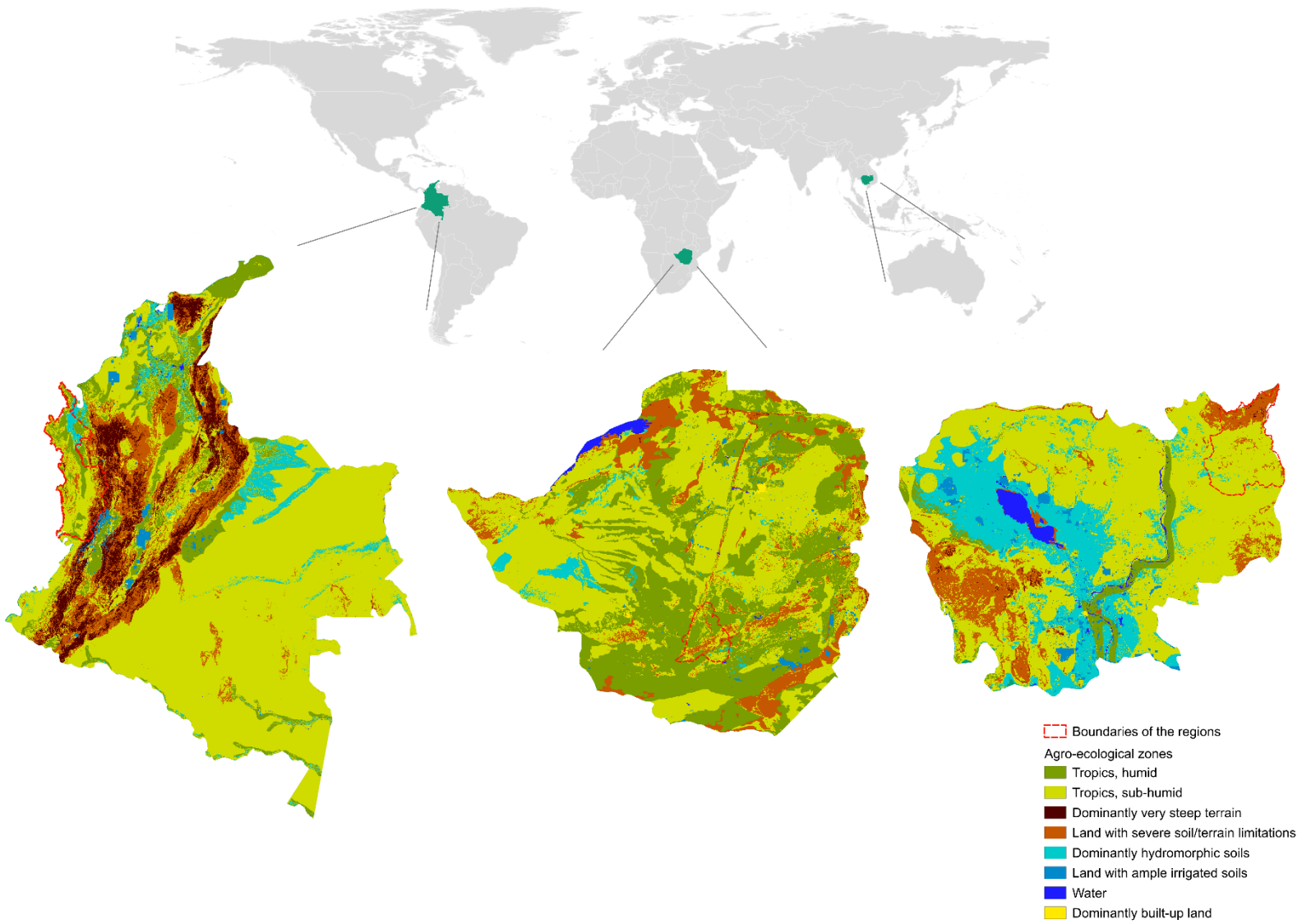


Climate risk profiles of Choco, Ratanakiri and Zvishavane-Mberengwa

Felm 2025, Peusa Jaakko



The goal of this work was to gather evidence for future actions, based on academic research done on effects of climate change and existing statistical data on the focus areas. Local stakeholder reports, analysis done with geographic information systems (GIS) and visualizations of available projection data are utilized to bring a more local context to the often global-scale assessments of climate changes impacts presented on research papers. Interviews with local professionals were conducted for further context and their views were consulted during the process of finalizing the report.

The areas to be included in the report were selected from a base of locations where the partners of Felm conduct their humanitarian work. The selection was further reduced to three after discussions with local experts to reduce the scope of the report. The author of the report, Jaakko Peusa, is a student of Aalto-university and was an intern at Felm. The supervisor of the work was climate and environment expert FL Eira Rosberg.

Summary

Felm's focus areas on Choco department in Colombia, Zvishavane and Mberengwa districts in Zimbabwe, and Ratanakiri province in Cambodia are particularly vulnerable to effects of climate change due to their poor socio-economical standing. This profile provides an overview of projected medium term (2050–2060) climate change related impacts on different sectors of the focus areas under the SSP3-7.0 scenario. In this future scenario, concerns about regional conflicts, security and competitiveness push countries to increasingly focus on domestic or, at most, regional issues. Policies are expected to shift over time to become increasingly oriented toward national and regional security issues at the expense of emission reduction. Population growth is expected to follow the current patterns of low in industrialized and high in developing countries.

Temperature

The average temperature in Choco is projected to rise by ≈ 1.8 °C, in Zvishavane and Mberengwa by ≈ 2.6 °C and in Ratanakiri by ≈ 1.95 °C, when compared to 1971–2000 levels. The number of very hot days (peak at 35 °C or more) will increase considerably in Zimbabwe and Cambodia, with their number expected to roughly double compared to the 1971–2000 baseline. Intricacies of the local climate of the Choco area shield it from temperature peaks.

Precipitation

Precipitation trends are uncertain and considered to be difficult to predict precisely, however certain clear historical patterns exist. The Choco department currently has the highest rainfall in the world, with the precipitation expected to further increase in both amount and intensity in the wet season in the future. Rainfall in Zvishavane and Mberengwa has high interannual variance, with a non-significant pattern of intensification also being observed. The climate projections expect a further reduction of rainfall during dry season in the future. Wet season precipitation amounts are expected to remain similar. Ratanakiri is expected to be distinctly different from climate patterns of western Cambodia, with trends pointing to more spread-out rainfall across the seasons, and a slight decrease in intensity.

Infrastructure

Climate change is likely to cause damage or demand adaptation in the infrastructure sector in all the focus areas, including roads, bridges and electricity grids. In Choco, road infrastructure outside the few regional towns and the roads linking them are expected to remain extremely limited, with rivers serving as the primary accessways to rural areas. Flood protection measures in riverside towns such as Quibdo have historically been insufficient. The increasing trend in peak rainfall and the continuing population growth in the region will further emphasize the need for more sustainable land use in riverside and coastal areas. In Zvishavane and Mberengwa, the poor quality and maintenance of roads and bridges has led to risks on river crossings and limits farmers' access to urban markets during wet season. Expected future investments are minimal, and further risk to locals' health and livelihoods from poor accessibility are expected. In Cambodia, the increase in average temperatures combined with the nation's rapid economic growth is expected to put a massive strain on the nation's electricity grid, with the electricity demand just for cooling doubling by 2055. In Ratanakiri, the yearly average temperature is expected to rise to $\approx 26^\circ\text{C}$, with the increase of very hot days increasing considerably, emphasizing the importance of access to cooling, and decreasing the number of households without electricity.

Water resources

Water availability is driven by climatic, hydrogeological and socioeconomic factors. Especially in Zvishavane district, the limits imposed on ground water utilization by local geology have already caused a risk on water availability, realized during El Nino induced droughts. The intensity of droughts in dry season is projected to grow further with the expected reduction in seasonal rainfall and increase in evapotranspiration. In Choco, the pollution of waterways and groundwater combined poses the largest medium-term risk to water availability. In Ratanakiri, the lack of sanitation and water infrastructure has created a risk for the spread of waterborne diseases, with the conditions expected to become more optimal for these pathogens in the future.

Agriculture

Agricultural yields are heavily dependent on local climate, and thus also the impacts of climate change. A global yield decline of 4,4 % per 1°C increase of global average temperature is estimated. As a general trend, long term effects of climate change will make achieving the same yields as before more expensive. However, the impacts are heavily regional, and dependent on multiple variables such as crop type and adaptation capability. On the medium term discussed in this report, the uncertainty of water availability caused by weather fluctuations, primarily ENSO, has more defined impact on agriculture over the effects of climate change. In the long term (by 2100), the estimates for Southern Africa predict Zimbabwe and Mozambique to suffer the most, with 10–20 % decline in maize yields under medium heating scenarios, even with adaptation, increase in incomes and CO_2 fertilization considered. Research puts a large emphasis on investment in irrigation infrastructure as primary measure to combat this decline. The Choco region is not expected to suffer any yield loss due to its local climate. In Ratanakiri, the effects of climate change are characterized by a delay in commencement and end of wet season, emphasizing adaptation to reduce impacts to crop yields. Long term simulations suggest maize may be better suited for the future conditions in the Ratanakiri area compared to rice. Generally, the efficiency of manual agricultural labor is expected to continue

decreasing and associated health risks increasing as average temperatures and temperature extremes rise in all areas considered in the report. It is also noteworthy that the latest research sees agriculture being hit the hardest by climate change in breadbasket regions such as US Midwest and India. This puts additional emphasis on agricultural self-sufficiency in the Global South.

Human displacement

Climate change is influencing most weather phenomena that lead to human displacement, such as long-term droughts or heavy rainfall. However, a decreasing trend in tropical cyclone frequency will continue due to weakening of the Hadley- and Walker circulations as temperatures increase, which makes conditions for cyclone formation less favorable. Displacement due to ENSO driven water uncertainty is expected to remain a defining issue on Zvishavane-Mberengwa area due to the poor groundwater potential, compounded by the projected intensification of drought during dry season. In Choco, local conflicts interlink with rural areas vulnerable to flooding and landslides, limiting access to aid and increasing the region's vulnerability to flood damage. In Ratanakiri, no increase in displacement events due to impacts of climate change are expected, as rainfall amounts are projected to remain stable and the frequency of cyclones to be reduced.

Human health

Increase of average temperatures, humidity and very hot days are projected to have a negative impact on human health and productivity of work in all focus areas. The effects are particularly severe on vulnerable groups like rural poor, women, children, elderly and chronically ill people. Climate change is expected to increase the prevalence of malaria and other tropical diseases in Ratanakiri and Choco due to more suitable temperatures and environments for carrier insects' lifecycles. Intensification of rainfall is expected to lead to an increasing trend of contamination of water sources in areas with lacking protection measures, impacting both Zvishavane-Mberengwa and Choco. In the Choco department, the problem of mercury originating from illegal mining contaminating food chains and soil is expected to be further emphasized by the increase in rainfall, and thus erosion.

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Climate scenarios and shared socio-economic pathways

Representative Concentration Pathways (RCP) are climate scenarios. They were developed as a part of IPCC fifth assessment report to showcase the effects of different greenhouse gas concentrations in the atmosphere. Socio-economic pathways (SSP) were developed as a part of IPCC's sixth assessment report and are utilized by researchers to link worldwide societal changes and development to greenhouse gas emissions. The shared socio-economic pathways function as a higher-level narrative baseline to build the scenarios on. The five SSPs are:

SSP1: The sustainable and “green” pathway describes an increasingly sustainable world. Consumption is oriented towards minimizing material resource and energy usage.

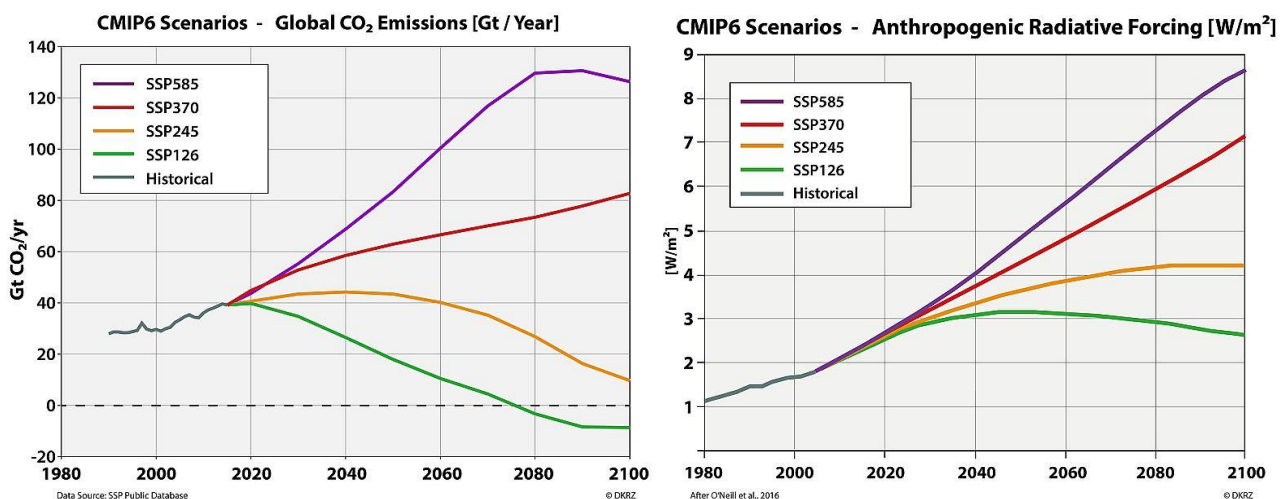
SSP2: The “Middle of the road” or medium pathway extrapolates the past and current global development trends into the future.

SSP3 Regional rivalry. A revival of nationalism and regional conflicts push global issues into the background. Inequality is rising and global population growth halts slowly.

SSP4 Inequality. The divide between globally cooperating developed societies and those stalling at a lower developmental stage with low income and a low level of education is widening.

SSP5 Fossil-fueled development. Integrated global markets and technological progress lead to rapid worldwide growth in standards of living. However, this growth comes with a cost of intensive energy use and exploitation of fossil fuels.

To construct scenarios based on these pathways, they were linked to two other factors. The intensity of additional radiative forcing (impact of human activity on the climate showcased by RCPs) and when required Shared Climate Policy Assumptions are included. SPAs describe political efforts in fighting and adapting to climate change. A key factor in this process was allowing for comparison of earlier RCP scenarios to the new SSP's by creating similar scenario classes to RCP scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5.



Figures 1 and 2, Anthropogenic radiative forcing and global CO₂ emissions per year by scenario
Source: DKRZ SSP scenarios

This report uses SSP3-7.0 as the basis for assessments of impacts due to the pathway's similarity to recent global developments and higher radiative forcing allowing for clearer visualization of trends. The number 7.0 indicates radiative forcing (W/m^2), a format shared by the RCPs. Thus, it is on the upper middle part on the range of scenarios, with 4.5 W/m^2 of radiative forcing by 2055 and 7 W/m^2 by 2100. The global goal of limiting global warming to $1.5\text{-}2^\circ\text{C}$ expects the radiative forcing to be limited to under 4 W/m^2 . However, without climate protection measures exceeding existing ones taken, the lifestyle associated with socioeconomic pathways SSP1 and SSP2 would already yield an additional radiative forcing of approx. 5 W/m^2 or 6.5 W/m^2 by 2100 (Riahi *et al.* 2017). In addition, the reports range is limited to 30 years in the future. On this time scale, there is not much difference in the model response to different emissions scenarios (Gettelman & Rood 2016).

Uncertainties in climate change modelling

Uncertainties are always part of assessing effects of climate change, as predicting the future has always an element of uncertainty with it (Gettelman & Rood 2016). The uncertainties arise from various factors, including natural variability, uncertainties in SSP emissions scenarios and differences in the models used in the projections (Gettelman & Rood 2016). Consequently, no climate change model comes without some level of uncertainty, and the model results used here are no different. For spatial scales used in this report, internal variability, which is natural fluctuations, background noise of earth's climate, dominates uncertainty in the first decade or two. Following those first decades, modelling uncertainty and internal variability are comparable, with scenario related uncertainty assuming a major or dominant position after 50 years (Gettelman & Rood 2016).

This report uses historical and climate projection data from IPCC AR6 Working Group I provided by the Copernicus climate data service. CMCC-ESM2 earth system model data is also used for portrayal of change in evapotranspiration. In research, general practice is to utilize aggregated averages of multiple, usually around 10 or more models for similar scale analyses. This is done for the data provided by the IPCC, and the projections are averages of multiple models (Iturbide *et al.* 2022). However, for CMCC-ESM2 due to the lack of comparisons between model estimates, the data is less reliable.

Generally, projections regarding temperature-related data are more certain than projections regarding precipitation-related data (Iturbide *et al.* 2022). Precipitation-related data is subject to higher uncertainty, as many of the atmospheric and surface processes that influence local precipitation patterns are difficult to model in their entirety. For example, whilst the formation of clouds is an important factor for precipitation, it takes place at a smaller scale than what is possible to simulate in global models. This gets further translated into unpredictability of analysis if it depends on accurate portrayal of future precipitation patterns, with agricultural projections being the most prominent example.

Climate risk assessment

In risk assessment, the consequences of considered phenomena to the system are a combination of possible hazards facing the system and the system's vulnerability to the hazards. Risk itself is the expected consequences of the hazards times the expected frequency of the hazards (Rome *et al.* 2019). The total risk facing a critical system can be expressed as sum of individual risks. Risks facing complex systems are usually addressed on scale, such as 'acceptable, tolerable, intolerable' based on the set criteria (GIZ 2021, Rome *et al.* 2019).

