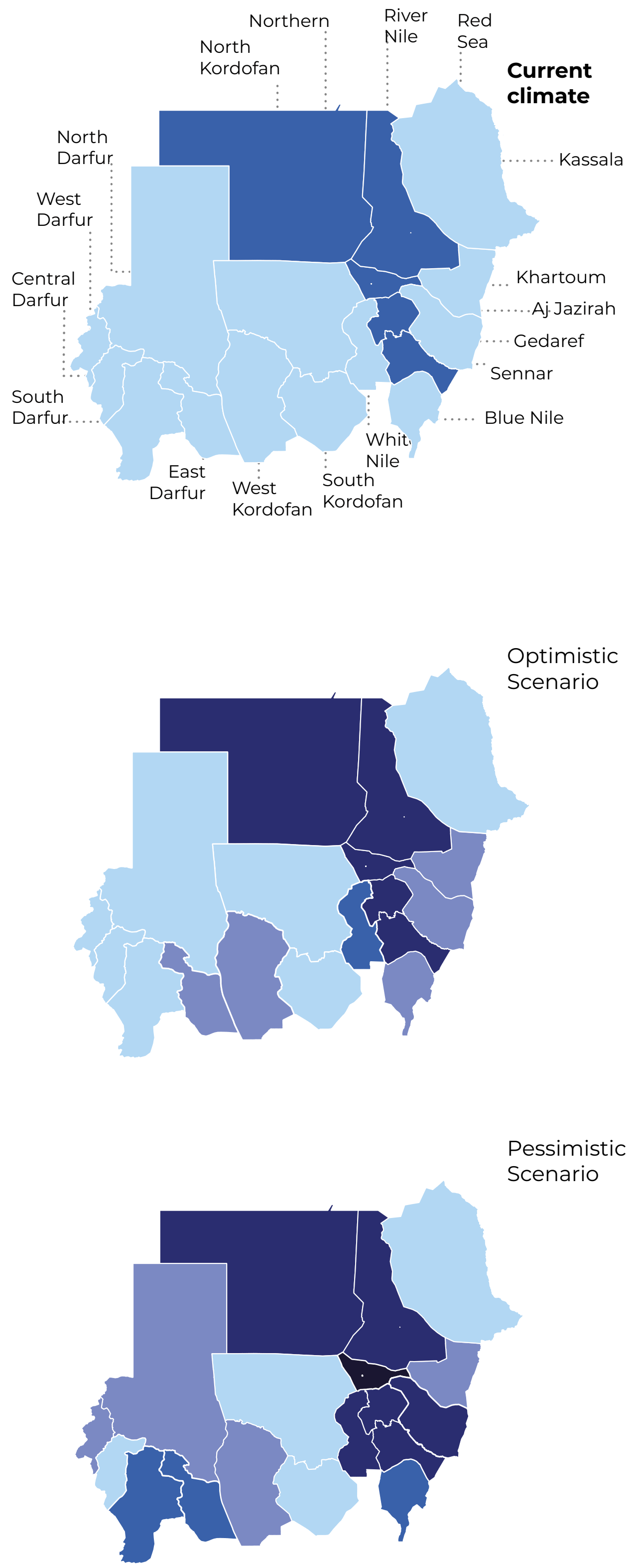


- Impacts of riverine floods on population in current climate conditions are spread mainly along the main stem of the Nile river in Sennar, Gezira, Khartoum, River Nile and Northern states, where the average annual number of people affected by flood is greater than 30 thousand people. Khartoum and Gezira states are the most densily populated ones.

- A general worsening in terms of population affected by riverine floods can be observed in projected climate conditions SSP1-RCP2.6, with mainly the eastern and southern regions increasing significantly. The same worsening pattern is exacerbated by considering projected climate conditions SSP5-RCP8.5, with relevant increase expected in both eastern, western and southern, especially in Darfur and Kordofan.

AAL POPULATION
Current climate and projected climate conditions



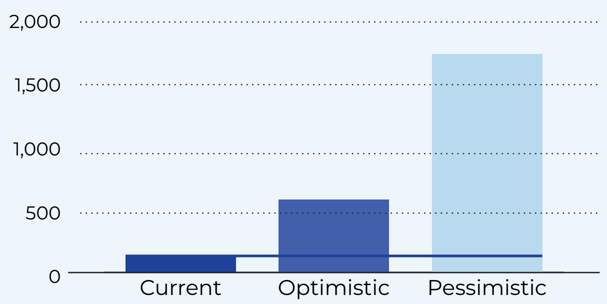


DISPLACEMENTS

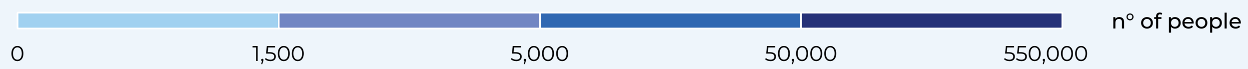
The analysis of flood displacement risk followed the approach developed in Rossi et al. (2024). Results at country level shows a value of an AAD of nearly 170,000 people, corresponding to about 0.3% of the overall population. The results highlight a strong influence of climate change. The optimistic and the pessimistic scenarios show AAD values that are from 5 to 10 times those in current conditions. In the PMD displacements would increase significantly for higher return periods. For instance, observing the current climate conditions, the displacements may triple when comparing frequent (e.g., T=5 years) with rare (e.g., T=250 years). Such a trend is confirmed also when analyzing the PMD associated to long term projected climate conditions, for both optimistic and pessimistic scenario. In this latter case, a 250-year event causes displacement ranging from 0.01% to 25% in the different Admin1, according to the total population of each region.

Comparison of AAD of population

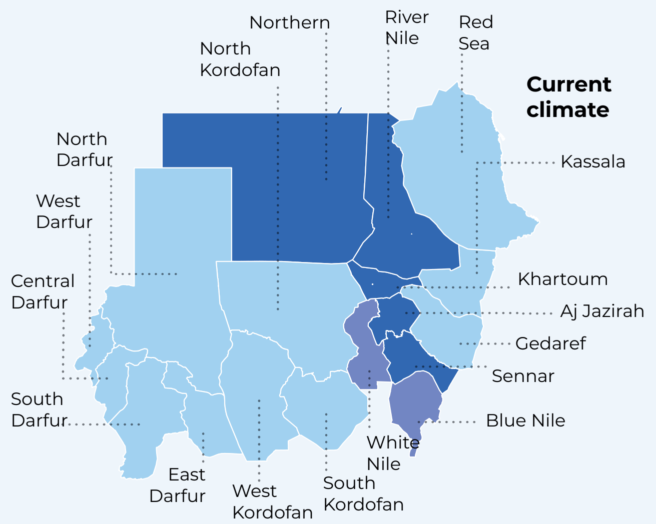
[Thousands of people / year]



AAD POPULATION
Current climate



	Current climate		
Aj Jazirah	**21,000** **0.42%**	Northern	**45,000** **4.14%**
Gedaref	**450** **0.02%**	Red Sea	**0** **0%**
Blue Nile	**3,000** **0.18%**	River Nile	**26,000** **1.41%**
CentralDarfur	**40** **0.01%**	Sennar	**21,000** **1.07%**
East Darfur	**<10** **0.00%**	South Darfur	**<10** **<0.01%**
Kassala	**400** **0.02%**	South Kordofan	**<10** **<0.01%**
Khartoum	**17,000** **0.18%**	West Darfur	**50** **0.01%**
North Darfur	**<10** **<0.01%**	West Kordofan	**<10** **<0.01%**
North Kordofan	**<10** **<0.01%**	White Nile	**1,600** **0.05%**

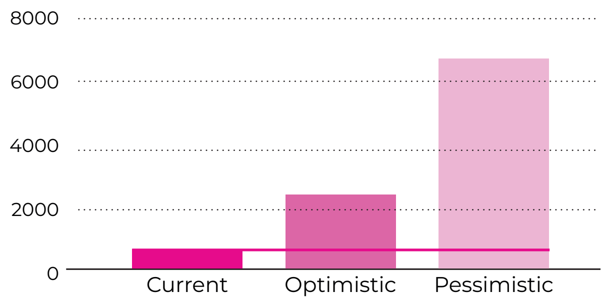


Direct economic loss to built-up area

- At national level, the annual average direct economic loss to built-up area grows from almost **USD 625 million in current climate conditions** to more than **USD 2,300 million in projected climate conditions SSP1-RCP2.6 & SEP,** and up to about **USD 6,600 million considering SSP5-RCP8.5 & SEP.**

Comparison of AAL of economic losses to built-up area

Loss [million $ / YEAR]



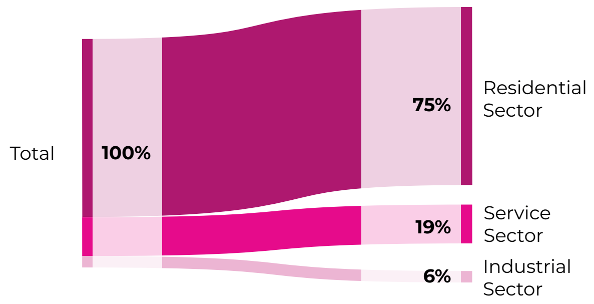
- When the PML curves are analyzed, one can observe that a 100-year return period loss can determine in current climate conditions up to almost USD 3.6 billion; the figure could increase up to almost USD 12 billion in projected climate conditions SSP1-RCP2.6, and increase up to USD 24.5 billion in projected climate conditions SSP5-RCP8.5.

Probable Maximum Loss curve of direct economic losses to built-up areas

Loss [million $]

- The riverine flood impact mainly on the housing sector, which represent the 75% of the economic loss to built-up area. A relatively smaller proportion is related to the industrial sectors, 19% and 6% respectively.

Percentage of economic losses considering different sectors of built-up area in current climate conditions