By IPCC definition, climate risk consists of climate phenomena, vulnerability, and exposure. Assessing local risk portrayed by climate change faces various challenges due to the complexness of the world and the phenomenon, but also due to often generalized effects of global change. Additionally, Felms's work to alleviate vulnerability of groups such as children, people with disabilities and other disadvantaged people to the impacts of climate change supports a further emphasis in embracing the local context. In this report, I will follow the 6 step guidelines and methodology of climate risk assessment made for German federal ministry for economic cooperation and development (GIZ 2021). With this method they have sought to remedy issues commonly found on assessment methods. These include considering a wider spectrum of hazards from slow onset processes to extreme weather events, and interdependencies of risks. Attention is also brought to prioritizing adaptation options and considering limits of adaptation as part of the assessment process. Another important part is a focus on non-economic losses and damage, such as loss of life, loss of ecosystem services, and proliferation of conflicts, which are vitally important for those affected, but are not sufficiently considered in previous approaches.

The six steps presented by the methodology are:

1. **Analysis of status quo:** literature and policy review, stakeholder interviews
2. **Hotspot and capacity analysis of system of interest:** compiling hazards, collecting spatial and historical data, utilizing GIS-systems to analyze the data if possible
3. **Development of context-specific methodological approach:** How can the impacts be assessed in the system/area?
4. **Qualitative and/or quantitative risk assessment:** assessing current and projected climate change impacts via chosen method such as a scenario analysis, economic valuation or risk modeling
5. **Evaluation of risk tolerance:** focus group surveys or expert judgement on risk level
6. **Identification and comparison of feasible options to avert, minimize, and address potential losses and damage:** cost-benefit or multifactor analysis, stakeholder-based elicitation of options

Colombia, Choco

Country overview

Colombia, a northwest South American nation straddling the Equator covers a vast area of 1 141 748 km² – larger than Turkey. Its defining geographic feature is the tripartite cordillera of the Andes Mountains, which split into three parallel ranges (Cordilleras Occidental, Central, and Oriental) upon entering Colombia from the south. These highlands, encompassing peaks over 5,000 meters, are flanked by the Caribbean coastal lowlands to the north, the Pacific coastal lowlands to the west, the vast eastern Llanos plains, and the southeastern Amazon rainforest. This topography of contrasts influences Colombia's climatic regions, which range from tropical rainforests and savannas to high-altitude páramos.

Colombia's recent history has been profoundly shaped by a complex, decades-long internal armed conflict primarily involving the government, left-wing guerrilla groups (notably the FARC and ELN), right-wing paramilitaries, and drug cartels. Rooted in historical inequalities, land disputes, and political feuds dating back to the mid-20th century, the most intense phase of the conflict peaked in the 1990's and early 2000's. The conflict resulted in hundreds of thousands of casualties and displaced an estimated 7-8 million people internally – one of the world's highest totals. A landmark peace agreement with the FARC was signed in 2016, significantly reducing violence, though challenges in implementation and sporadic conflict with remaining armed groups persist. The legacy of violence, displacement, and coca cultivation linked to the drug trade continues to impact development, particularly in rural and remote areas.

As of 2023, Colombia's population exceeded 52 million people, maintaining moderate annual population growth. A significant majority of Colombians at over 77 % reside in urban areas, with major cities like Bogotá, Medellín, Cali, and Barranquilla serving as primary hubs. Ethnically, Colombia is highly diverse, with a mestizo majority, alongside significant Spanish descended, Afro-Colombian, and Indigenous populations. Colombia ranks in the high human development category according to the UNDP's HDI, reflecting improvements in life expectancy, education, and income over recent decades. However, significant inequalities persist, particularly along geographic and ethnic lines.

Despite being classified as an upper middle-income country, Colombia faces significant poverty and inequality challenges. The national poverty rate based on the lower middle-income line at \$6.68/day was around 39,3% in 2021, with the nation generally experiencing a trend of reducing poverty during that last two decades. Latest multidimensional poverty assessment in Colombia is from 2016, with 4,8% of national population being affected. Income inequality, as measured by the Gini coefficient, is the highest in Latin America at 54,8. Access to services like clean water and sanitation also shows stark urban-rural divides.

The Fragile States Index reflects ongoing challenges, ranking Colombia 63rd out of 179 countries globally in 2024, indicating moderate fragility driven by group grievance, state legitimacy issues, and internal refugee pressures. Conversely, the nation's medium ranking of 93 in the ND-GAIN Index highlights Colombia's high vulnerability to climate-related hazards to agriculture, expected damage to marine life and limited capacity of dams to handle increase in rainfall.

Region overview

The department of Chocó is located in northwestern Colombia, between 4°N and 8°N latitudes along the Pacific coast. The region is large, spanning 46,530 km² – roughly comparable to entirety of Denmark. It is Colombia's only department with coastlines on both the Pacific Ocean and the Caribbean Sea. Administratively the area is divided into 30 municipalities, with Quibdó as its capital. Chocó is dominated by the dense, humid rainforests of the Chocó biogeographic region – one of Earth's wettest and most biodiverse areas – with the Baudó and San Juan mountain ranges paralleling the coast. Lowland river basins, notably the Atrato and San Juan Rivers, form critical transportation corridors through the inhospitable geography and dense forests. Annual rainfall exceeds 10,000 mm in some areas, creating extensive wetlands and flourishing biodiversity. Due to the local climate and topography, floods are common with larger flood effects having significant impact on the area. For example, floods in 2022–23 affected 70% of the regions municipalities (IFRC).

Chocó is home to approximately 595 000 people by 2023, with over 85 % living in rural riverine or coastal communities (DANE). Quibdó and the towns of Istmina, Nóvita; Acandí on the coast of the Caribbean Sea, and Solano on the coast of the Pacific Ocean anchor limited urban development. The population is predominantly Afro-Colombian (73%), with significant Indigenous Emberá, Wounaan, and Tule communities (15%) concentrated in autonomous resguardos (DANE). Afro and Indigenous communities exercise constitutional autonomy through Community Councils and resguardos. Chocó is one of Colombia's worst performing departments in human development indicators: life expectancy is 10 years below the national average, multidimensional poverty affects 65% of residents, and illiteracy rates are triple the national figure (UNDP, HDI database). Ethnic discrimination and states neglect exacerbate gaps in health access, with infant mortality rates 40% higher than Colombia's average (UNDP).

Chocó's economy is rich in resources but functionally underdeveloped. Economic growth is additionally stifled by the region's isolation. While generating 40% of Colombia's gold output and 80% of its platinum, official employment rate is below 40%. Formal employment is composed of mining, forestry, commerce and fishing. The region has a small tourism sector (Todacolombia). Subsistence fishing, artisanal mining, and small-scale agriculture employ the rest of the residents, contributing minimally to GDP (Todacolombia). Illegal mining is a considerable employer in the area due to economic desperation and limited state intervention. The states limited ability to control the sparsely inhabited area combined with the region's vast mineral wealth has led to large scale illegal and semi-legal gold mining operations along the riverbanks. Their usage of mercury has contaminated rivers and groundwater, whilst the careless excavating threatens the coasts of rivers with heavy manmade erosion (Garcia *et al.* 2021). Only the most major roads are paved and in large parts of the region rivers serve as primary transport routes.

Due to the difficult to cross terrain and the states limited presence on the area, FARC and ELN guerrillas and drug-trafficking networks compete for control of cocaine transit routes, illegal mining, and timber. Violence displaced 9,900 people in 2023 alone (ICRC). Violence and instability have led to additional restrictions on movement. Over 100,000 people, constituting roughly fifth of the region's population, have faced confinement by armed groups in 2023 (Indepaz).

Observed and projected climate

Present Climate

The Chocó Department possesses one of the world's most humid tropical climates, primarily dictated by its unique geographic position on Colombia's Pacific coast, backed by the steep slopes of the Western Andes. Mean annual temperatures exhibit minimal variation, consistently ranging between 23 and 28 °C throughout the year due to the equatorial proximity. Precipitation in Chocó is exceptionally high and driven by the interaction of several key factors: the year-round influence of the Intertropical Convergence Zone, the moisture-laden winds of the southwesterly Chocó Jet stream from the Pacific Ocean, and intense orographic lift as these winds encounter the Andes mountains. The wet season extends from May to October, although significant rainfall occurs even during the drier months. Precipitation amounts are extraordinarily high but follow a gradient, generally increasing from the coastal lowlands towards the Andean foothills. Annual precipitation sums range from approximately 6,000 mm to over 10,000 mm, making Chocó one of the rainiest places on Earth. Furthermore, the region experiences significant year-to-year variability influenced by the El Niño-Southern Oscillation abbreviated ENSO (Cai *et al.* 2015). There is significant year-to-year variability, strongly influenced by the El Niño-Southern Oscillation. El Niño is a climate pattern that describes the unusual warming of surface waters in the eastern tropical Pacific Ocean. El Niño is the warm phase of the El Niño-Southern Oscillation (ENSO) phenomenon. La Niña, the cool phase of ENSO, is a pattern that describes the unusual cooling of the region's surface waters. El Niño and La Niña are considered the ocean part of ENSO, while the Southern Oscillation is its atmospheric changes. El Niño has an impact on ocean temperatures, the speed and strength of ocean currents, the health of coastal fisheries, and local weather from Southern Africa to Southern America. El Niño events occur irregularly at two- to seven-year intervals. However, El Niño is not a regular cycle, or predictable in its amplitude. During El Niño events, precipitation typically decreases, sometimes leading to short dry spells, while La Niña events usually bring above-average rainfall, exacerbating flooding risks (Cai *et al.* 2015). ENSO also modulates the intensity and frequency of extreme weather events, particularly heavy rainfall leading to floods and landslides.

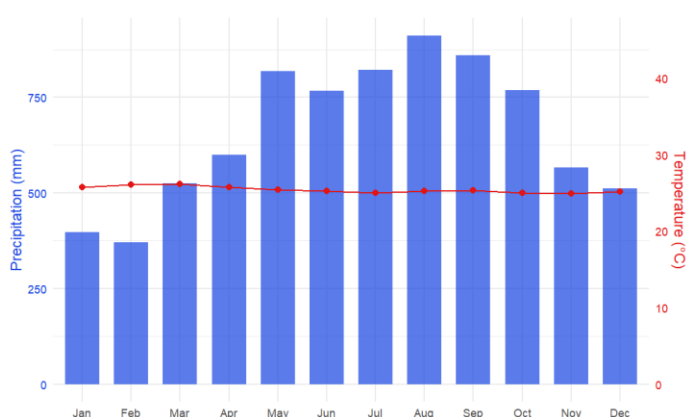


Figure 3: Annual precipitation and temperature averages in Chocó department, measuring station Quibdo. Data: <https://weatherandclimate.com>

Climate trends

Observations and climate model analyses indicate that mean annual temperatures in Chocó have increased over recent decades. Regional trends suggest warming of approximately 0.8 °C to 1.2 °C since the mid-20th century, consistent with broader trends across tropical South America (IPCC AR6, Veneros *et al.* 2025). The frequency and intensity of very warm days and nights has increased (Veneros *et al.* 2025).

Regarding precipitation, despite the strong natural variability, there is evidence suggesting a potential intensification of the region's extreme rainfall events over the past 30-50 years, consistent with global warming predictions for very humid tropical zones (Fan *et al.* 2024). At the same time, studies focusing on Colombia and South America have had mixed results gauging historical precipitation trends (Ceron *et al.* 2022). However, the on the coastal regions under the direct influence of Chocó Jet, the pattern has been clearly showing an increase in both precipitation amount and extremes (Ceron *et al.* 2022). Total annual rainfall also shows high interannual variability, linked strongly to ENSO (Cai *et al.* 2015). ENSO's amplitude strength has increased around 10% since 1960's, suggesting that stronger and more frequent events are not solely due to large internal variability (Cai *et al.* 2023). The frequency and severity of flood and landslide events, often triggered by prolonged heavy rainfall episodes, have also shown an increasing trend in recent decades, partly attributed to both climatic changes and land use alterations (Stäubli *et al.* 2018).

Projected precipitation

By the mid-century, projected precipitation amounts under SSP3-7.0 scenario show a positive precipitation trend of 5-10 % on northern parts of the Choco region, following the trend patterns modeled by Ceron *et al.* (2022). Due to the complex climate patterns of Colombia, the average precipitation and the average projected precipitation change have large regional variance. Both wet and dry seasons are getting wetter on the coastal regions under the influence of the Chocojet. Not only do the amounts of precipitation change vary, but also their direction and magnitude vary (Figures 5 and 6). Overall, the already dry southeast and north of Colombia are projected to become drier under the scenario. A similar trend is projected for the Caribbean coast. In contrast, precipitation amounts will increase over the northern Colombia, including Choco. The remainder of the region shows a mixed picture of increases and decreases, in addition to uncertainties regarding the direction of change. In the context of extremely high regional precipitation averages, an increase of any precipitation in the Choco region will have a considerable impact on the waterflow on the rivers. The estimate of the climate models point to similar outcomes as the assessment of climate changes impacts on rainfall in Colombia's third national communication on climate change, where upwards to 30% increases of rainfall extremes in Choco region are projected.

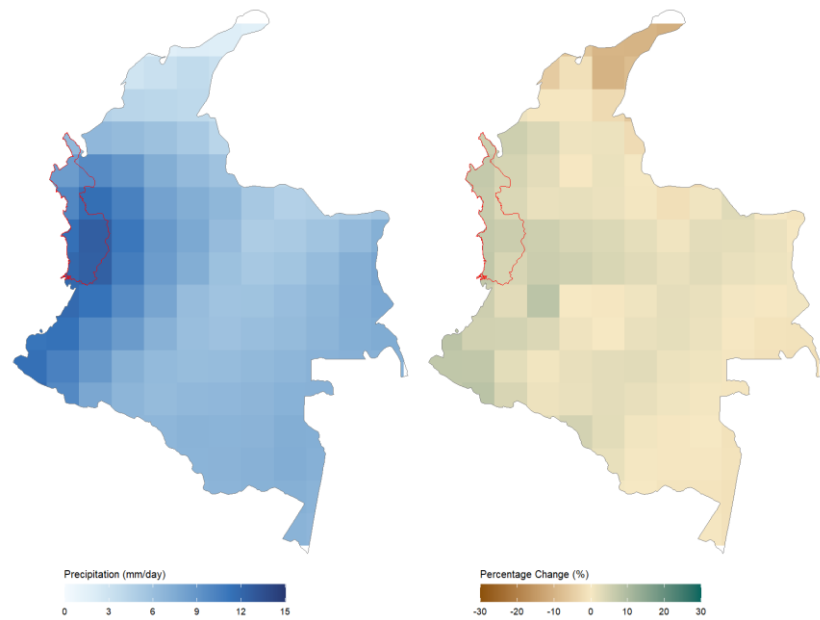
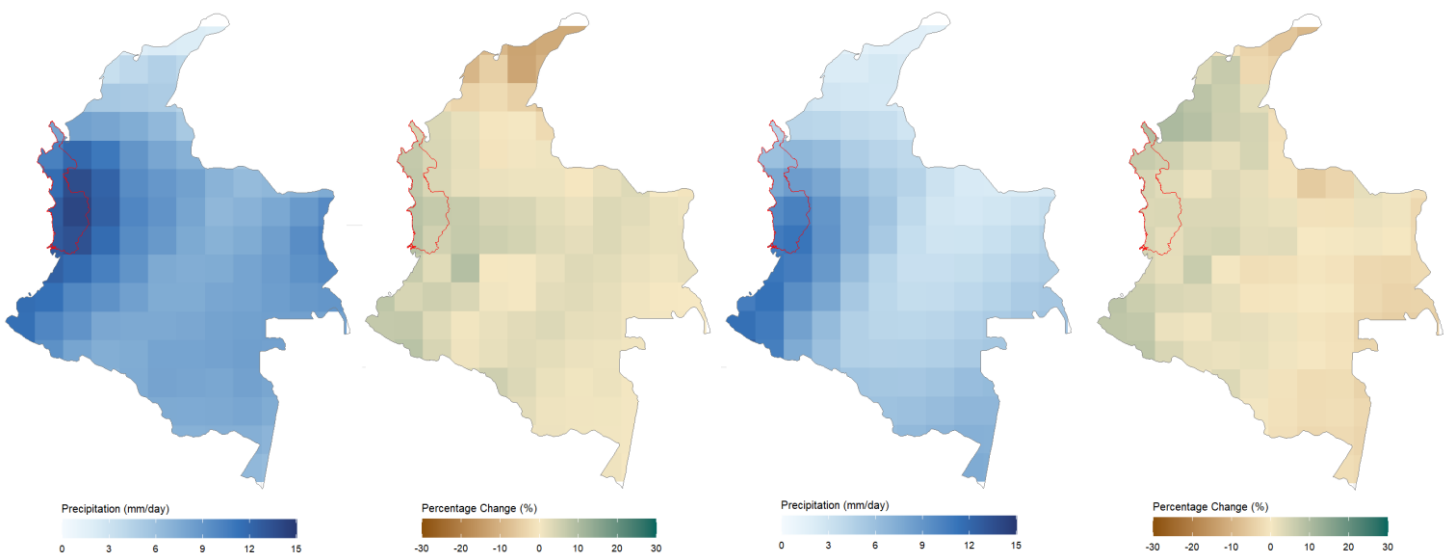


Figure 4: Annual daily rainfall averages and projected annual precipitation change, Colombia, comparison between 1971–2000 baseline and 2050–2060 projected SSP3-7.0 average, Data: Iturbide *et al.* 2022



Figures 5 and 6: Projected seasonal precipitation change in wet season (March to September) and dry season (October to February), Colombia, comparison between 1971–2000 baseline and 2050–2060 projected SSP3-7.0 average. Data: Iturbide *et al.* 2022