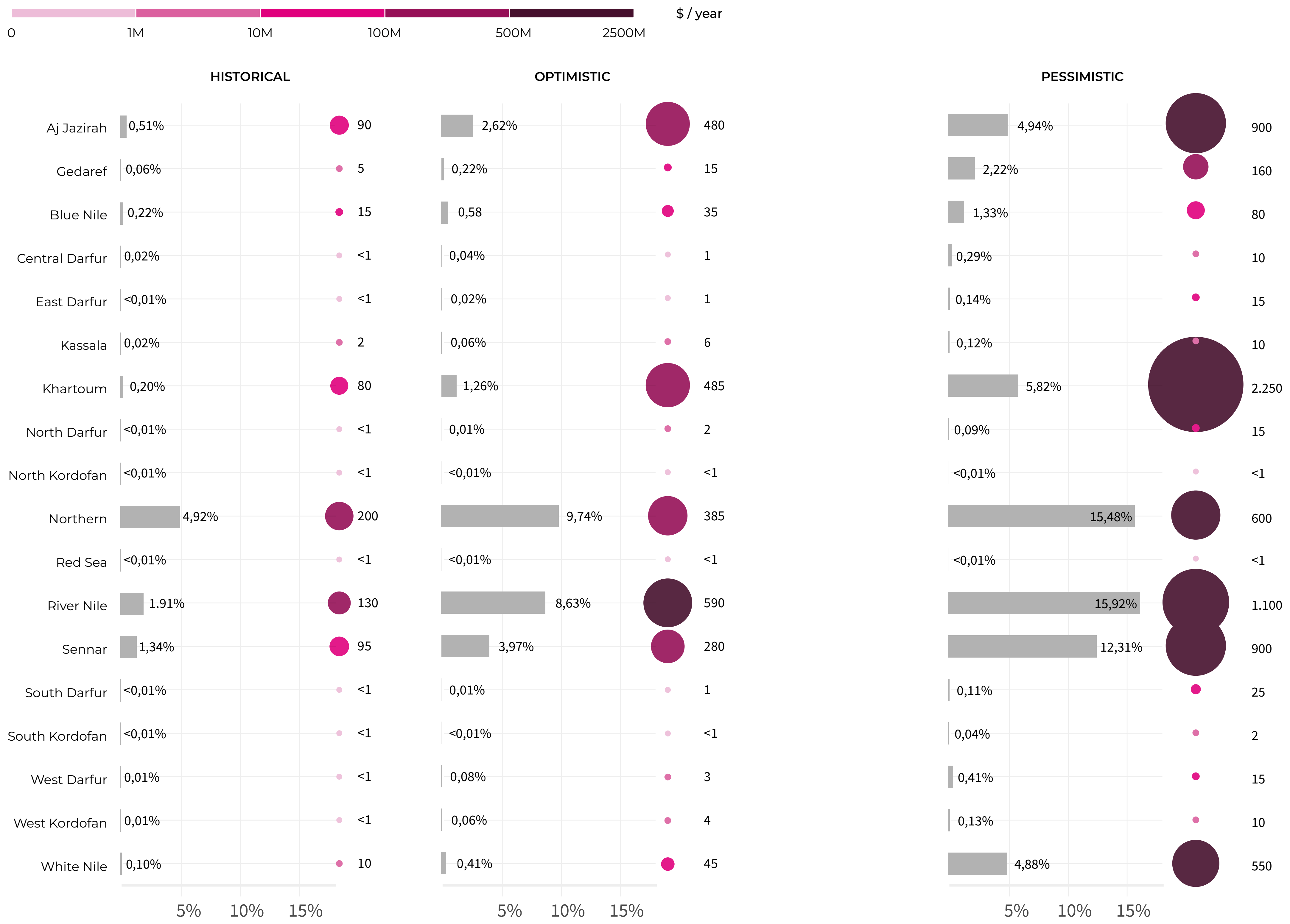


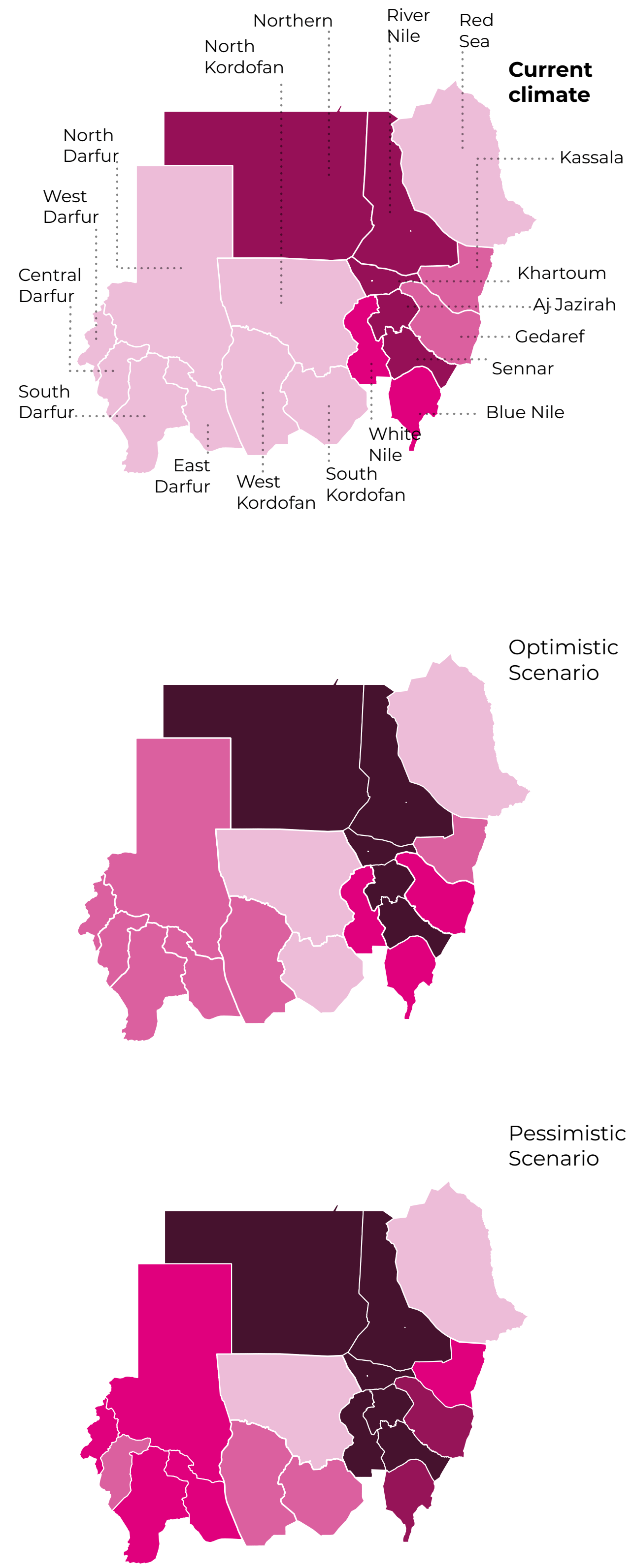
- Impacts of riverine floods on economic loss in current climate conditions are spread mainly along the main stem of the Nile river in Sennar, Gezira, Khartoum, River Nile and Northern states, where the average economic loss per year is above USD 75 million.

- A general worsening in terms of direct economic loss by riverine floods can be observed in projected climate conditions SSP1-RCP2.6, with mainly the eastern and western regions increasing. The same worsening pattern is exacerbated by considering projected climate conditions SSP5-RCP8.5.

09. Results

AAL OF ECONOMIC LOSSES TO BUILT-UP AREA
Current climate and projected climate conditions

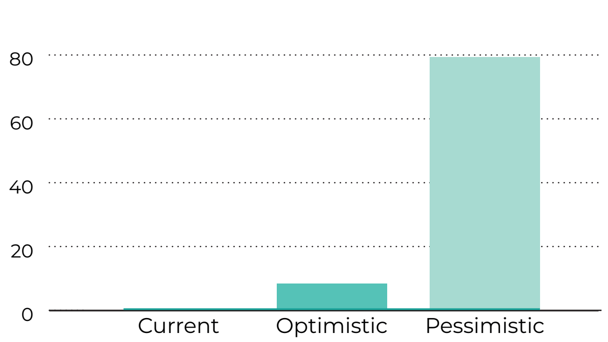




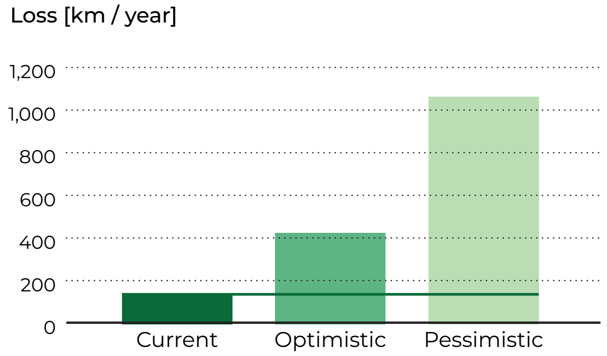
Direct loss to critical infrastructures

- In current climate condition, almost 145 km of transportation network, 2 education facilities and 2 health facilities could be damaged yearly on average. In projected climate conditions SSP5-RCP8.5 the number of the critical infrastructure damages more than 10 times higher.
- Impacts of riverine floods on economic loss to critical infrastructures in current climate conditions are spread mainly along the main stem of the Nile river in Sennar, Gezira, Khartoum, River Nile and Northern states.