Projected temperature

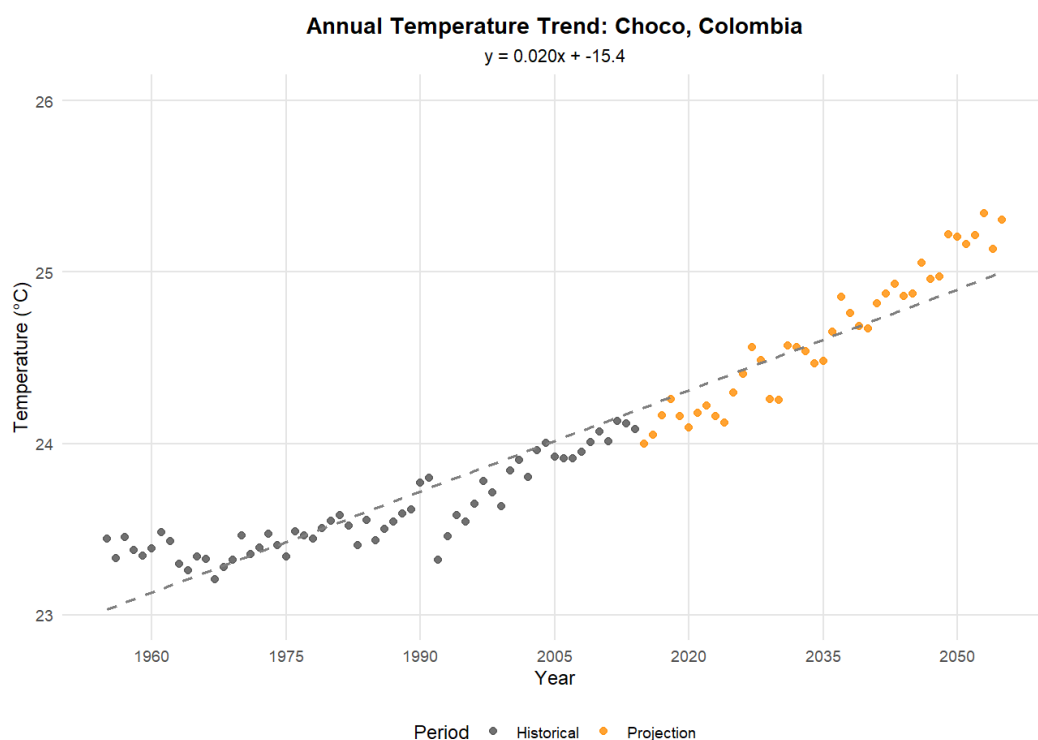


Figure 7: Annual temperature trend and future temperature projection, SSP3-7.0, Choco region. Data: Iturbide *et al.* 2022

The mean average temperature in Choco under SSP3-7.0 scenario is projected to shift by 1,1 °C for 2055 when compared to 2015–2025 average, and by 1,8 °C when compared to 1971–2000 average (Figure 7, Iturbide *et al.* 2022). However, there exists a large variance in increase of very hot days (peak at over 35 °C) between different climate areas of Colombia. Whilst the average temperature is projected to increase throughout the rest of the country, in Choco it is expected to remain at under 30 degrees annually. Thus, the western coastal region, including Choco, is almost unaffected by extreme heat due to the Choco ecoregions’ unique climate conditions sustaining stable temperatures. Furthermore, mountainous regions will not experience additional very hot days. In eastern and northern Colombia, where very hot days are already common, a sharp increase is expected (Figure 8). Under SSP3-7.0, by 2055, the prevalence of very hot days can more than triple in these areas when compared to baseline 50 years prior.

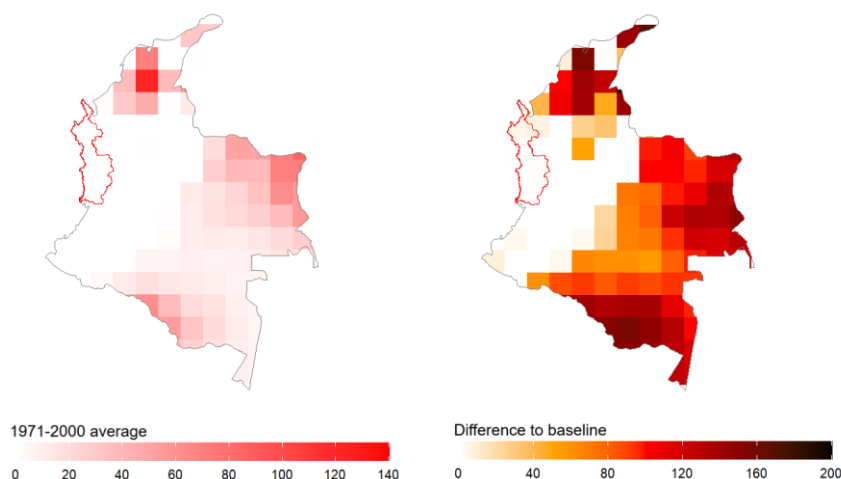


Figure 8: Projected increase of very hot days (peak at over 35 °C) in Colombia between 1971-2000 baseline and 2050-2060 average. Data: Iturbide *et al.* 2022

Potential evapotranspiration is the amount of water that would be evaporated and transpired if sufficient water was available at and below the land surface. Since warmer air can hold more water vapor, it is expected that global warming will increase potential evapotranspiration in most regions of the world. In line with this expectation, hydrological and temperature projections for Colombia indicate a continuous rise of potential evapotranspiration under SSP3-7.0, with it projected to increase by 2-4 % in the Choco region. An increasing trend in potential evapotranspiration can be observed all over Colombia and with high agreement from research papers (e.g. Fan *et al.* 2024). The highest percentage increases will take place in the mountainous regions. Higher evapotranspiration affects the water supply and the amount of surface water available for agriculture. It can reduce the fraction of precipitation that flows over land and into streams and rivers. Long-term shifts in recharge patterns can change groundwater levels and subsequently groundwater surface water interactions and soil moisture.

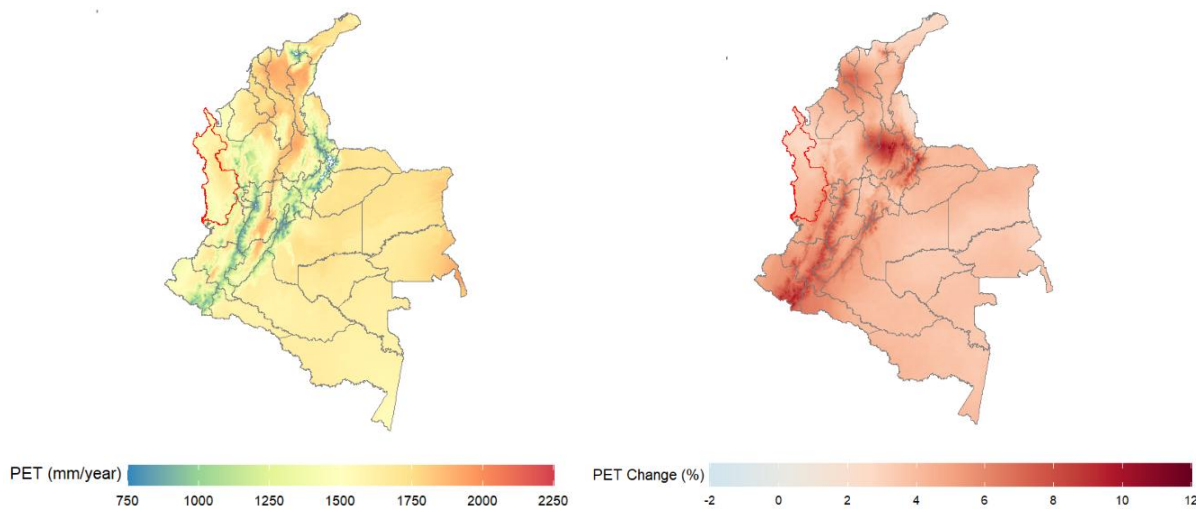


Figure 9: Projected change in potential evapotranspiration in Colombia between 1971-2000 baseline and 2041-2060 projected SSP3-7.0 average, CMCC-ESM2 model, Data: CMCC Global AI-PET database

Projected impacts

Flooding, landslides and sea level change

Choco is a region highly susceptible to rainfall related extreme events due to its location, the influence by the Inter-Tropical Convergence Zone, the three low-level jets, the Amazon, the topography, and the impact of processes in both the Pacific and Atlantic oceans (Ceron *et al.* 2022). The ENSO in both phases, warm El Niño and cold La Niña, is one of the main phenomena that has the greatest effects on Colombia (Ceron *et al.* 2022). The consensus between researchers on the changing climates impact on ENSO itself is mixed due to the phenomenon's large internal variability, with the latest research suggesting that ENSO strength may have increased since 1960's (Cai *et al.* 2023). Strong El Niño and La Niña are also considered to amplify the local effects of climate change, leading to increasing prevalence of extreme events (Funk *et al.* 2021).

Landslide risk increases with intense rainfall events, exacerbated by factors such as land clearance, substandard urban development and poor drainage, especially along slopes (Herrera-Coy *et al.* 2023). They are the largest single natural hazard in Colombia, causing almost half of all damages and loss of

life by natural disasters (Herrera-Coy *et al.* 2023). A total of 32,022 landslides in the period between 1900–2016 were compiled, where the precipitation showed a dominant influence on the occurrence of landslides. 92 % of the landslides were triggered by rainfall, with a greater influence of rainfall duration instead of rainfall intensity. During the 2024 La Niña induced emergency, a rainfall induced landslide in Choco near Carmen de Atrato killed 33 people seeking shelter from the flooding and rain. The Quibdó municipal disaster risk management plan (2012) has further assessed that the lack of sewage infrastructure on the slopes surrounding the El Carano airport has led to destabilization of landmasses, causing a distinct urban landslide hazard.

The Choco department is especially vulnerable to both floods and rainfall-initiated landslides, with increases in precipitation and the local population expected to lead to increasing exposure to these hazards. The department's population is almost completely concentrated along waterways and shoreline due to extremely limited road infrastructure (figure 11). The scenario specific population growth simulation for the area suggests the growth to follow the current pattern of settlement (figure 13, Zhuang *et al.* 2024). The area's history of large-scale damage due to rainfall further reinforces this view. During the 2024 La Niña, as one recently reported example, 200 000 people in Choco alone, 40 % of provinces population, were affected by heavy rains and the following damage. During the event, 27 municipalities in the area were in an emergency, caused by heavy rains and the subsequent collapse of three river basins - Alto y Medio Baudó, the Atrato and the San Juan (IFRC).

Limited road infrastructure, long distances and the inaccessibility of much of the rural areas due to insurgents leads to areas residents and their property being extremely vulnerable to the impacts of extreme events. Even in urban areas where basic services are accessible such as in Quibdo, unplanned settlements with poor infrastructure and access are still very vulnerable to rainfall induced hazards. Due to extending along two streams, Atrato and its side stream Caraño, Quibdo has a history of flooding induced damage, and based on local reports, the city's riverside suburbs have the highest riverine flood hazard exposure of the region (Franzia Meyviz). Due to local land use practices, minimal elevation difference from river, and lack of flood safety measures, housing in Quibdo is built in immediate vicinity of the shoreline, exacerbating vulnerability to flooding.

With projected increases in rainfall combined with increase the frequency of higher magnitude flood events, it is expected that the hazard posed by flooding events will increase in the future. Rainfall induced landslide risk is expected to increase due to the rainfall projections and larger exposure due to population growth. Expected increasing extent of logging and other land cover changes will further contribute to higher risk. The difficult humanitarian situation of the department, population growth concentrated on flood prone areas, poor infrastructure, long travel distances and little support from the central government is expected to lead to a trend of more people exposed to rainfall inducing extreme events with limited resilience to cope with the effects.

Due to flooding being a constant hazard, especially in Quibdó, the local government has planned several infrastructural and dredging initiatives to alleviate some of the worst vulnerability to flooding. Latest Quibdó municipal disaster risk management plan from 2012 includes measures such as improvement of urban drainage, reforestation of watersheds and construction of flood control structures. Additionally, non-structural measures such as including flood hazard assessment into the land use plan have been taken with the intention of restricting construction on these areas, whilst also

allocating funds for relocating people to less vulnerable locations. All these initiatives for vulnerability management are sound in theory, but an assessment of their state of funding, progress or effects does not exist, which makes drawing further conclusions difficult. However, the existence of these documents proves that there has been considerable effort put into risk assessment and planning of countermeasures in the Quibdó area.

Coastal flooding impacts both the Caribbean and Pacific coasts of Choco department. Climate changes impacts on sea level rise are projected to have considerable impacts on these areas both through coastal flooding as a primary mechanism, and inundation by sea level rise as a secondary one (figure 10). On the report's timescale, the direct inundation caused by sea level rise will be moderate, as sea-levels expected to rise by 22 cm on the Caribbean coast, and by 11 cm on the Pacific compared to 2020 values under SSP3-7.0 scenario (NASA Sea level Projections). These changes are too small to accurately portray the impacts of via utilizing publicly available digital elevation models. The difference between the two seas is explained by rapid land subsidence rates on the Caribbean coast, which is portrayed as a differing level of sea level rise on the measurements (Nevermann *et al.* 2023). The main effects of sea level rise are linked to strengthening of coastal flooding phenomenon, with studies showing that 68 % of coastal areas flooded as a result of climate change will be caused by extreme tide and storm events, which are coastal flooding events (Kireczi *et al.* 2020). The coastal flooding projections for 2050 utilized in figure 10 account for sea level rise, which is reflected accordingly in the high exposure risk rating of municipalities with coastal towns. As the population in the area is concentrated along water as a general rule and exclusively on the coast in municipalities such as Nuquí and Baja Baudó, the hazard ratings in these areas are expectedly high (figure 13).

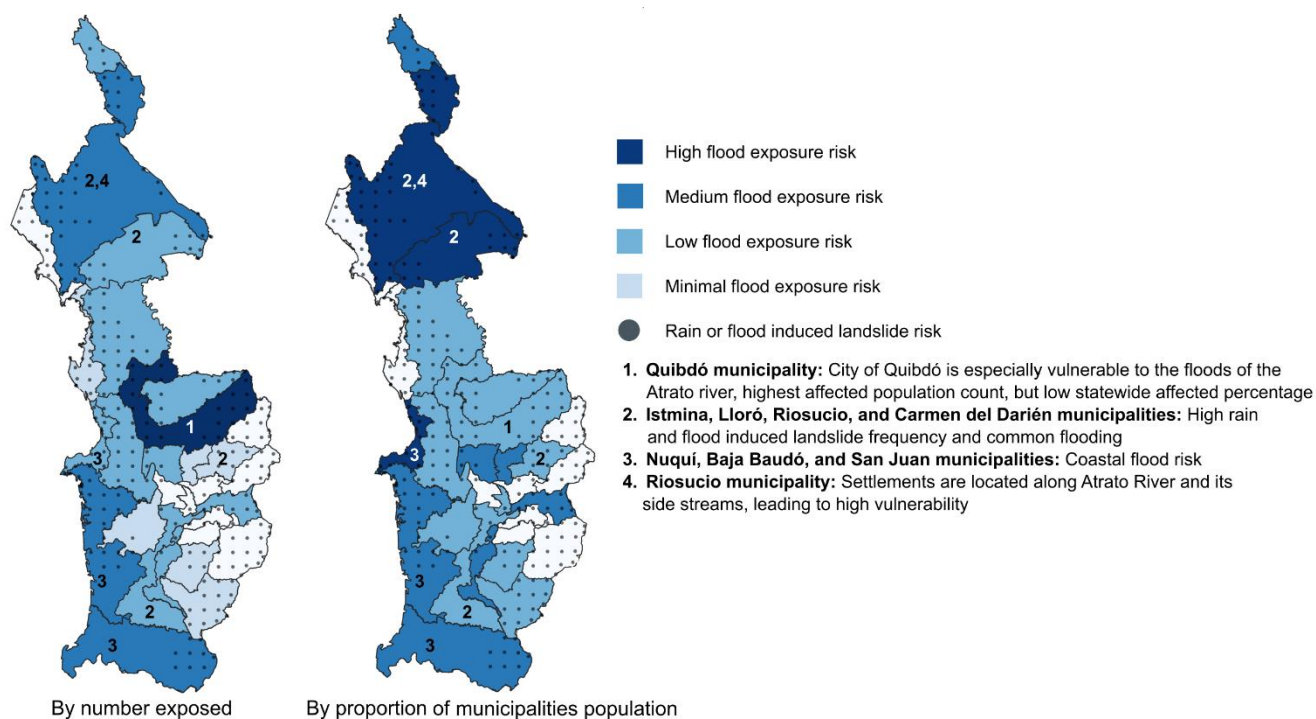
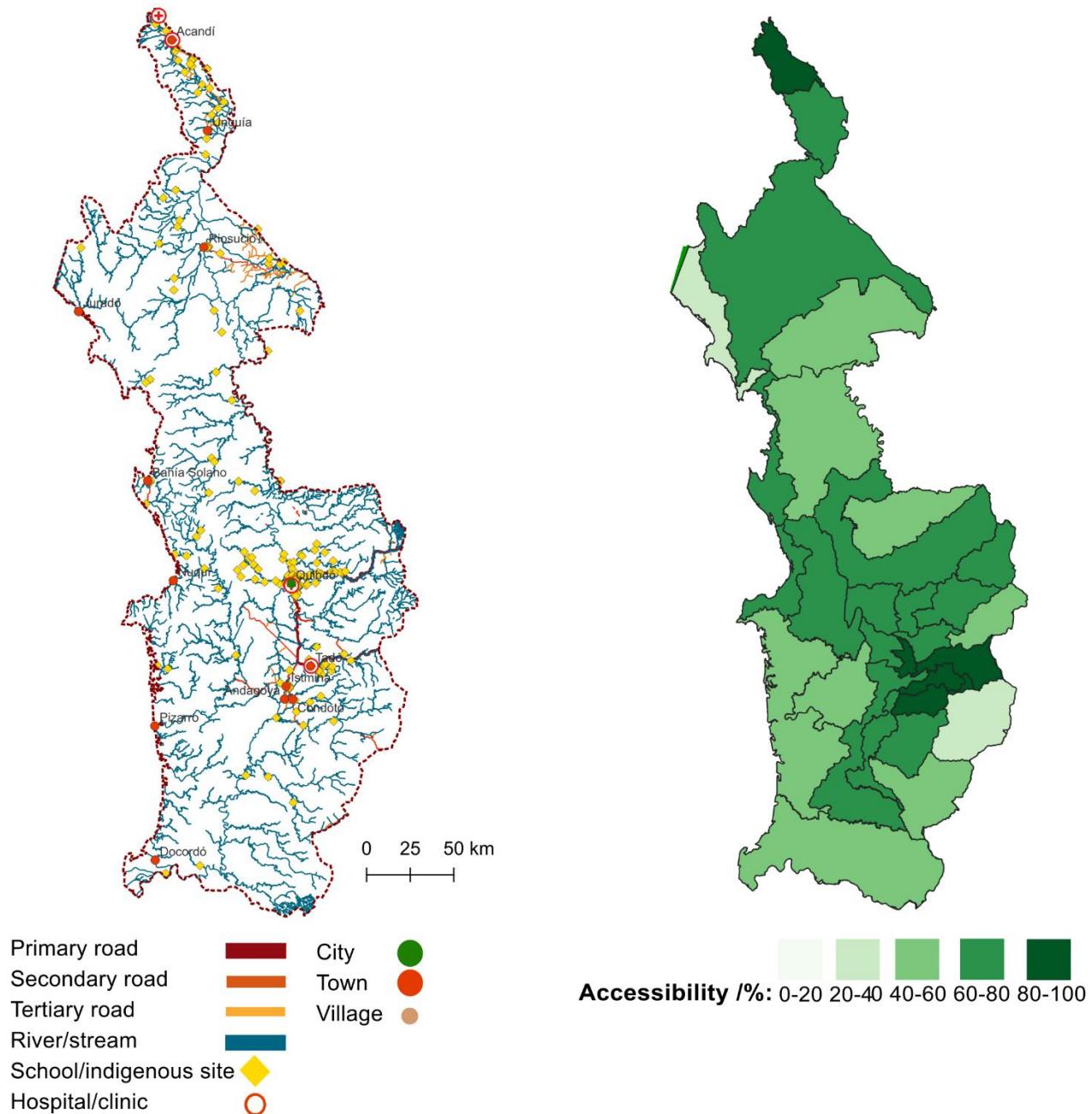


Figure 10: Flood exposure and landslide risk under SSP3-7.0 in 2055, two-year flood extent. Riverine and coastal flood risk ranked by percentage of affected population per municipality, classes by natural breaks (Jenks). Landslide risk by areas affected by rain-initiated landslide hazard. Data: Aqueduct flood hazard maps, Zhuang *et al.* 2024, Francia Meyvez, World Bank landslide risk maps

Critical infrastructure and economy



Figures 11 and 12: Infrastructure and rivers in Choco, Data: OSM. Access index calculated on current road and waterways, population inside distance of 2 km or less of a road or a waterway, 2055 population estimate. Best case scenario with no impediments to movement. Data: Zhuang et al. 2024, OSM, utilizing World Bank Rural Access Index (RAI) method

Economic activity and infrastructure networks in Choco department already face a significant risk of impacts from flooding, landslides, sea level rise and extreme rainfall. This risk is exacerbated by much of the region's population needing to cover long distances to reach basic services (figure 11). Additionally, the area has extremely scarce paved road infrastructure, limited only to cities, route 50 linking town of Las Animas to the eastern departments, and route 13 from Quibdo southwards through Las Animas to Novita. The state maintained and recorded unpaved road network does not expand much beyond that, being mostly limited to road 60 going east from Quibdo (figure 11). Thus,

the region is reliant on waterways and unmaintained footpaths for transport (figure 11). High rainfall around the year makes mud a considerable issue, with many of the smaller paths impassable.

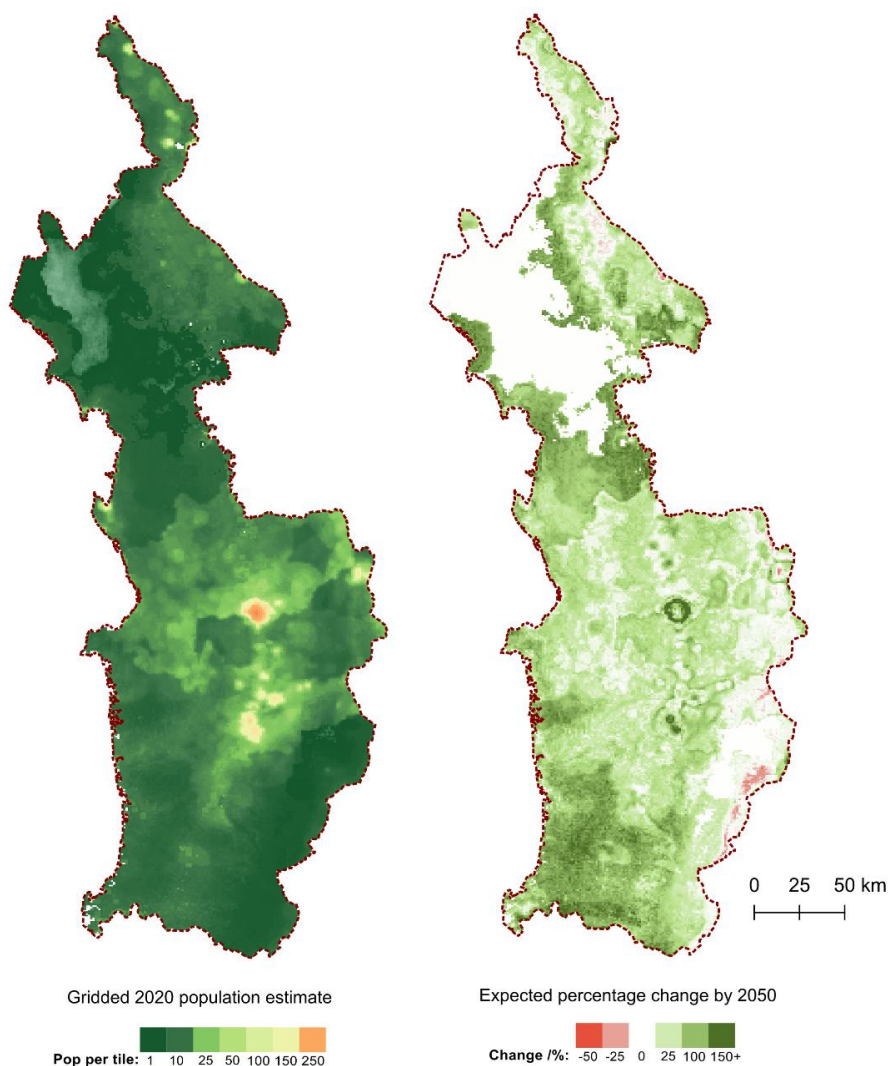


Figure 13: Current population distribution in Choco, and expected population change by 2050. Data: Zhuang *et al.* 2024

Whilst Choco won't be affected by intensification of hot days unlike large sections of the country, urban areas will still experiencing intensified heat islands due to rising average temperatures and the high humidity will further increase heat stress. The area has substantial regional divide when it comes to electricity and thus cooling availability. The coverage of the network follows the coverage of other infrastructures, with Quibdo municipality having electricity coverage of 93-95%, whilst sparsely populated areas have no grid access (Quibdo-choco.gov). Increasing temperatures and drastic increase on hot days in northern and eastern regions of the country will lead to an increasing need for electricity and possibly shift investment priorities away from Choco (figure 8). Colombia's third national communication on climate change projects a country wide 2.1% GDP loss potential due to climate change induced increases in flooding. Due to Choco being one of the most hazard prone and vulnerable regions in the nation, the expected loss of income is even greater. However, assessing the economy of the area and the possible regional damage is difficult due to its extremely informal nature. Based on figure 10 and figure 13, the general expectation is that the main economic damage from increase of rainfall and flooding will be focused on coastal towns and in riverside suburbs of Quibdo.

Human displacement

Chocó has endured decades of violence involving guerrillas, paramilitaries, and other armed groups, resulting in massive human displacement both inside and away from the region. The department consistently ranks among Colombia's highest in historical and ongoing forced displacement due to conflict (ICRC, Shulz *et al.* 2014). While nationwide peace processes since the early 2000's led to fluctuating violence levels, Chocó remains a hotspot for clashes between residual armed groups, particularly along its major river corridors. Government stabilization programs since the 2016 Peace Accord have sought to address displacement, yet Chocó continues to report significant new displacement events yearly, both by armed conflict and natural disasters. Thousands of people in Chocó remain in situations of protracted displacement or face repeated cycles of forced movement due to ongoing violence (ICRC, CP-Colombia).

Simultaneously, Chocó's extreme vulnerability to rainfall induced hazards exacerbates these challenges. Major flood events have repeatedly triggered large-scale displacement, often affecting populations already vulnerable due to conflict. Significant flood-induced displacement events occurred throughout the department during the 2010-2011 La Niña (impacting tens of thousands), the 2022 rainy season (displacing over 20,000 people), and the 2024 floods (displacing more than 15,000 people in the first quarter alone) (NOAA). In addition, the prevalence of armed groups in the area limits the movement of people in substantial sections of the area, leading to increased vulnerability to hazards (NCEI).

Comparing reported displacement patterns within Chocó to other hazard data reveals high risk geographic concentrations where conflict and high risk from natural hazards intersect, particularly along the Atrato, San Juan, and Baudó river basins (CP-Colombia, Figure 10). Municipalities such as Litoral San Juan, Lloró, Alto Baudó and Domingodó are highly vulnerable to floods, whilst reporting high displacement numbers from violence (CP-Colombia, Figure 10).

Water resources and human health

Chocó is exceptionally rich in water resources due to its extreme rainfall. However, its water security faces multiple threats primarily driven by human activities and weak governance. The importance of clean natural water sources is emphasized, as only 44 % of urban population in Chocó have piped water and more than 90 % of sewage goes untreated (Defensoria del Publico 2023). These issues in the coverage of the local water infrastructure increase vulnerability to flooding, as floods or heavy rainfall can overwhelm unprotected water sources, leading to the spread of waterborne diseases.

Mercury contamination of rivers and sediments is a massive issue in the area. This is caused by illegal gold mining on the upstream riverbanks of Atrato river, with the processes consuming large amounts of mercury to separate the product from other minerals. Atrato River sediments are especially contaminated by mercury in Quito, Quibdo, and San Jose areas (Palacios-Torres *et al.* 2021). Widespread mercury contamination in fish consumed by local communities is documented, posing significant health risks, with every species of fish in Atrato river posing hazard quotient above 1, indicating long term systemic effects with exposure through diet (Salazar-Camacho *et al.* 2022, Palacios-Torres *et al.* 2021). Guerrero-Latorre *et al.* (2016) detected mercury-resistant bacteria in Atrato River sediments, indicating long-term pollution. In addition, mining operations such as

dredging directly destroy riverbeds, banks, and floodplains, causing severe sedimentation, increased turbidity, altered hydrology, and habitat loss.

The risks caused by these hazards are exacerbated by projected effects of climate change and an increase in population during the next 30 years. As extreme rainfall events have the capacity to rapidly erode terrain and wash soil to rivers, the trend of increase in rainfall is expected to lead to furthering of the pattern of soil contaminated with both sewage and mercury dissolving to rivers and other water sources, increasing local populations exposure to pollutants (Hirabashi *et al.* 2021, Palacios-Torres *et al.* 2021). In addition, ENSO induced variance on precipitation will continue to contribute to uncertainty in water management in the area (Ceron *et al.* 2022). Local reports of increase of seasonal droughts fit with the trend of increasing variance presented by IDEAM projections, especially when combined with ENSO induced variance (Ceron *et al.* 2022).

The Defensoria del Publico report from 2024 paints a clear picture that people are driven to mining due to lack of other options to make a living, even knowing about the damage they are doing to their homes. Combating this issue is considered very difficult for a variety of reasons, especially as mining is one of the primary sources of income to the armed groups residing in the area. The state does not have enough resources to police the sparsely populated and difficult to traverse region effectively. Thus, the actions taken have largely been ineffective in the long term with the organizations having enough resources to keep the operations active even with equipment lost to policing operations (Defensoria del Publico 2024).

Long-lasting solutions to the illegal mining problem are difficult to undertake as they require dealing with the armed organizations and the widespread unemployment. However, the environmental damage caused by mining is one of the primary environmental concerns in the area and considered to be the primary issue to be dealt with for other developments to succeed (Santisteban Ruth). Offering stable alternative incomes, or even official mining permits, to the locals could be one of the most practical approaches to the problem and would also potentially reduce the discontent feeding into the guerilla organizations. For example, the problem with the peace settlements has been new dissident actors taking over in the cover of the jungles when old ones settle with the government, like has happened with the FARC settlement in 2016.

Ecosystems and agriculture

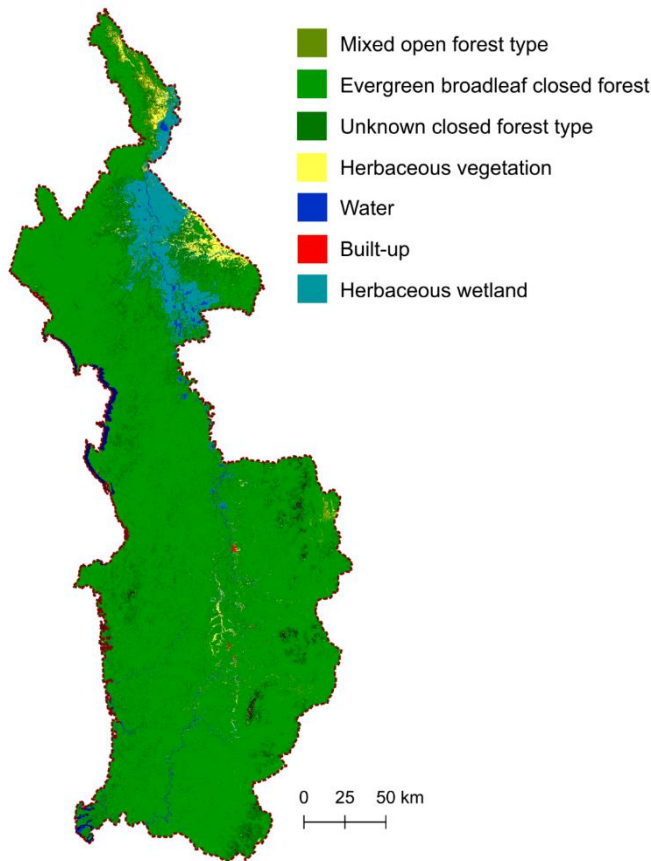


Figure 14: Landcover of the Choco department. Data: Copernicus Land Cover 2019

Chocó's forests are part of the Chocó-Darién-Western Ecuador Hotspot, a once continuous corridor of rainforests reaching from the southeastern portion of Panamá, along the western portions of Colombia and Ecuador, as far as northwestern Perú (CEPF). Within it, the Chocó biogeographic region is globally recognized as one of the world's most biologically diverse. Illegal logging, mining and slash and burn agriculture have been reducing the extent of this rainforest corridor for decades. The projected patterns of intensifying settlement south of Quibdo, illegal gold mining on riverbanks and expected increase of oil palm farming in Riosucio municipality are the expected future threats to these protected territories (EJAtlas, Zhuang *et al.* 2024, WWF). Deforestation further reduces the landscape's resilience to erosion and flooding. Healthy forests regulate microclimates, maintain soil moisture,

reduce runoff during heavy rain, and sustain baseflow during dry periods. Their loss amplifies flood-drought cycles (Velásquez *et al.* 2020) However, protected areas and indigenous territories cover over 2.5 Mha of the Chocó, even with forceful eviction of natives in Curvarado and Jiguamiando river basins to clear way for palm oil production (WWF, EJAtlas). The protection measures combined with the impassable terrain, armed groups using the area as a base, and hostilely humid climate have prevented some of the worst damage due to human activity quite successfully (WWF). Research on impacts of climate change on the area is scarce, but generally climate change is expected to lead to shift or reduction in species communities to different latitudes as they lose suitable areas in the Choco region (Mota *et al.* 2024).

Agriculture in the area can be divided into two categories, small scale subsistence agriculture practiced by the locals near settlements, and intensive export focused farming of cash crops such as oil palms. It is of small scale enough that the satellite imagery based landcover classification with resolution of 100x100 meters (figure 14) has not identified any cropland in the area. Oil palm farms show as evergreen forests, and thus merge with local vegetation on the categorization. Because of this, the agriculture's vulnerability to flooding in the area is difficult to assess. Generally, the changes in climate are not expected to have a major impact on crop yields in the area, even in higher heating scenarios extending to 2090 (Hultgren *et al.* 2025). However, the projected increase in precipitation extremes will make adaptation even more important than it already is.

Zimbabwe, Zvishavane and Mberengwa

Country overview

Zimbabwe is a landlocked country in southern Africa, spanning approximately 19°S to 22°S latitude. It covers 390,757 km² — comparable in size to Germany. The country is divided into 10 provinces, including two major cities with provincial status (Harare and Bulawayo). Geographically, Zimbabwe is dominated by the Highveld plateau (1200–1600 m), which spans the central parts of the nation and hosts most of the population. The Great dyke cuts the Highveld from the north to the south. This volcanic formation hosts most of the nation's mineral wealth. The Highveld transitions to the Midveld (900–1200 m) and Lowveld (< 900 m) in the south and southeast, flanked by mountain ranges like the Eastern Highlands. Zambezi river forms the nation's northern border, with the Kariba dam holding the world's largest manmade reservoir behind it.