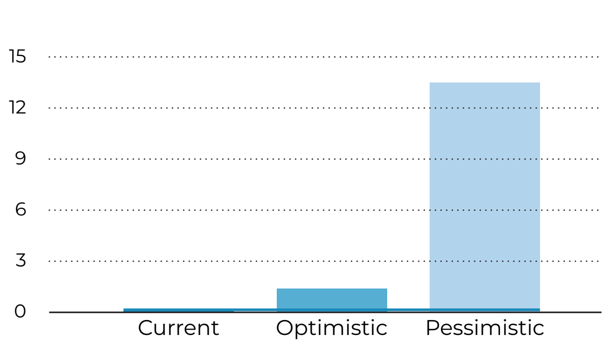
Comparison of AAL of affected health structures



Comparison of AAL of affected roads

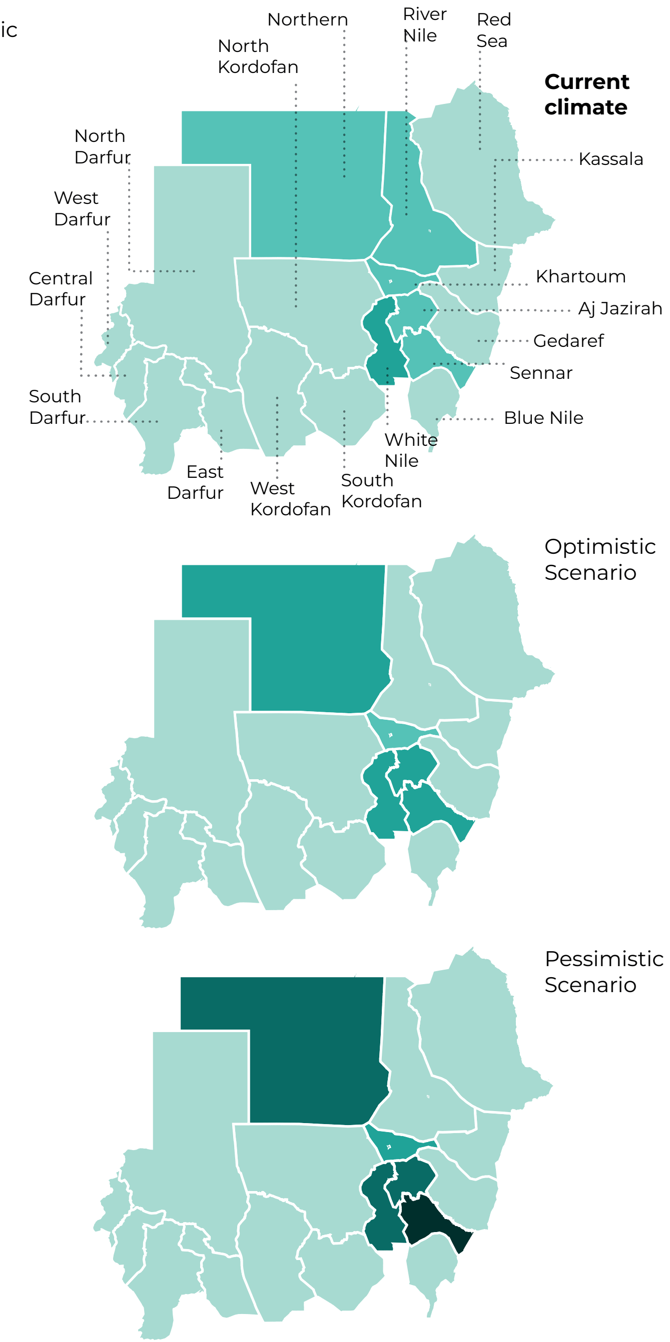


Comparison of AAL of affected education structures



AAL HEALTH INFRASTRUCTURES
Current and projected climate conditions

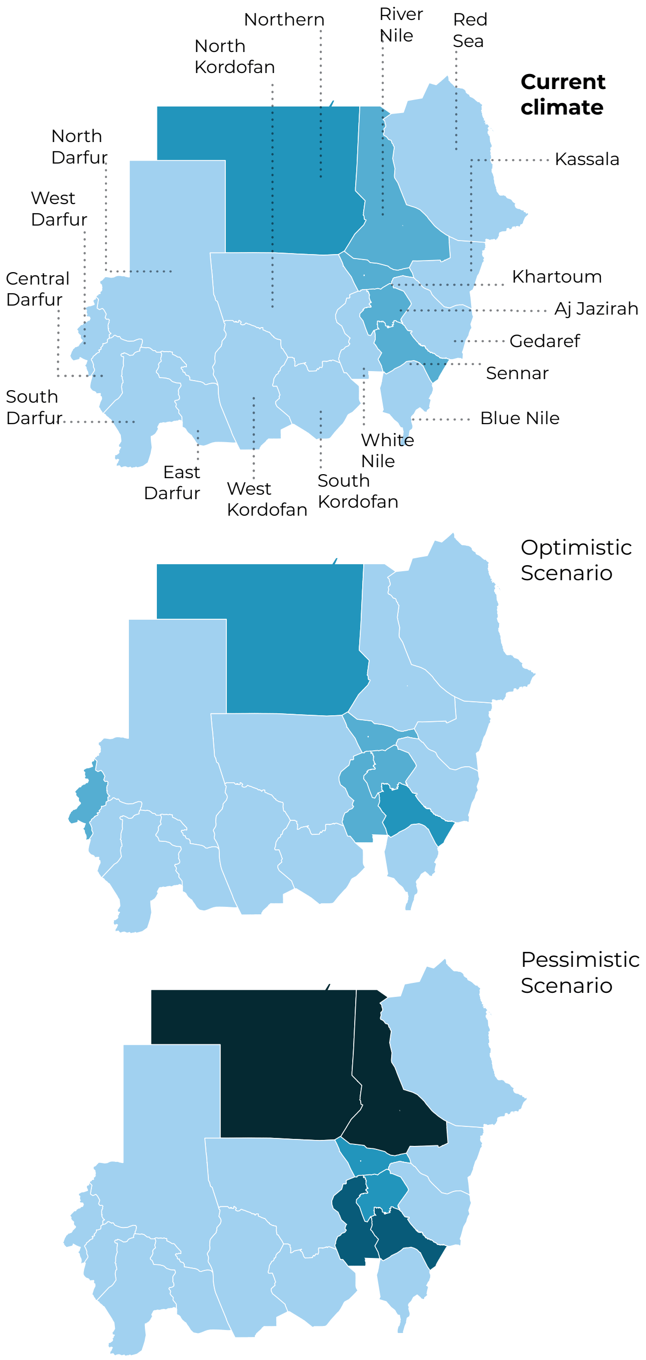
	Current climate	Optimistic Scenario	Pessimistic Scenario
Aj Jazirah	**0.08%**	6.36%	14.49%
Gedaref	**0%**	0%	0%
Blue Nile	**0%**	0%	0%
CentralDarfur	**0%**	0%	0%
East Darfur	**0%**	0%	0%
Kassala	**0%**	0%	0%
Khartoum	**0%**	0.61%	8%
North Darfur	**0%**	0%	0%
North Kordofan	**0%**	0%	0%
Northern	**0.03%**	3.82%	12.86%
Red Sea	**0%**	0%	0%
River Nile	**0%**	0%	0%
Sennar	**0.11%**	9.63%	26.24%
South Darfur	**0%**	0%	0%
South Kordofan	**0%**	0%	0%
West Darfur	**0%**	0%	0%
West Kordofan	**0%**	0%	0%
White Nile	**3.71%**	7.30%	13.25%



AAL EDUCATION INFRASTRUCTURES
Current and projected climate conditions

0 | 0% | 1% | 5% | 10% | 20%

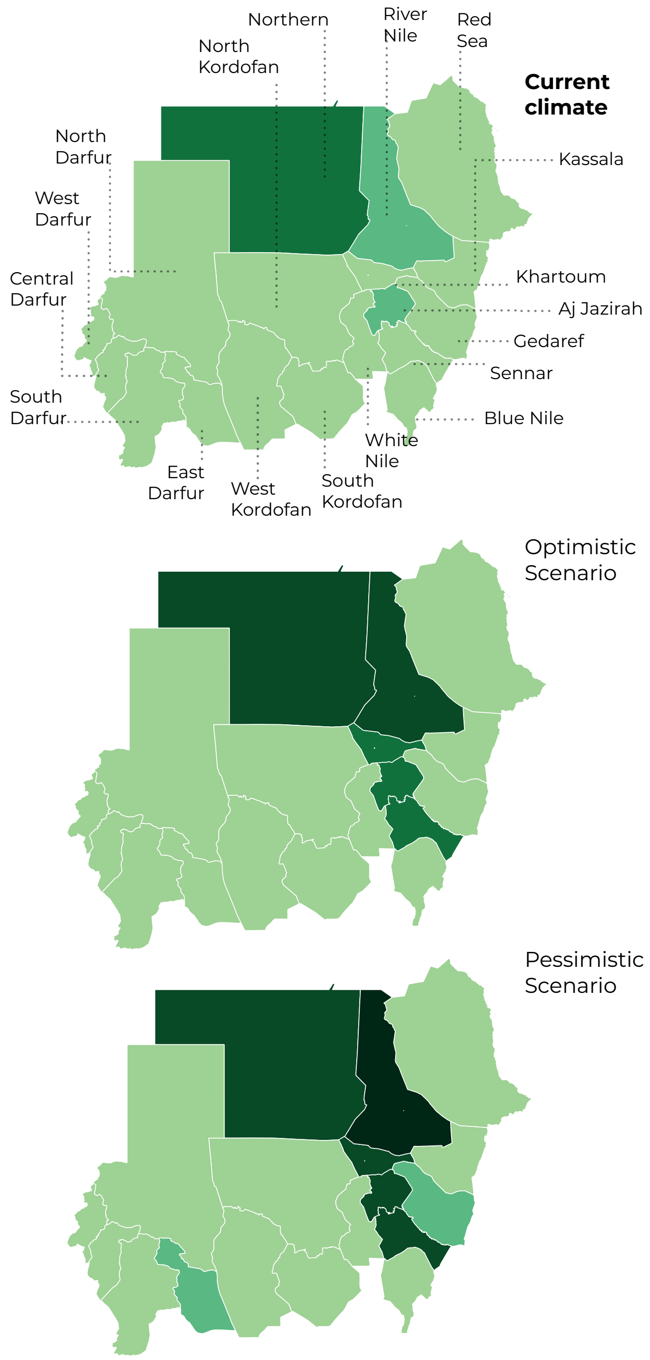
	Current climate	Optimistic Scenario	Pessimistic Scenario
Aj Jazirah	**<0.01%**	0.96%	3.16%
Gedaref	**0%**	0%	0%
Blue Nile	**0%**	0%	0%
CentralDarfur	**0%**	0%	0%
East Darfur	**0%**	0%	0%
Kassala	**0%**	0%	0%
Khartoum	**<0.01%**	0.31%	3.96%
North Darfur	**0%**	0%	0%
North Kordofan	**0%**	0%	0%
Northern	**2.31%**	4.82%	13.76%
Red Sea	**0%**	0%	0%
River Nile	**0.03%**	4.93%	16.16%
Sennar	**0.89%**	2.68%	6.54%
South Darfur	**0%**	0%	0%
South Kordofan	**0%**	0%	0%
West Darfur	**0%**	<0.01%	0.35%
West Kordofan	**0%**	0%	0%
White Nile	**0%**	0.04%	5.79%