Zimbabwe has a history of extremely rapid population growth, with the nation's population almost tripling from 5 million in 1970's, to over 13 million by 2010's. However, during the recent decades the growth has slowed down, with population reaching 17,3 million in 2024 according to macro trends. The annual population growth rate has been roughly 2 % during the last 10 years. Around 67 % live in rural areas, though displacement to urban areas is common due to economic pressures caused by unreliability of agriculture. The capital Harare and Bulawayo are the largest urban centers. The Shona at 80 % and Ndebele at 15 % are the dominant ethnic groups, with smaller minorities including Europeans, Asians, and mixed-race communities.

Zimbabwe's registered GDP was \$35.2 billion as of 2024 with the World Bank ranking the nation as a lower middle-income country, but with 67 % of the nation living under the \$3.65 a day poverty line. The nation has the second largest informal sector in the world, considered to cover 64 % of the de facto size of the economy (World Economics.com). Agriculture is the most major employer with 67 % of the workforce working in agriculture-related fields. Mining and remittances, which together make up 25 % of the GDP, are critical to national income (IMF). According to UN multidimensional poverty index 2023, 25,5 % of Zimbabwe's population suffer from multidimensional poverty. Lacking standards of living are the primary contributor at 59 %, over health and education. This is due to the nation having relatively high literacy and primary school completion rates of 89 % and 86 % respectively, though the latter has declined considerably from its peak of 98 % in 2001 (World Bank).

Zimbabwe ranks 18th out of 179 on the Fragile States Index (2024), with instability of public institutions and the political system being the primary drivers of fragility. Aging and poorly maintained public infrastructure have created additional vulnerabilities to disturbances, with the national electricity grid being especially unreliable (Pushak & Briceño-Garmendia 2011). Climate hazards compound the societal fragility: recurrent El Niño-induced droughts, floods, and cyclones have disrupted agriculture, which largely relies on rain-based irrigation. The ND-GAIN Index ranks Zimbabwe 174 out of 187 as the nation is highly vulnerable to climate change with low adaptive capacity. The index rates the health sector especially vulnerable with the expected increase in prevalence of tropical vector borne diseases combined with the trend of declining availability of medical services. Agriculture is another sector where expected damage from climate change is conjoined with very low adaptive and technological capacity.

Region overview

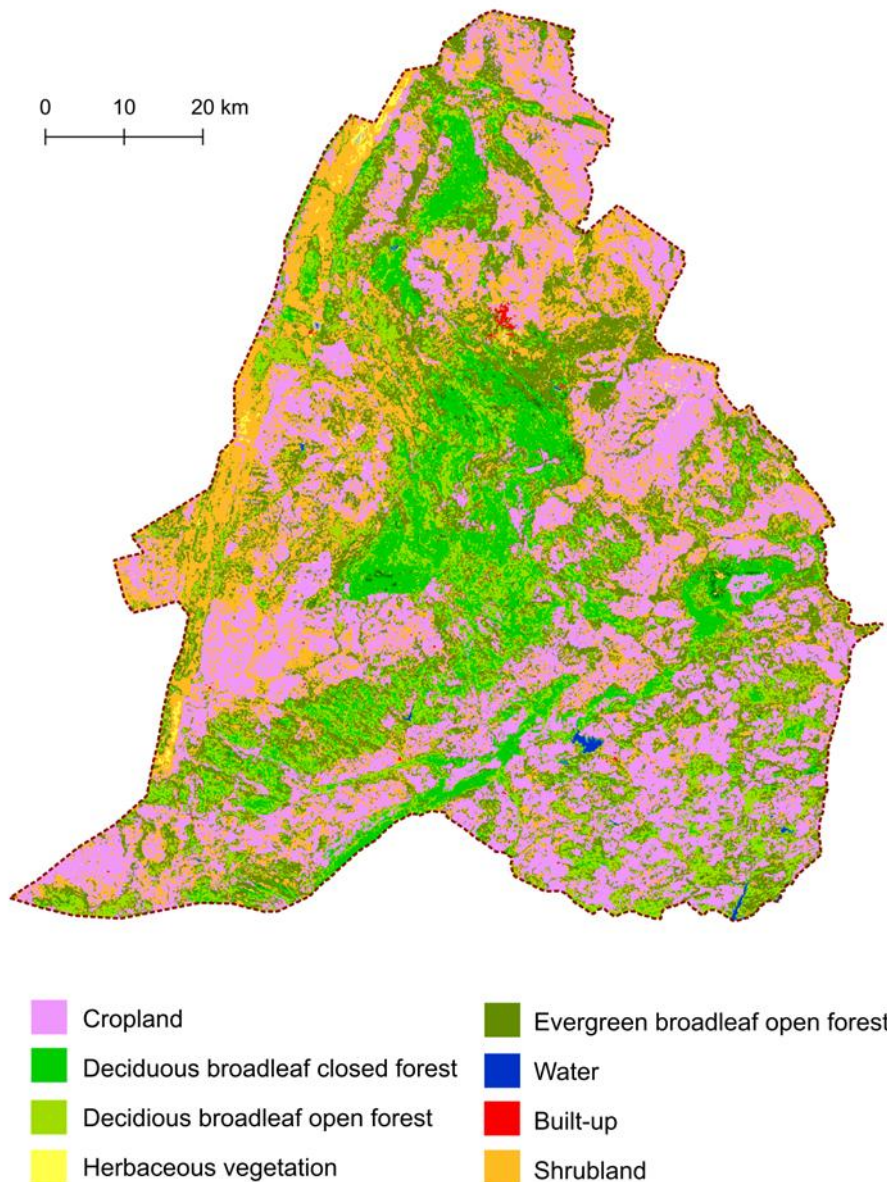


Figure 15: Landcover of the Zvishavane and Mberengwa. Data: Copernicus Land Cover 2019

Zvishavane and Mberengwa together at 9,030 km² are neighboring districts in southern Midlands Province, Zimbabwe, situated between 20°S and 21°S latitude. The terrain is defined by the mineral-rich Great Dyke formation – a 550-million-year-old ridge stretching northeast-southwest – flanked by savanna grasslands and granite kopjes. Mberengwa’s eastern highlands reach 1,500 m, contrasting with Zvishavane’s lower valleys. Critical water sources include the Runde and Ngesi rivers flowing through the districts, though drought frequently reduces flow. Both districts fall under Zimbabwe’s communal and resettlement land tenure systems, with limited protected areas.

According to the 2019 census, the districts host approximately 352 000 residents, with 83 % living in rural villages. Zvishavane district has the

largest town in the area, Zvishavane, with a population of 60,000 and an economy focused on mining and informal enterprise. The town hosts Zimbabwe’s largest platinum mine Zimplats, and emerald operations. Mberengwa’s population remains largely dispersed across communal lands, with main income being agriculture. Remittances are a large part of the economy as in other parts of Zimbabwe, with the effect being especially noticeable in southern Zimbabwe with proximity to South Africa encouraging migrant work. Whilst direct municipal statistics on the matters such as health, education and incomes do not exist on public sources, the area is expected to share similar issues to rest of rural Zimbabwe and the Midlands province in general.

Mashura (2024) studied urban-rural divide in Zimbabwe and found a considerable gap between living standards based on urban proximity. Food poverty increases from 7,8 % from wards within 15 km of a city to 23 % for ones between 50-100km from one. A similar phenomenon was observed for access to sanitation, with decrease from 23 % to 13 %, and electricity, dropping from 19,5 % to just 4,3 %. Similar but less significant effect can be observed even with distance from rural towns (Mashura 2024). The urban rural divide is further exacerbated by poor quality of roads, with only 35 % of the

nation's roads being passable year-round, isolating poorly linked countryside areas during wet season (Pushak & Briceño-Garmendia 2011, Nhongo & Makunura ZCC).

Observed and projected climate

Present Climate

Zvishavane and Mberengwa districts experience a subtropical climate, significantly influenced by their inland location and moderate elevation within Zimbabwe's Midlands Province. Mean annual temperatures are relatively warm but moderate compared to lower-lying areas. Daytime peak temperatures frequently reach the low to mid-30's °C during the peak of the hot wet season (October-November), whilst winter months (June-September) are mild and dry.

Precipitation in these districts follows a unimodal regime, characteristic of much of Zimbabwe. The region receives the majority of its rainfall during a single rainy season, typically extending from October to April. This rainfall is primarily driven by the seasonal north-south migration of the Intertropical Convergence Zone (ITCZ) and moisture influx from the Indian Ocean. There is a significant dry season from June to September. Mean annual precipitation generally ranges between 550 mm and 750 mm across the districts, exhibiting moderate local variation influenced by topography; areas on the higher ground of the Mberengwa range may receive slightly more, while lower-lying valleys might receive slightly less. Like the broader region, the municipalities experience high inter-annual rainfall variability, strongly correlated with the El Niño-Southern Oscillation ENSO. El Niño is a climate pattern that describes the unusual warming of surface waters in the eastern tropical Pacific Ocean. El Niño is the warm phase of the El Niño-Southern Oscillation (ENSO) phenomenon. La Niña, the cool phase of ENSO, is a pattern that describes the unusual cooling of the region's surface waters. El Niño and La Niña are considered the ocean part of ENSO, while the Southern Oscillation is its atmospheric changes. El Niño has an impact on ocean temperatures, the speed and strength of ocean currents, the health of coastal fisheries, and local weather from Southern Africa to Southern America. El Niño events occur irregularly at two- to seven-year intervals. However, El Niño is not a regular cycle, or predictable in its amplitude. El Niño events typically bring hotter, drier conditions and increased drought risk, while La Niña events are associated with higher probabilities of above-average rainfall and potential for localized flooding. This variability also influences the occurrence and severity of dry spells within the rainy season and heat extremes.

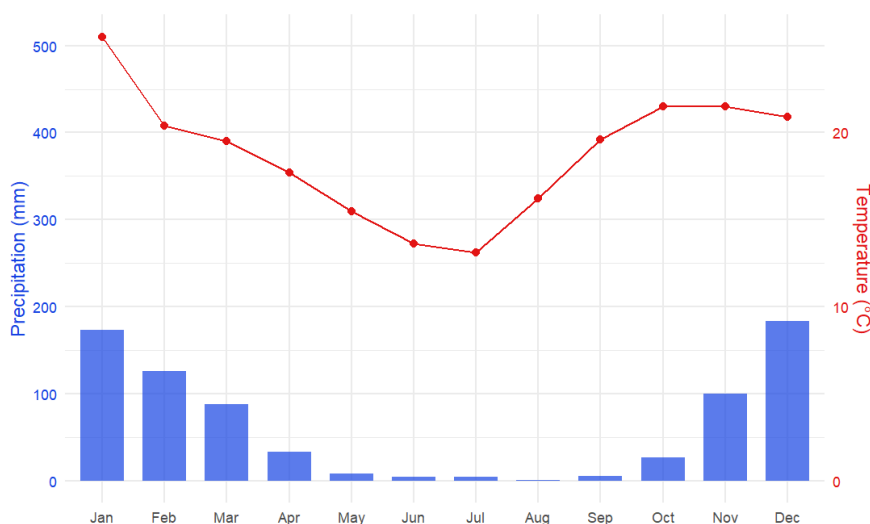


Figure 16: Annual precipitation and temperature averages, Zvishavane measuring station Data: weatherandclimate.com

Climate trends

Analysis of historical climate records indicates a clear warming trend in Zvishavane and Mberengwa over recent decades, consistent with broader patterns observed across Zimbabwe and the region. During the last 50 years, mean annual temperatures over Southern Africa increased by between 1,04 and 1,44 °C (Gutiérrez *et al.* 2021). In Zimbabwe the warming has been more considerable, with Meteorological Services Department of Zimbabwe reporting that the daily minimum temperature has risen by approximately 2,6 °C and the daily maximum temperature by 2 °C over the last century. Warming has brought forth an increase of frequency and intensity of hot days and heatwaves, while cooler nights and cold spells have become less common (Fan *et al.* 2024).

The latest study done on annual precipitation trends in Zimbabwe was done by Mazvimavi in 2010, analyzing the precipitation data from 1892 to 2000. On this period, the study found no statistically significant trends in reduction of rainfall, with the trends generally pointing at an increase during this period. However, the interannual variability is considerable, and statistical evidence exists of bunching of years with below or above average rainfall (Mazvimavi 2010). Precipitation characteristics in Zimbabwe between 1960–2010 have been studied by Gwatida *et al.* (2023). The study found no statistically significant nationwide trends regarding rainfall, with the results pointing at only a statistically insignificant change towards intensification of rainfall patterns. Global studies on intensification of rainfall for eastern southern Africa are equally non-conclusive with clear trend missing (Sun *et al.* 2021). The results of Gwatida *et al.* (2023), and the variance in preceding studies point to the rainfall trends in the area being highly uncertain in terms of both spatial and temporal extent, magnitude and direction of change. The study considers this attributable to the inter-annual variability of rainfall over southern Africa (Gwatida *et al.* 2023).

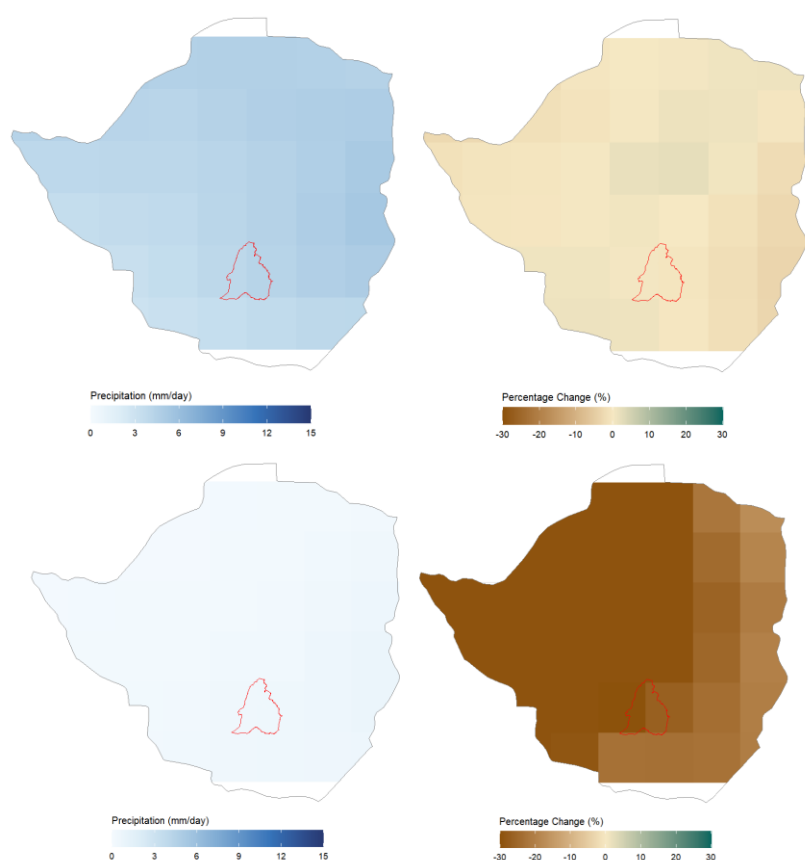
In Zvishavane-Mberengwa area the results of Gwatida *et al.* (2023) point at the area following the wider trends, with the number of wet days slightly increasing, maximum rainfall per day decreasing, and the number of consecutive dry days having no trend over the study period. Research done on the rainfall patterns of Mzingwane catchment south of Mberengwa instead supports the pattern of intensification of rain. A clear trend towards more intense, concentrated rainfall exists, with 34 % decrease in rainy days in period from 1950 to 2015, but with rainfall amounts having remained stable (Sibinda *et al.* 2019). The results of Gwatida *et al.* (2023) see maximum rainfall per day decreasing in Zvishavane, but increasing in Mberengwa and areas west of it, suggesting that results of Sibinda *et al.* (2019) are not in conflict with the study, but the area having considerable spatial variability between Mzingwane and Runde catchments when it comes to rainfall patterns. Similar analysis does not exist for the Runde catchment, which would be extremely helpful for the impact assessment.

ENSO has had an impact on prevalence of extreme events in the region's climate records, with El Niño bringing long term droughts. For the 1950–2022 period, 9 Eastern Pacific El Niño events and 10 Central Pacific El Niño events have been identified (Mphesea *et al.* 2025). There exists a significant variability in ENSO impacts on a sub-seasonal scale across the region during the summer half of the year (October-March). Eastern pacific events have been more impactful of the two, affecting rainfall throughout the summer, with the strongest impacts in the core months (Dec-Jan), characterized by less rainfall, more frequent dry spells and extended dry periods. Consequently, the likelihood of experiencing a significant summer rainfall deficit is higher during astern Pacific events, but the risk is still prevalent during Central Pacific events (Mphesea *et al.* 2025). ENSO's amplitude strength has

increased around 10 % since 1960's, suggesting that stronger and more frequent events are not solely due to large internal variability (Cai *et al.* 2023). Tropical cyclone frequency is expected to follow the current decreasing trend, as climate change has led to the weakening of Hadley and Walker atmospheric circulation patterns. Result is more hostile conditions for cyclones to form on the Indian Ocean, with 15–27 % decrease between pre-industrial and historical climate periods (Chand *et al.* 2022).

Projected precipitation

By 2055, projected precipitation amounts under SSP3-7.0 scenario show negative annual precipitation trend on Zvishavane and Mberengwa area with the negative trend in rainfall being focused on the dry winter months from June to September. Decrease in rainfall in wet season is projected to be minimal, which coincides with the historical trend pointing at no change or intensification in rainfall (Gwatida *et al.* 2023, Mazvimavi *et al.* 2010). In certain parts of Midlands and southern Zimbabwe slight increases of precipitation during rainy season are expected. Overall, the projections suggest the already dry climate becomes even drier during the three-month winter season. However, this decrease does not affect the annual precipitation amounts in a considerable way, as the baseline rainfall during the rainy season is already so low. The visualizations of projections provided by the IPCC point to roughly similar but less extreme outcomes as the Zimbabwe's fourth national communication on climate change, where around to 10 % national decrease of rainfall compared to 1981–2001 period is projected for 2020–2040. However, in the short to medium term, clear directional trends remain difficult to determine due to, among other things, model uncertainty and considerable variety caused by the local climate and ENSO.



Figures 17 and 18: Projected seasonal precipitation change in rainy season (October to May) and dry season (June to September), Zimbabwe, comparison between 1971–2000 baseline and 2050–2060 projected SSP3-7.0 average, Data: Iturbide *et al.* 2022

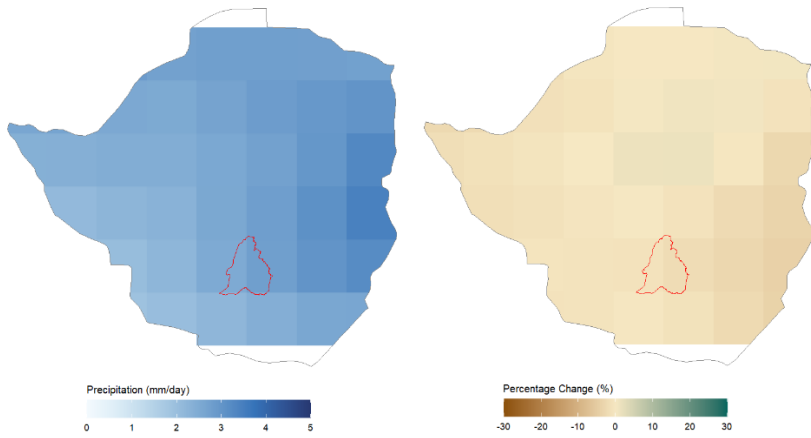


Figure 19: Annual daily rainfall averages and projected annual precipitation change, Zimbabwe, comparison between 1971-2000 baseline and 2050-2060 projected SSP3-7.0 average, note different base precipitation color scale, Data: Iturbide *et al.* 2022

Projected temperature

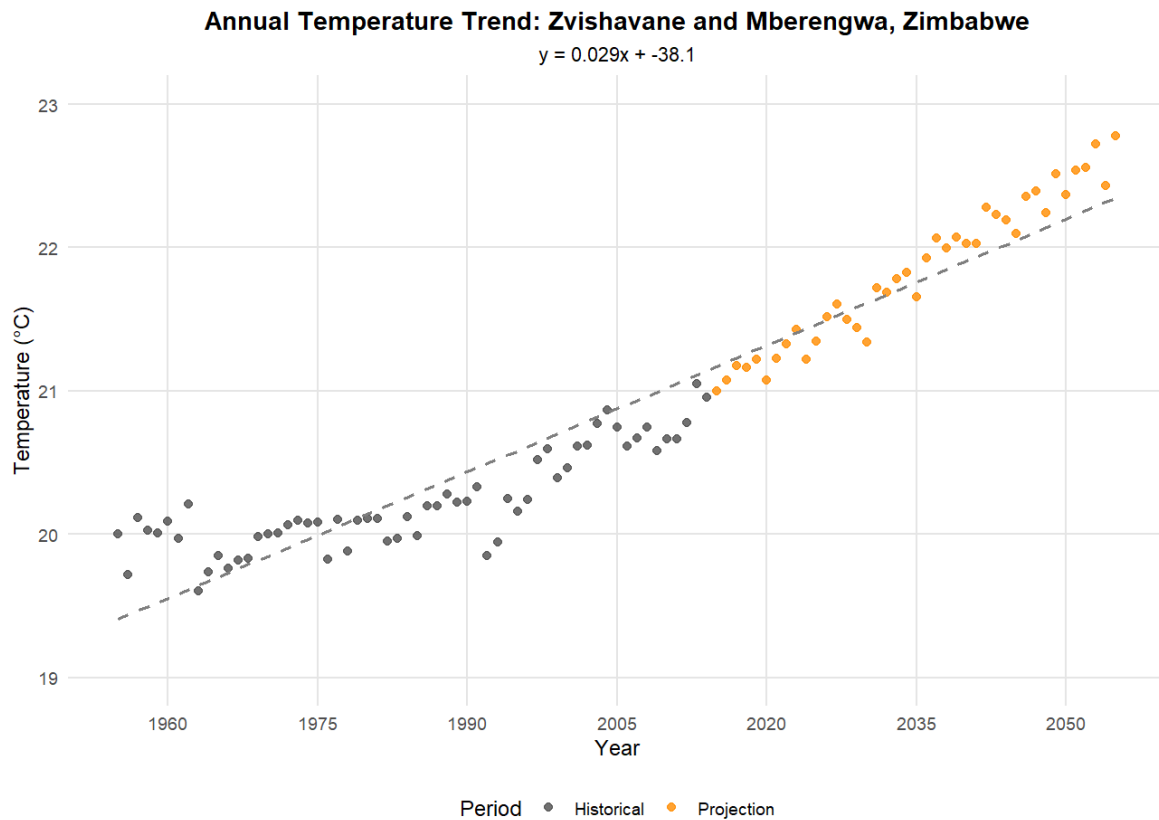


Figure 20: Annual temperature trend and future temperature projection, SSP3-7.0, Zvishavane and Mberengwa region. Data: Iturbide *et al.* 2022

The mean average temperature in Zvishavane and Mberengwa under SSP3-7.0 scenario is projected to shift by 1,6 °C for 2055 when compared to 2015–2025 average, and by 2,64 °C when compared to 1971–2000 average (Figure 20, Iturbide *et al.* 2022). Peak temperature increases will affect the entire nation (Figure 21). The magnitude of peak temperature increases is expected to follow historical patterns, with the prevalence increasing most drastically in western and eastern regions of the

country (Figure 21). Under SSP3-7.0, by 2055, the prevalence of very hot days is expected more than double in western parts of Zimbabwe when compared to the baseline.

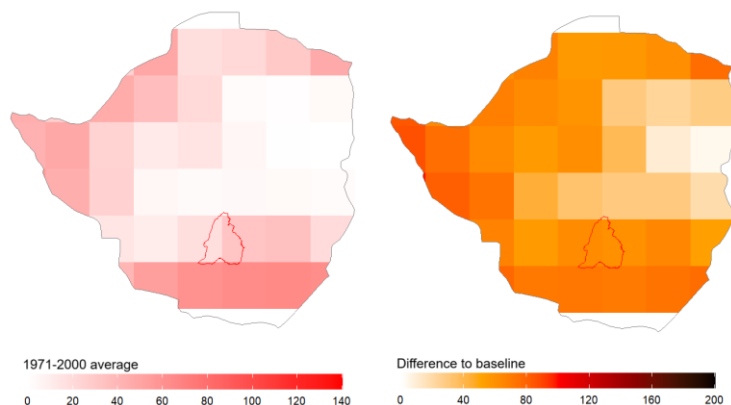


Figure 21: Projected increase in annual average of hot days by 2055 (maximum temperature over 35 °C), SSP3-7.0 scenario. Data: Iturbide *et al.* 2022

Potential evapotranspiration is the amount of water that would be evaporated and transpired if sufficient water was available at and below the land surface. Higher evapotranspiration affects the water supply and the amount of surface water available for agriculture. It can reduce the fraction of precipitation that flows over land and into streams and rivers. Long-term shifts in recharge patterns can change groundwater levels and subsequently groundwater surface water interactions and soil moisture. Since warmer air can hold more water vapor, it is expected that global warming will increase potential evapotranspiration in most regions of the world. In line with this expectation, hydrological projections for Zimbabwe indicate a continuous rise of potential evapotranspiration under SSP3-7.0. Potential evapotranspiration is projected to increase by up to 8 % in the Highveld area, and by 6–4 % in the lowlands. An increasing trend in potential evapotranspiration can be observed in entirety of Zimbabwe with high agreement from research papers (e.g. Fan *et al.* 2024). Certain regions which already experience very high rates of potential evapotranspiration, such as Matabeleland North, are expected to suffer the most from the percentual increase in evapotranspiration.

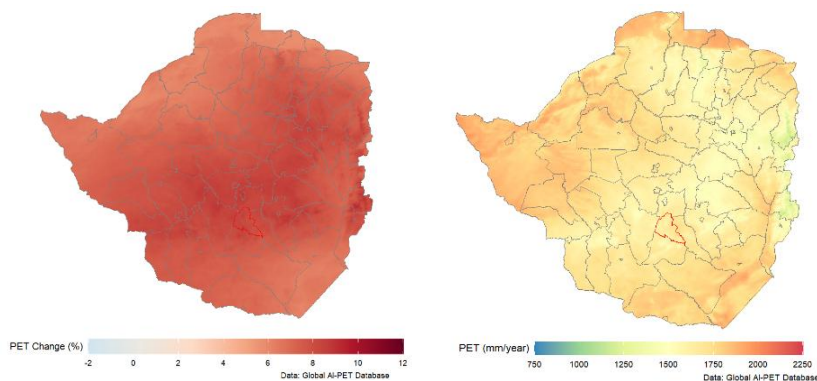


Figure 22: Projected change in potential evapotranspiration in Zimbabwe between 1971–2000 baseline and 2041–2060 projected SSP3-7.0 average, CMCC-ESM2 model, Data: global AI-PET database

Projected impacts

Agriculture and water availability

As Mberengwa and Zvishavane were reported to be at peak 46 % cereal insecurity in 2024 by ZimLAC Rural Livelihoods Assessment Report, information on impacts of climate change is especially important when trying to reduce the vulnerability of rural livelihoods. The dominant staple crop during wet hot season in Zimbabwe is maize, farmed by 82 % of households, with crops such as groundnuts being also popular, with wheat being farmed on dry and cold winter season (ZimLAC). The optimum temperature for maize cultivation is 28 to 32°C, which is relatively high compared to the optimum temperatures required by other crops. The average temperature in Zvishavane and Mberengwa is expected to rise to around 23°C by 2055, with daily peaks of over 35°C becoming more common. On the rainy hot season precipitation amounts are estimated to remain mostly unchanged from historical averages, with the rainfall's seasonality being further reinforced (Sibinda *et al.* 2019).

Process based models such as AgMIP projections, using experimental farms for data and researcher-defined adaptation rules generally tend to predict global increases in yields as temperatures increase (Hultgren *et al.* 2025). The expected long-term impacts of climate change on global and southern African yields also varies considerably between different research (Rosenzweig *et al.* 2014). Whilst the previous estimates are theoretically possible, Hultgren *et al.* (2025) aimed to reflect more realistic conditions across diverse socioeconomic contexts and capacities for adaptation with their research. This approach has produced considerably different results, with an estimated decline of 4,4 % in calory supply per 1°C of global temperature increase, even when accounting for adaptation and Co2 fertilization (Hultgren *et al.* 2025). Li *et al.* (2025) also observed a trend of declining national calory output, with the damage rapidly scaling between heating scenarios. The study expects the decline in maize yields to vary from – 3.8 % under SSP1-2.6, to – 22 % under SSP5-8.5 by 2100 when compared to 2015 average.

The maize yields in Zimbabwe and Mozambique are expected to suffer from considerable drop in the long term due to limited adaptive capacity and local climate conditions, with expected loss of yield for maize in Zimbabwe being up to 30–40 % by 2100 under the most extreme anthropogenic heating scenario (8.5 W/m² of radiative forcing). Simulations done for RCP4.5 scenario at 2100 are close to expected heating from SSP3-7.0 by 2060 at 4.5 W/m² of radiative forcing. The decline is still considerable but expected to remain under 20%. However, as modeling has not been done for the exact scenario for the report's timeframe by Hultgren *et al.* 2025, exact conclusions outside of a declining trend are difficult to draw. This is emphasized by Li *et al.* (2025) not expecting a comparable decline under any scenario. This proves the large variance between studies. However, the general declining trend in yields of all staple crops in the area is illustrated in both studies, even if the magnitude of the effect varies considerably. Li *et al.* (2025) also estimates Zimbabwe being able to sustain required calory demand under any heating scenario. Even if Zimbabwe in theory is expected to be able to meet its national calory demand, nations on the region like Mozambique, Zambia and Angola are not, which can lead to increased instability and potential refugee flows in the region (Li *et al.* 2025). In global context, Hultgren *et al.* (2025) projects impacts of climate change to hit modern-day breadbaskets with currently favorable climates and limited present adaptation the hardest, although losses in the global south are also substantial. These projected effects promote the

increasing importance of local adaptation and increased food independence as the worldwide supply is projected to face increasing challenges past 2055 in higher heating scenarios.

Increasing uncertainty in agricultural yields for the most vulnerable farmers usually has differing impacts for men and women, who have different access to resources and whose tasks in rural households are often gendered. In addition, women farmers tend to be responsible for feeding their families, which increases their vulnerability to climate-related crop losses and failures. Furthermore, women farmers are less mobile and, accordingly, have fewer opportunities for income diversification. While men can search for alternative work in other sectors and in the cities, these opportunities are rarely available to female farmers and their children. Children are also heavily impacted by food uncertainty, with surveys in the midlands area reporting that the primary expected effect of droughts is children receiving less and less diverse food (IOM DTM Zimbabwe).

The effects of climate change on local agricultural production on the timespan of the report can be felt in increased water stress during the dry season. Increasing evapotranspiration due to rising average temperatures will further emphasize the effects of droughts. However, ENSO will remain the defining factor dictating rainfall and surface water availability fluctuations in Zvishavane and Mberengwa (Mugiyo *et al.* 2023, figure 18). For example, during 2023–2024 El Nino 89 % of households which reported experiencing shocks linked at least one of them to prolonged drought, and 70 % and 59 % respectively reported shocks linked to cash shortages and being surprised by rapid increase of cereal prices (ZIMLac). Due to agriculture of Zimbabwe being very vulnerable to effects of El Nino and the high natural variability of the local climate, water conservation techniques and utilization of groundwater are considered especially important in building resilience to water risks (Mugiyo *et al.* 2023).

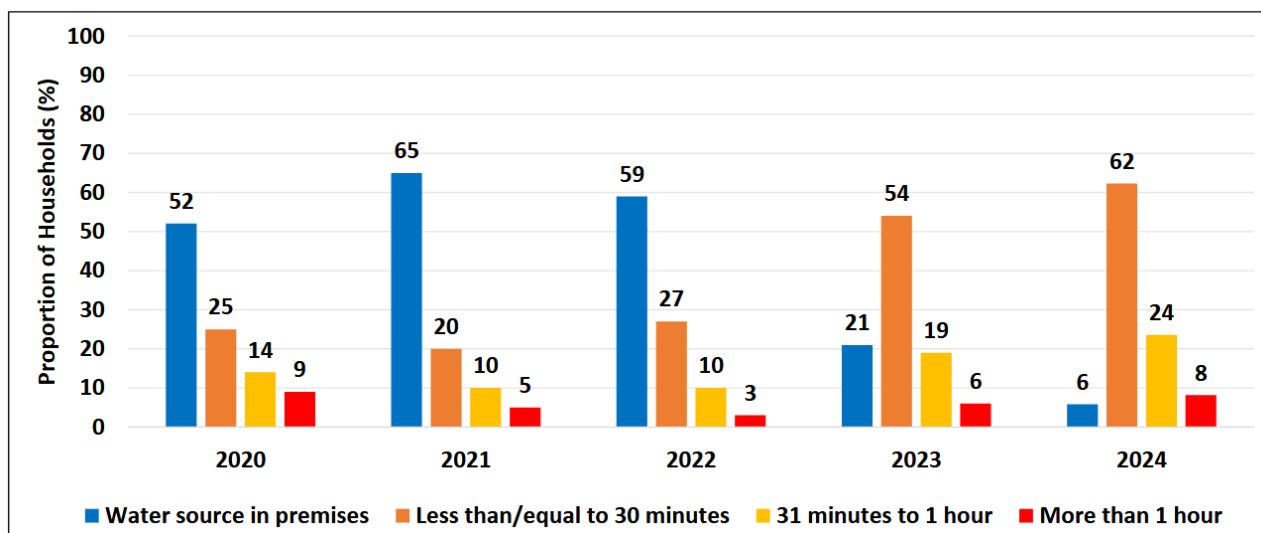


Figure 23: Assessment of rural households’ access to water, 2020–2022 compared to 2023–2024 El Nino years. Data: ZimLAC Rural Livelihoods Assessment Report 2024