AAL ROADS INFRASTRUCTURES
Current and projected climate conditions

0% | 0.5% | 1% | 5% | 10% | 15%

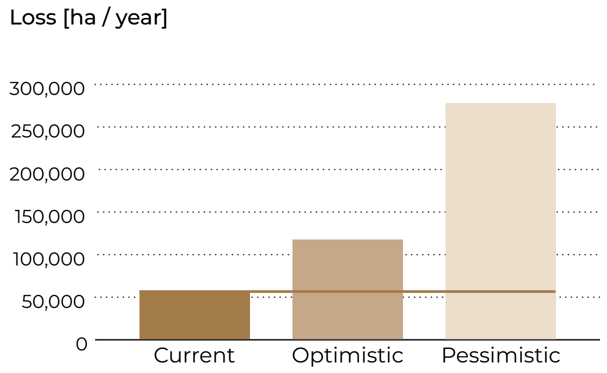
	Current climate	Optimistic Scenario	Pessimistic Scenario
Aj Jazirah	**0.55%**	3.46%	6.96%
Gedaref	**<0.01%**	0.07%	0.66%
Blue Nile	**0.01%**	0.10%	0.27%
CentralDarfur	**<0.01%**	0.03%	0.17%
East Darfur	**<0.01%**	0.13%	0.78%
Kassala	**<0.01%**	0.01%	0.09%
Khartoum	**0.29%**	1.75%	7.60%
North Darfur	**<0.01%**	0.01%	0.07%
North Kordofan	**0%**	0%	<0.01%
Northern	**3.09%**	5.90%	9.17%
Red Sea	**0%**	0%	0%
River Nile	**0.81%**	5.26%	11.22%
Sennar	**0.34%**	1.51%	5.35%
South Darfur	**<0.01%**	<0.01%	0.05%
South Kordofan	**0.01%**	<0.01%	0.02%
West Darfur	**<0.01%**	0.03%	0.20%
West Kordofan	**<0.01%**	0.10%	0.50%
White Nile	**0.05%**	0.35%	4.94%



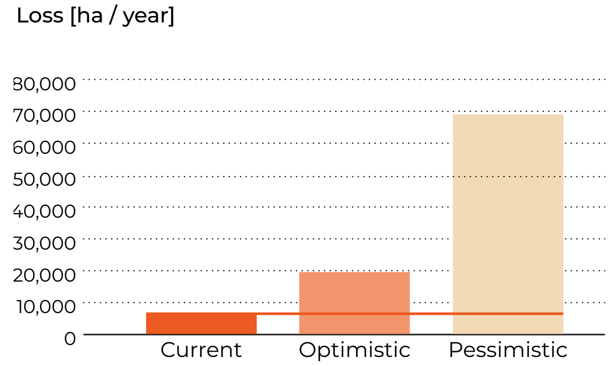
Direct loss to agricultural sector

- Two different types of impacts on agriculture have been evaluated: the number of hectares of crop-land and grazing land flooded, and the number of cattles (units).
- In current climate condition, up to 56,000 hectares of cropland, more than 6,300 hectares of grazing land and 56,000 livestocks could be damaged yearly on average. In projected climate conditions SSP5-RCP8.5 the damage to the agriculture sector is expected to be more from 5 to 10 times higher.
- The Probable Maximum Curves indicates that even frequent events (small return periods) trigger significant losses. Today, a 100-year return period flood event could affect almost 22,000 hectares of grazing land, 215,000 livestock and 256,000 hectares of cropland.
- Impacts of riverine floods on economic loss to cropland in current climate conditions are spread mainly along the main stem of the Nile river in Sennar, Gezira, Khartoum, River Nile and Northern states. For grazing land and livestock, the impact is more relevant in the southern regions.