Groundwater and irrigation

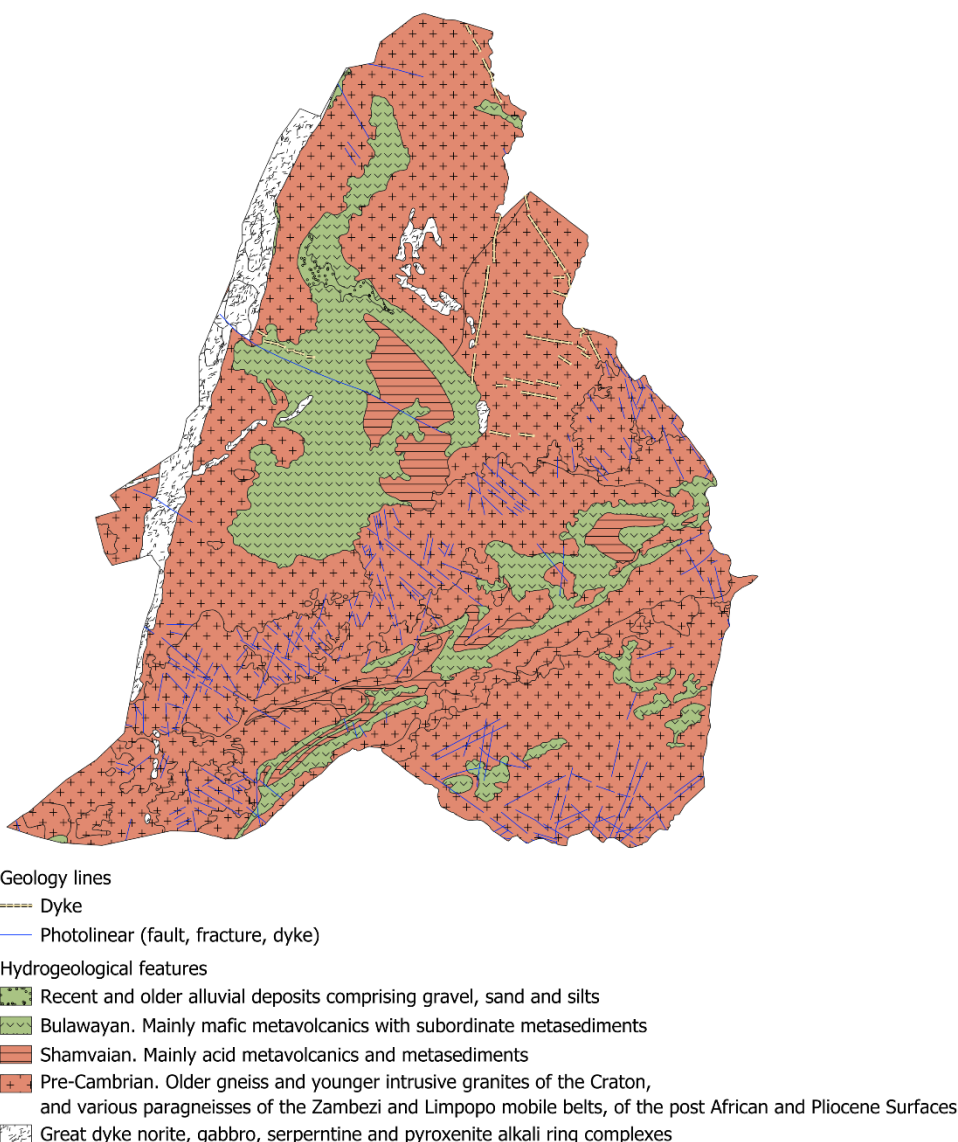
Zvishavane and Mberengwa suffer from multiple issues preventing efficient use of groundwater to negate the risks induced by rainfall fluctuation. The most major of them is local hydrogeology. The impermeable Precambrian basement aquifer covering the entire area is lowly fractured. As groundwater only exists in the fractures, in practice it leads to certain areas having very high borehole

failure rates and the average yields can be as negligible as 0,1 liters per second, too little for sustenance (Manyakaidze *et al.* 2024). Additionally, limited availability of operational and maintenance services has led to a third of the boreholes becoming partially or completely non-functional (Manyakaidze *et al.* 2024). Due to the minimal water yields and considerable increase of distances to water sources, conflicts at water points are expected to further increase in dry season and become especially prominent during El Nino (Figure 17, Mugiyo *et al.* 2023). This exposes locals and especially women to heat stress and health hazards, whilst taking time away from other important tasks.

Gona *et al.* (2022) have performed a GIS based assessment of climate impacts on water resources of the Runde catchment, on which Zvishavane and Mberengwa are located. However, their assessments are based on the estimates that rainfall will increase considerably in the medium term in both Zvishavane and Mberengwa, which goes against both historical precipitation trend of the area, and the international climate projections utilized in this report. Even with these factors preventing its direct use in the report, the study shows that the groundwater reservoirs in Zvishavane and Mberengwa region recharge slower than the ones on surrounding areas, combined with overall weaker groundwater potential than rest of the catchment. This effect is portrayed by the analysis in differing rainfall conditions. This coincides with analysis done by Manyakaidze *et al.* (2024) on the area's

hydrogeology. Figure 24 clearly illustrates the lack of fracturing of geological features in the Zvishavane district.

Figure 24: Hydrogeology of Zvishavane-Mberengwa. Data: GGRETA-3 project



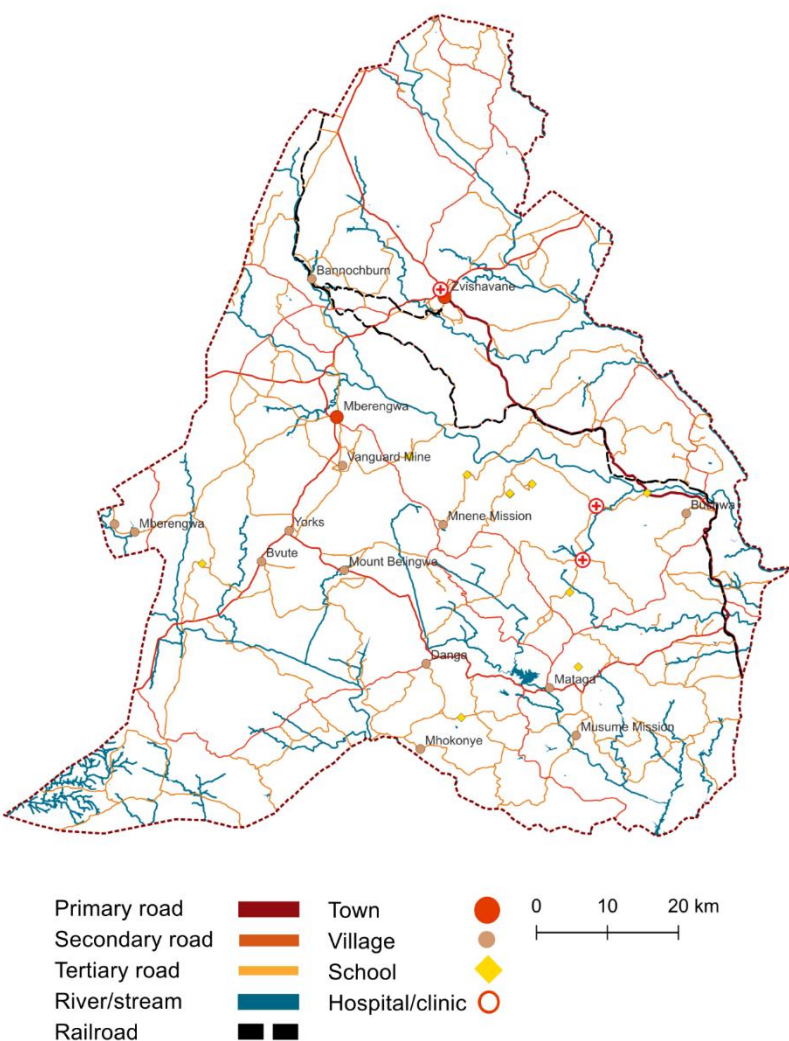
The increasing strain on water resources is expected to further increase the instability of smallholder agriculture (Mwadzingeni *et al.* 2022). A heavy reliance on climate-sensitive irrigation, poor hydrogeology, limited investment capability of the average farmer, as well as the lack of access to markets, contribute to the agricultural and water systems of Zvishavane and Mberengwa having little resilience to variability in rainfall. In addition, the weakness of local institutions further exacerbates the vulnerability of the poor farmers and especially vulnerable groups to extreme events.

Groundwater or rainfall-based smallholder irrigation schemes have been proposed as a primary solution to the increasing water risk posed by climate change to the agriculture of Zimbabwe (Mwadzingeni *et al.* 2022). However, these systems have proven to suffer various challenges mostly linked to poor management, lacking involvement of farmers, high reliance on public funding and politics, and partaking in the systems usually not being economically viable to the farmers, even if having a stabilizing effect on yields (Mwadzingeni *et al.* 2022). In the context of Zvishavane-Mberengwa, Pushak & Briceño-Garmendia (2011) assessed that the area, like most of Zimbabwe, has very low potential for rainfall collection-based irrigation. Instead, the region has the geographical potential to support large, dam-based irrigation schemes. This emphasizes the key problem with Zimbabwean agriculture, which is stable and profitable yields requiring substantial capital and expertise to achieve due to the need for active fertilization and irrigation.

Critical infrastructure and economy

Figure 25: Infrastructure in Zvishavane and Mberengwa, Data: OSM

Zimbabwe’s infrastructure is above its neighbors in many respects due to the progress done in 1960’s–1980’s, but during the last three decades it has suffered large scale decay from chronic lack of funding due to the nation’s economic situation (Pushak & Briceño-Garmendia 2011, Nhongo & Makunura ZCC). The nation’s economic situation is not expected to improve enough to even partially remedy these issues in the term this report considers. The rural road network is considered to be extensive and well interconnected, at least on paper, which is illustrated by figure 25. However, in practice the situation is far from what is portrayed on maps, and the decades of neglect have left everything except the most major roadways in very poor condition (Pushak & Briceño-Garmendia 2011, Nhongo & Makunura ZCC). In Zvishavane and Mberengwa only road links to mines are maintained. Maintenance and number of bridges is minimal, and crossing



rivers by unsafe means is common. The increase in flow of the rivers during heavy precipitation events has proven to pose threats to poorly maintained bridges, and to kids crossing rivers to school (Nhongo & Makunura ZCC). These issues will get exacerbated further by increasing population, leading to more strain on the existing infrastructure. Figure 27 presents the large impact the usability of rural tertiary roads has on the accessibility of much of the region, with the limits imposed on their use directly increasing the vulnerability of the rural population by limiting their access to healthcare, education and urban markets.

Access to cooling has a considerable effect on combating the health effects of projected increase in extreme heat. Reliable access to electricity is also one of the cornerstones of economic stability. Zimbabwe has estimated electricity production capacity of 2,240 gigawatts, substantially more per capita than its similar income peers, with around 50 % of population having access to electricity (World bank, Pushak & Briceño-Garmendía 2011). Around half is generated by the hydropower of the Lake Kariba dam, with its role in the nation's power generation and its water consumption further expanded by the installation of new generators in 2010's. Lake Kariba's surface levels have been recently threatened by increasing drought, with the levels on the lake reaching minimum limits for electricity production during dry seasons 2022 and 2024 according to Zambezi water authority. Due to the dam's significance to the nation's economy, Dube & Nhamo (2023) have studied the rainfall data and projections regarding the Zambezi basin feeding Lake Kariba. The study points that whilst climate change has led to increasing variability of waterfall, the trend in the catchment area does not show a decline on vast majority of regions feeding to the catchment. Based on available data, the waterflow to the reservoir has in fact increased during the last 50 years, with increasing evaporation due to higher average temperatures not having a significant effect to counteract this change. Thus, the researchers point that the recent problems with the water levels have been the result of increasing water use of the dams on Zimbabwe's and Zambia's sides of the reservoir, since hydropower has been unsustainably utilized to account for shortfalls in other power generation methods. Based on their research climate change has not affected the power production averages of the dam. However, the focus on single reservoir for most of the nation's power requirements shows a massive vulnerability to waterfall fluctuations in the catchment area.

World Banks review of Zimbabwe's economy (2025) projects potential yearly GDP loss of up to 12% due to effects of climate change. It emphasizes public coordination of mitigation efforts, primarily focused on stabilizing farm yields in case of droughts with irrigation infrastructure. Possible risks include cascading effects of droughts through the vulnerable electricity generation sector, to water pumping infrastructure, and to the general national economy. With the expected effects of climate change limiting already pessimistic nationwide economic prospects, risk management with infrastructural investment such as diversification of electricity production, improvement of condition of road infrastructure or irrigation schemes recommended by World Bank will be difficult.

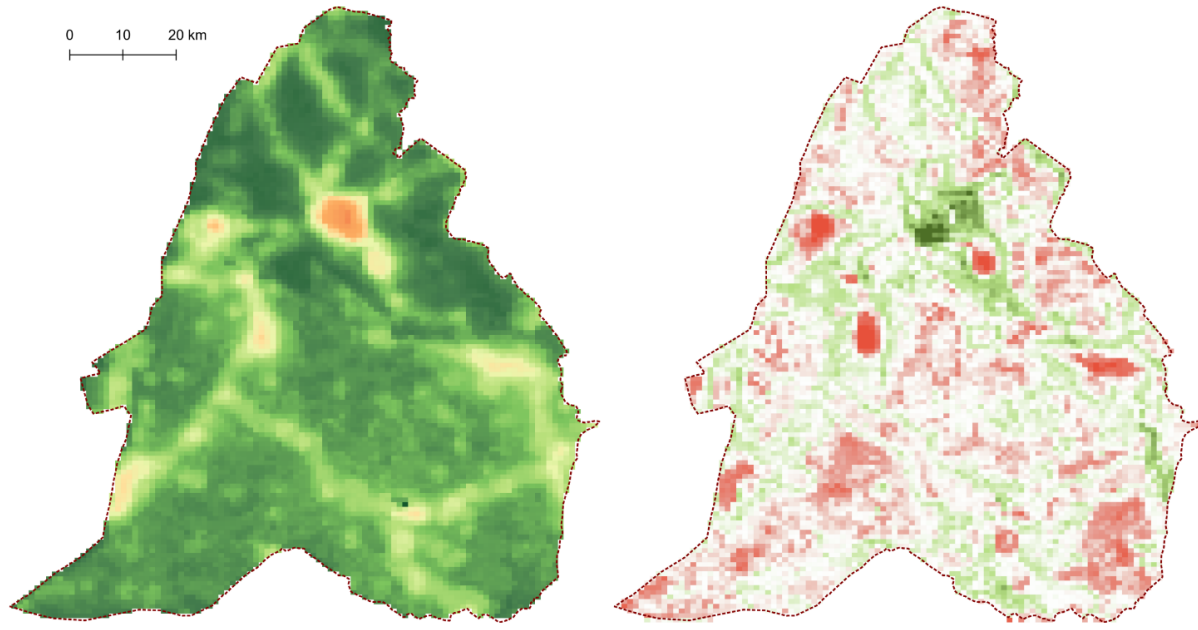
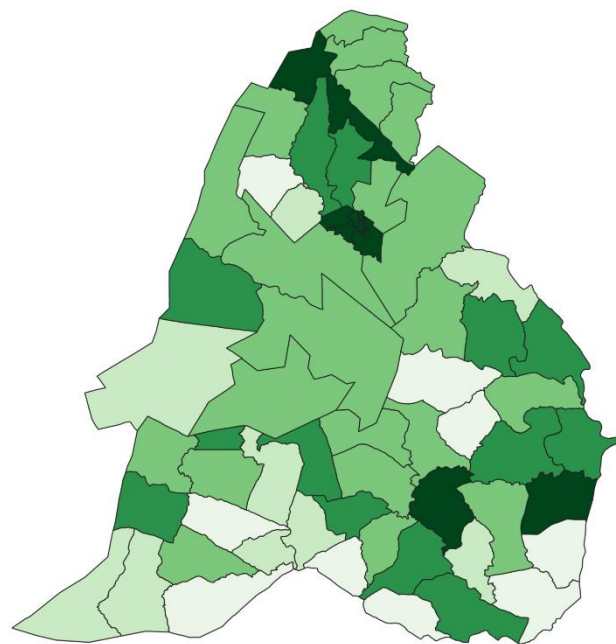
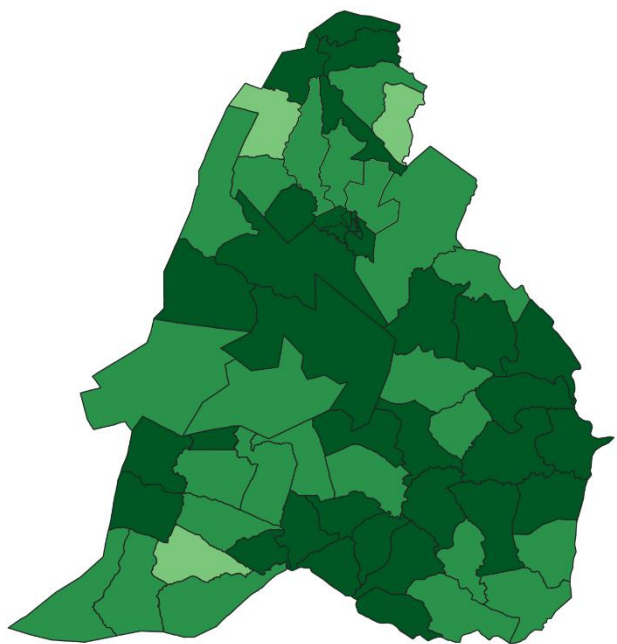
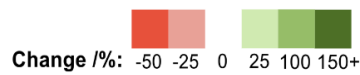
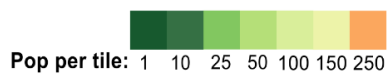


Figure 26: Current population distribution in Zvishavane-Mberengwa, and expected population change by 2050. Data: Zhuang *et al.* 2024

Gridded 2020 population estimate

Expected percentage change by 2050



Optimal scenario

Tracks and pathways not usable



Figure 27: Access index calculated on current roadways, population inside distance of 2 km or less of a road or a waterway, 2055 population estimate. Best case scenario with no impediments to movement, expected scenario with impediments outside main roadways. Data: Zhuang *et al.* 2024, OSM, utilizing World Bank Rural Access Index (RAI) method

Human health

Projected increase in heat extremes and decline in water security has wide ranging impacts on health situation in Zvishavane and Mberengwa. Extreme (1-in-100 year) heat-mortality seasons are expected to become more frequent, with non-extreme seasons becoming rare as the global temperature increase approaches 2°C (Lüthi *et al.* 2024). As vast majority of the people living in the area work outside, with most doing heavy labor, the effects of extreme temperatures are not only expected to

affect the livelihoods via decrease in productivity, but also negatively affecting health and further compromising stability of livelihoods (Dunne *et al.* 2013).