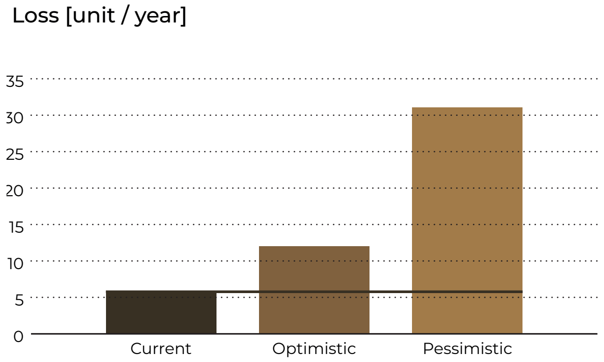
Comparison of AAL of affected cropland



Comparison of AAL of affected grazingland



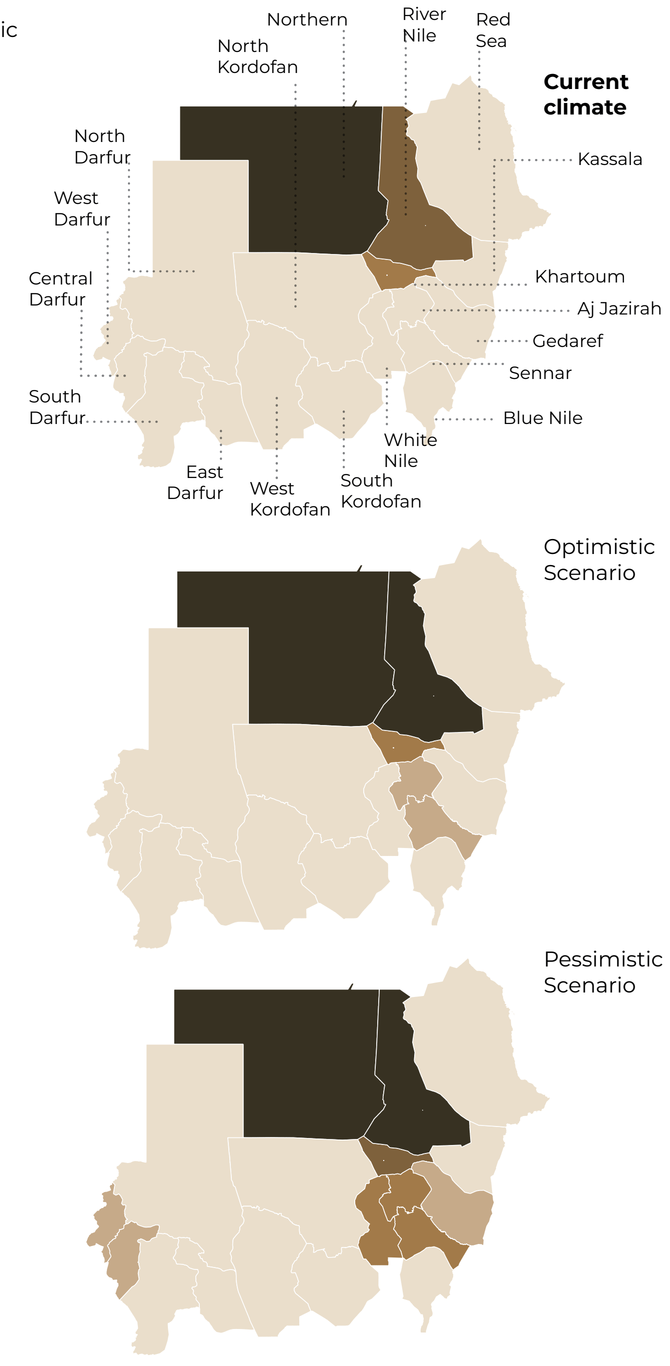
Comparison of AAL of affected livestock



AAL AFFECTED CROP LAND
Current and projected climate conditions

hectares/y: 0 | 0.5% | 1% | 5% | 10% | 20%

	Current climate	Optimistic Scenario	Pessimistic Scenario
Aj Jazirah	**4,800** **0.24%**	18,500 0.94%	34,000 1.71%
Gedaref	**2,800** **0.08%**	6,500 0.19%	32,000 0.88%
Blue Nile	**1,400** **0.08%**	2,500 0.15%	4,600 0.27%
CentralDarfur	**350** **0.10%**	800 0.23%	2,700 0.78%
East Darfur	**50** **0.01%**	400 0.04%	4,700 0.49%
Kassala	**500** **0.04%**	1,600 0.14%	2,400 0.21%
Khartoum	**3,000** **1.27%**	9,300 3.93%	18,500 7.88%
North Darfur	**<20** **<0.01**	250 0.02%	1,000 0.07%
North Kordofan	**<20** **<0.01**	<20 <0.01	160 0.01%
Northern	**11,000** **10.10%**	14,000 12.76%	18,200 16.97%
Red Sea	**0** **0%**	0 0%	0 0%
River Nile	**17,500** **7.03%**	30,000 11.89%	37,200 14.93%
Sennar	**10,200** **0.45%**	22,000 0.98%	60,000 2.65%
South Darfur	**70** **0.01%**	400 0.03%	4,700 0.37%
South Kordofan	**60** **<0.01**	160 0.01%	2,600 0.15%
West Darfur	**250** **0.08%**	800 0.27%	1,800 0.60%
West Kordofan	**25** **<0.01**	230 0.01%	1,100 0.06%
White Nile	**4,300** **0.19%**	11,200 0.50%	54,000 2.38%

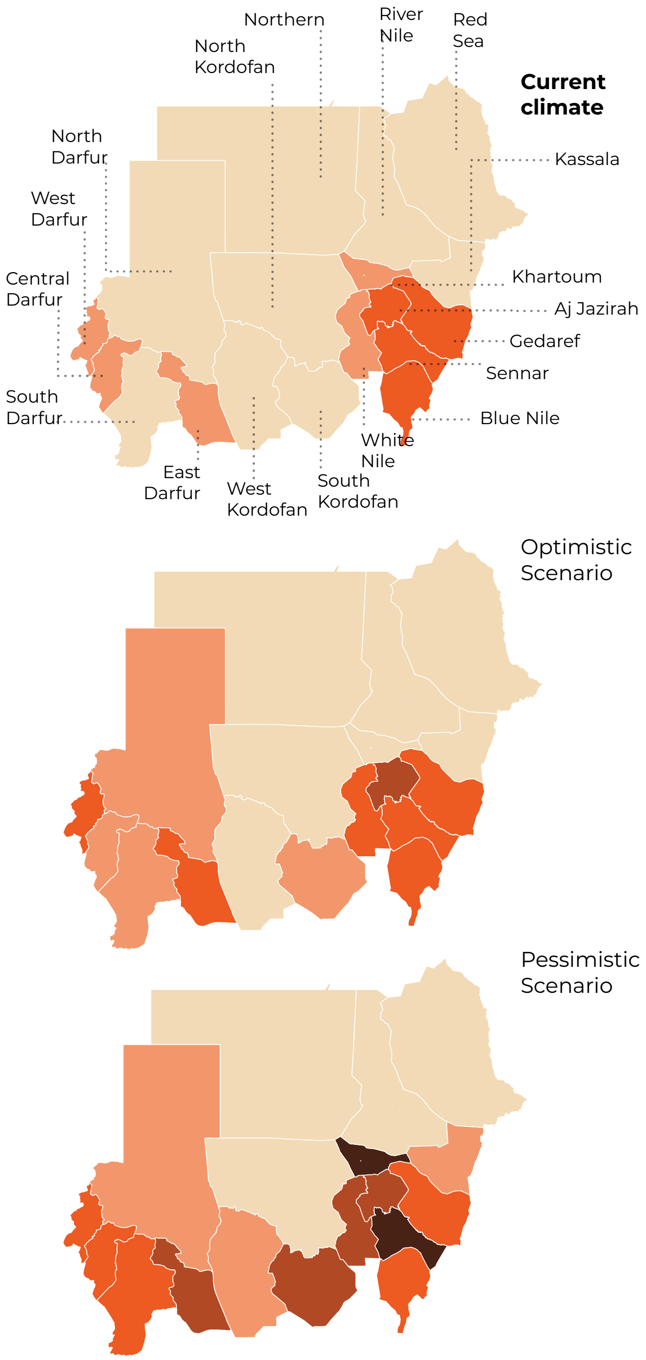


AAL AFFECTED GRAZI RANGELAND
Current and projected climate conditions

hectares/y

0 | 0% | 0.1% | 1% | 2% | 4%

	Current climate	Optimistic Scenario	Pessimistic Scenario
Aj Jazirah	**1,850** **0.70%**	3,800 1.42%	4,100 1.58%
Gedaref	**1,400** **0.15%**	3,700 0.39%	8,600 0.90%
Blue Nile	**650** **0.17%**	1,000 0.25%	1,800 0.48%
CentralDarfur	**120** **0.01%**	370 0.04%	1,200 0.13%
East Darfur	**170** **0.01%**	3,000 0.21%	20,700 1.46%
Kassala	**<10** **<0.01%**	35 0.01%	90 0.01%
Khartoum	**<10** **0.03%**	<10 0.72%	40 3.05%
North Darfur	**250** **<0.01%**	1,900 0.03%	6,500 0.09%
North Kordofan	**<10** **<0.01%**	<10 <0.01%	35 <0.01%
Northern	**0** **0%**	0 0%	0 0%
Red Sea	**0** **0%**	0 0%	0 0%
River Nile	**0** **0%**	0 0%	0 0%
Sennar	**1,000** **0.37%**	2,100 0.79%	6,500 2.40%
South Darfur	**70** **<0.01%**	1,100 0.06%	3,500 0.20%
South Kordofan	**20** **0.01%**	150 0.04%	5,200 1.46%
West Darfur	**325** **0.03%**	1,300 0.14%	2,600 0.27%
West Kordofan	**15** **<0.01%**	80 0.01%	850 0.07%
White Nile	**500** **0.10%**	1,100 0.21%	7,300 1.45%

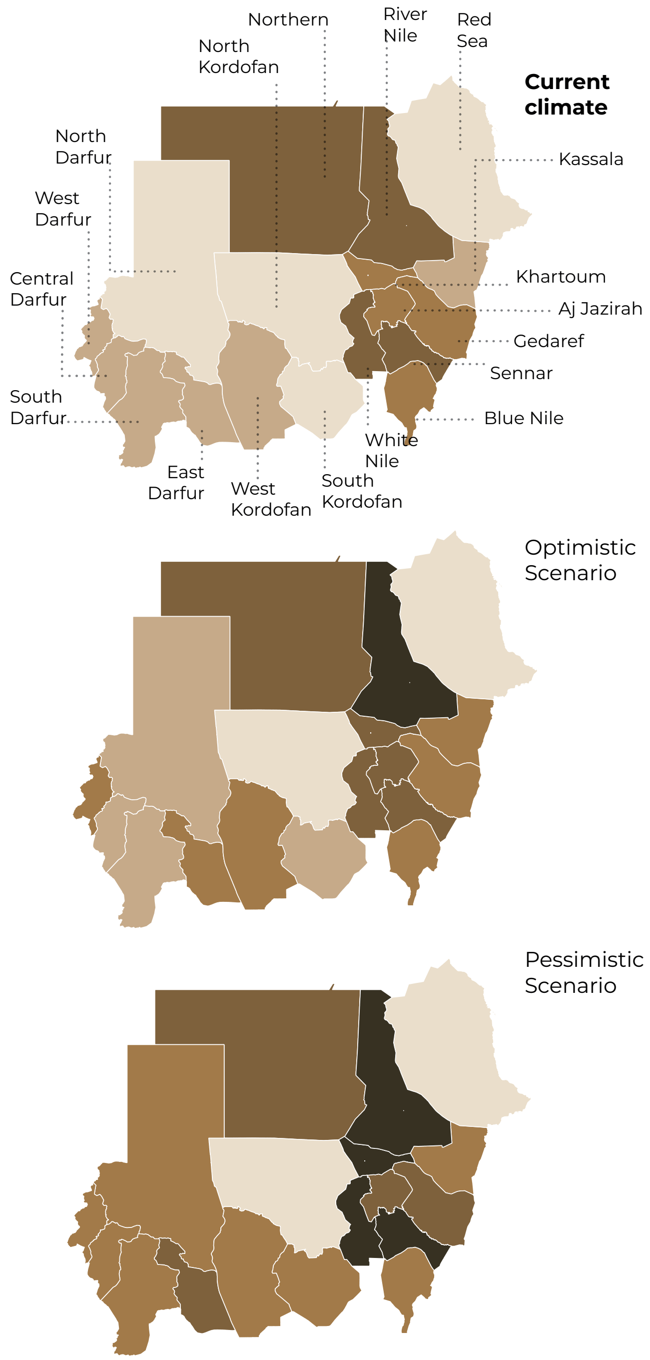


AAL AFFECTED LIVESTOCK
Current and projected climate conditions

unit/y

0 | 0.01% | 0.1% | 0.5% | 2% | 6%

	Current climate	Optimistic Scenario	Pessimistic Scenario
Aj Jazirah	**9,500** **0.35%**	31,200 1.15%	51,200 1.88%
Gedaref	**2,400** **0.15%**	6,100 0.37%	19,000 1.12%
Blue Nile	**3,700** **0.16%**	5,100 0.22%	10,500 0.45%
CentralDarfur	**670** **0.03%**	2,100 0.09%	6,500 0.28%
East Darfur	**450** **0.02%**	5,100 0.29%	27,500 1.55%
Kassala	**450** **0.04%**	1,300 0.12%	2,000 0.19%
Khartoum	**850** **0.35%**	4,000 1.71%	9,000 3.82%
North Darfur	**40** **0.01%**	500 0.06%	1,500 0.19%
North Kordofan	**<10** **<0.01%**	10 <0.01%	200 0.01%
Northern	**2,150** **0.70%**	3,000 0.99%	4,400 1.42%
Red Sea	**0** **0%**	0 0%	0 0%
River Nile	**1,800** **1.67%**	3,800 3.52%	5,700 5.28%
Sennar	**11,200** **0.74%**	20,400 1.35%	51,100 3.39%
South Darfur	**380** **0.01%**	2,300 0.09%	12,500 0.47%
South Kordofan	**100** **0.01%**	300 0.02%	4,500 0.29%
West Darfur	**1,300** **0.07%**	4,800 0.26%	8,400 0.45%
West Kordofan	**1,100** **0.05%**	4,500 0.21%	9,500 0.45%
White Nile	**20,500** **0.58%**	26,000 0.74%	88,000 2.51%



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