Possible increase in precipitation extremes would also favor the spread of waterborne diseases during the wet season, such as bacterial diarrhea and cholera (Bastin *et al.* 2024). Events caused by extreme rainfall have a history of causing local and nationwide disease outbreaks due to contaminated water sources. Cholera epidemics are a major problem in Zimbabwe, usually caused by contamination of wells due to heavy rainfall combined with poor sewage handling. These epidemics can have nationwide implications due to poor vaccination coverage and lacking water infrastructure. For example, the nation had been suffering from a major cholera epidemic from 2023 to 2024, which by April 2024 was reported to have impacted over 30 000 people with cases on all provinces.

Studies point that the increase in temperature creates more optimal conditions for tropical diseases, but long-term scenarios are difficult to predict and cannot be utilized to base accurate planning upon (Klepac *et al.* 2024). Certain trends exist, but Klepac *et al.* (2024) points to the number of variables and the unpredictable impact of developments in mitigation and countermeasures further complicating assessments. For example, constantly wet conditions created by steady precipitation and extreme events disrupting sanitation generally create the most optimal conditions for vector born tropical diseases, especially when combined with temperatures in 25–30 °C range. Mosquitoes as the vector for malaria and the parasitic agent, Plasmodium group, rely on optimally warm temperatures with them being in the upper 20–30 °C range. Based on temperature projections for Zvishavane and Mberengwa, the conditions for mosquitoes are expected to be more optimal by 2050's, with the duration of incubation shortened, and mosquitoes becoming infective much sooner (Rahmani *et al.* 2023). However, climate projections expect more concentrated rainfall combined with increased evapotranspiration, which is expected to lead to more contrast between wet and dry periods. Thus, the effect of climate change on vector born tropical diseases in the area is unclear.

Assessment of vulnerability of Zvishavane and Mberengwa to tropical diseases when compared to national or provincial context is difficult due to very limited availability of district level statistics and possible future changes. As a general trend, countryside lags behind urban areas in all health-related metrics, such as improved water sources (almost 100 % vs 60–70 %), and improved household sanitation facilities (95 % vs 50 %) with it being improbable that this divide will change in the future (Mashura 2024, Zimbabwe demographic survey). Distances to healthcare facilities in Zvishavane and Mberengwa are long, with walking being the primary form of transport and rural roads poorly, if ever maintained (figure 25, Pushak & Briceño-Garmendia 2011).

The direct impacts of increased temperatures on human health and the potential increase in waterborne disease outbreaks on the region leads to an increase in the risk to human health in the area. The rural poor are especially vulnerable to these impacts due to the considerable gap in water and sanitation infrastructure compared to urban areas, and worse access to health services. Increasing coverage of vaccinations against waterborne diseases and improved rural water handling are some of the ways to combat these risks, with increased access to electricity and cooling being the primary way to increase resilience to hazards posed by increasing peak temperatures. Zimbabwe's poor economic situation has led to stagnation or even a general decline of the nation's health

services, electricity grid and water infrastructure, which makes reducing this vulnerability more difficult (Pushak & Briceño-Garmendia 2011).

Human displacement

The districts of Zvishavane and Mberengwa suffer from a history of human displacement from the countryside due to combination of ENSO induced variation, naturally dry climate and poor local hydrogeology limiting ground water usage. Environmental unreliability has led to cyclical human displacement both within and away from the region (ZimStat 2022, IOM DTM Zimbabwe). Nationwide economic programs such as Pfumvudza/Intwasa conservation farming schemes have sought to address food insecurity and displacement drivers, but local and nationwide displacement events are still very common. Significant displacement events due to widespread crop failure have occurred throughout the region during the 2015–2016 and 2023–2024 El Niño, and droughts during 2018–2019 season (SADC FANR Vulnerability Report, FAO GIEWS). The effects of climate change on local water availability are expected to further exarate this unreliability, as it is expected to keep declining during dry season. The decreasing recharge rate of groundwater reservoirs due to less annual rainfall will further affect the viability of solutions such as smallholder irrigation schemes, which have often been proposed as the most effective solution to reduce vulnerability of agricultural income (Mwadzingeni *et al.* 2022, Gona *et al.* 2022). However, the projections by Zhuang *et al.* (2024) illustrated by figure 26 clearly support the historical trend of displacement to urban centers like Zvishavane continuing at the cost of the rural areas.

Rainfall and flooding

The historical variance in precipitation combined with ENSO has a distinct impact on the flood risk profile of Zvishavane and Mberengwa. ENSO alone, in both phases, warm El Niño and cold La Niña, is the phenomena with the greatest effects on variations in Zimbabwe's climate, with this applying to Zvishavane-Mberengwa area as well (Mamombe *et al.* 2016, Ceron *et al.* 2022). The consensus between researchers on the changing climates impact on ENSO itself is mixed due to the phenomenon's large internal variability, with the latest research suggesting that ENSO strength may have increased since 1960's (Cai *et al.* 2023). Strong El Nino and La Niña are also considered to amplify the local effects of climate change, leading to increasing prevalence of extreme events (Funk *et al.* 2021).

Periods of increased rainfall intensity are linked to higher peak flow in rivers, overwhelming drainage and the resulting flash floods. In banks of Zimbabwe's main rivers, such as Runde passing through the region, flash floods are common (Samu & Kentel 2018). Soil's ability to infiltrate water is of key importance in preventing flash floods in rural areas and in developing urban areas with minimal water management infrastructure. Generally, soil with natural vegetation cover has the most infiltration capacity (Saco *et al.* 2021). Deforestation and damage to natural land cover are major issues in Zimbabwe and further contributes to the prevalence of flash floods (Samu & Kentel 2018).

Karimanzira (2018) studied local experiences of climate-based hazards such as flooding. The interviews revealed that riverine floods have caused extensive damage to the area, with 2014 floods affecting 686 people in over 100 households. Ward 16 covering Gwemombe is separately mentioned as having suffered extensive agricultural damage. This matches with flood hazard estimations in figure 28, with Gwemombe area being one of the ones expected to be at highest risk in the future. Based on

reports by Karimanzira (2018) and Nhongo & Makunura (ZCC), the damage done by flooding is primarily to farmland with crops being inundated. This is especially severe as maize is farmed during the wet hot season, with flooding compromising livelihoods in addition to hazards to health and property.

Poor bridge infrastructure on the area has been reported to be unable to cope with the unexpectedly heavy increases in river flow, leading to unsafe crossings and possible collapses (Nhongo & Makunura ZCC). In addition, schoolkids crossing rivers and getting caught by the flow is a major issue on the area, with increased flow leading to children being endangered or being cut off from schooling (Nhongo & Makunura ZCC). In addition to flooding, heavy rainfall and associated winds themselves pose a threat to the low-quality dwellings in the area.

Flooding in the area poses a risk to both food security and travel. Consideration of measures to manage this risk is affected by multiple factors. First is the expected continuing pattern of displacement from the countryside due to unreliable incomes. This leads to the population growth in the region being concentrated on larger towns such as Zvishavane, with large areas on the countryside having a negative growth trend (figure 26). This trend will lead to less people being exposed to riverine floods. Second is the increasing need for water reserves to combat possible dry periods during the cropping season. This will promote the increasing proximity of agriculture to bodies of water for irrigation, which are mostly rivers in the area, but also possible loss of income due to flooding. Solutions to managing flood risks to crops excluding expensive infrastructure projects such as dams or channels are mostly limited to margins of safety based on local mapping of hazard prone areas. However, this will limit the farmable area and income of both private and communal land for only an increase in certainty. Thus, the best local option would be the increase of resilience by diversification of income in flood prone areas.

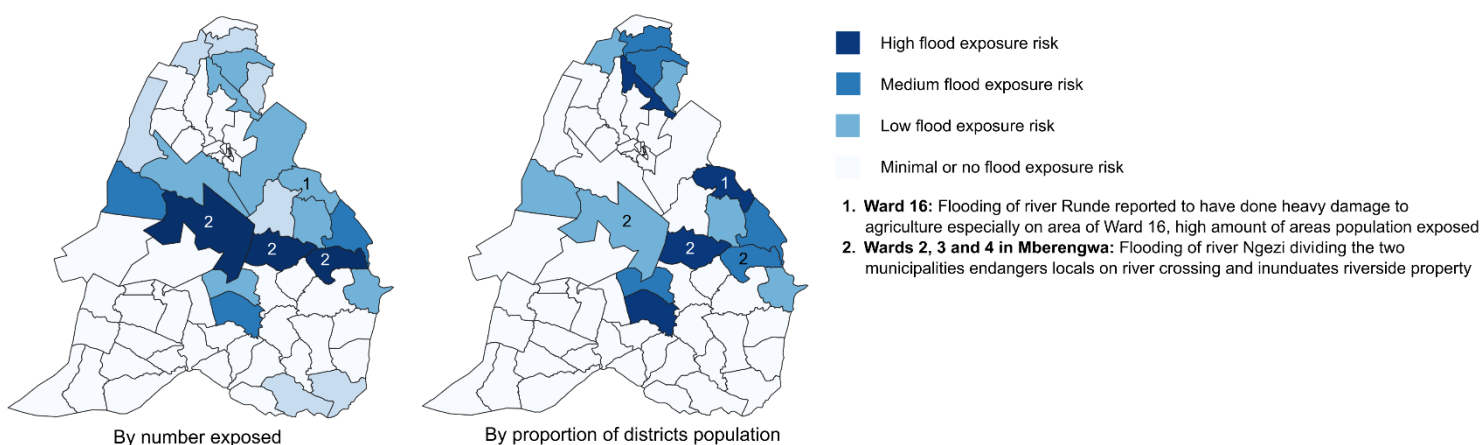


Figure 28: Flood exposure under SSP3–7.0 in 2055, two-year flood extent. Riverine and coastal flood risk ranked by percentage of affected population per municipality. Landslide risk by areas affected by rain-initiated landslide hazard, classes by natural breaks (Jenks). Data: Aqueduct, Zhuang *et al.* 2024, Karimanzira 2018, Nhongo & Makunura ZCC

Cambodia, Ratanakiri

Country overview

Cambodia, situated in mainland Southeast Asia between latitudes 10°N and 15°N, spans 181 035 km² - comparable to the size of Belarus. The country is administratively divided into 24 provinces and the special municipality of Phnom Penh, the capital. Geographically, Cambodia is dominated by the low-lying Tonlé Sap Basin, which seasonally floods around Southeast Asia's largest freshwater lake. Elevations rise to the southwest in the Cardamom Mountains peaking at 1,813 m and to the north along the Dângrêk Mountains bordering Thailand. The fertile floodplains of the Mekong River support most of the agricultural activity.

As of 2024, Cambodia's population reached 16,9 million, with macro trends estimating the annual growth rate to be 1,4 %. An estimated 74 % of inhabitants reside in rural areas, though urbanization is rapid, centered on Phnom Penh with population upwards of 2,2 million. Khmer comprise ~ 95 % of Cambodian population, alongside minority Vietnamese, Cham, Indigenous, and Chinese communities. Theravada Buddhism is the state religion.

Cambodia's economy has been growing rapidly, with GDP reaching \$46 billion in 2024, more than doubling from 22 billion in 2014 (IMF). The growth has been driven by garment exports (70 % of total exports, employing 1 million), tourism (6,6 million visitors pre-pandemic), and agriculture (35 % of employment). Economic risks include overdependence on garment manufacturing, land tenure insecurity, and corruption. Rural poverty remains elevated due to the benefits of industrialization being concentrated on cities. According to UN multidimensional poverty index 2024, 16,6 % of Cambodia's population suffer from multidimensional poverty, with lack of education being the primary contributor. The nation ranks in the medium human development category with a rating of 0,6 (UNDP 2024). Considerable gains on all indicators comprising the index have been made during the last 30 years, though the nation still lags behind East Asian averages (UNDP 2024).

The nation is ranked 55th of 179 on the Fragile States Index in 2024, with Cambodia exhibiting a historical trend of decreasing fragility due to economic progress. However, the ND-GAIN Index still classifies Cambodia as one of worlds most vulnerable countries to effects of climate change, with a ranking of 161. The ranking on the index stems from both high vulnerability and lacking readiness. The main climate threats facing the nation include flash floods on main rivers such as Mekong, large scale coastal erosion, droughts and a trend of increasing temperature extremes.

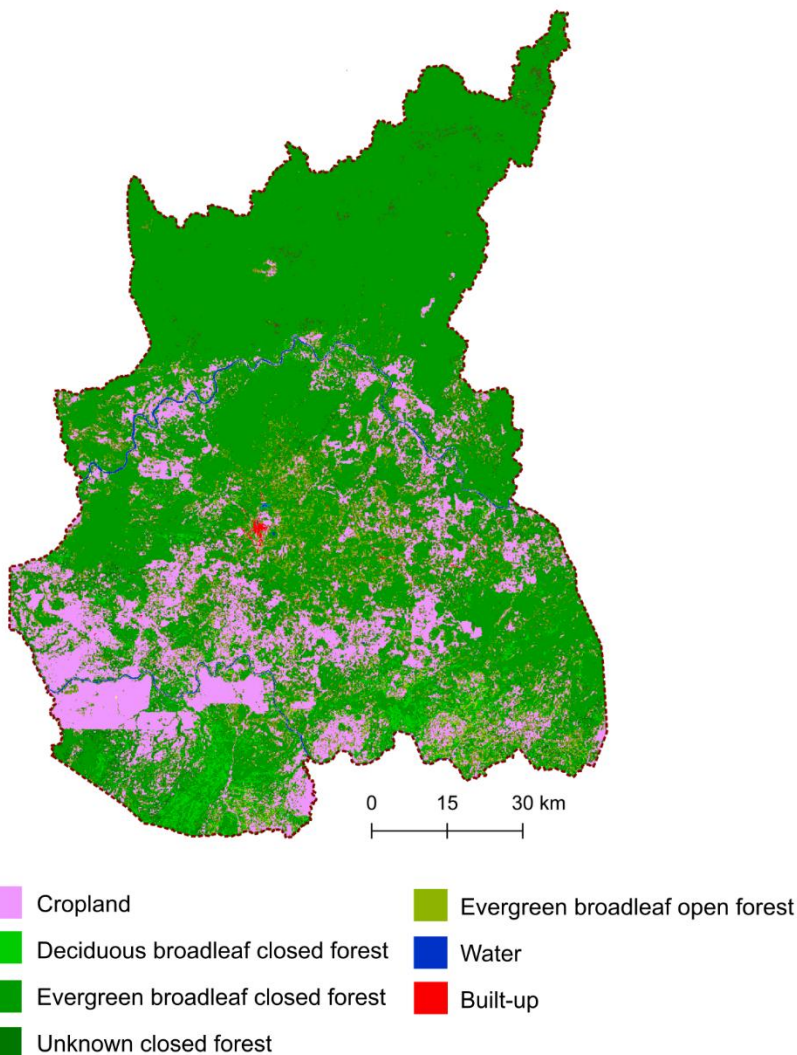
Region overview

Ratanakiri Province is situated in northeastern Cambodia between 13°N and 14°N latitude, bordered by Laos to the north and Vietnam to the east. With an extent of 10,782 km² the province comprises 8 districts and one municipality, with Banlung at ~25,000 residents as its capital. The landscape is defined by densely forested volcanic plateaus, the Dângrêk Mountains along the northern frontier, and the Sesan and Srepok River basins, tributaries of the Mekong. Basaltic soils support Cambodia's largest remaining primary forests, whilst the area is dotted by crater lakes like Yeak Laom. According to Global Forest Watch, the province has suffered from considerable deforestation during the 2000's, with the area losing 34 % of its tree cover during the last two decades.

Ratanakiri is home to approximately 217,000 people in 2023, with over 85 % residing in rural villages. Indigenous groups constitute a majority (~ 65 %). Historically Ratanakiri province served as a headquarters area of the Khmer Rouge from 1966 onwards, exploiting local resentment of the central government. In 1970, Ratanakiri was subjected to a massive US bombing campaign, which left unexploded ordnance on large parts of the area. After the fall of the Khmer Rouge in 1979, the area was left under neglect by the central government. At early 2000's, a change in policy has led to a mass immigration of lowland Khmers to the area with some improvements in infrastructure with a policy focused on plantation agriculture and tourism. The local economy also reflects this spatial inequality. Ratanakiri has a rapidly growing tourism sector driven by local waterfalls and indigenous villages. However, beyond the provincial capital of Banlung 80–90 % of households practice agriculture and forestry, with rice being the staple crop. Since 2007, economic land concessions covering 22 % of the province have been granted for rubber, cashew, and cassava plantations, displacing 15,000+ indigenous people (Bugalski & Thuon 2015). Rubber plantations employ <5 % of residents but occupy 150,000 hectares, exporting exclusively to Vietnam (Bugalski & Thuon 2015).

Due to the areas neglected and conflict-ridden history, human development indicators lag below Cambodia's average. However, even in the most remote regions like Ratanakiri the progress made during the last two decades has been considerable. Indicators such as infant mortality have declined from 121,7 per 100 000 in 2005 to 36,9 by 2022 (CDHS mortality report 2024). Literacy rate has risen from 27,1 % in 2005 to 65,5 % in 2019, but the rates in the province remain Cambodia's second lowest (Census 2019).

Figure 29: Landcover of the Ratanakiri province. Data: Copernicus Land Cover 2019

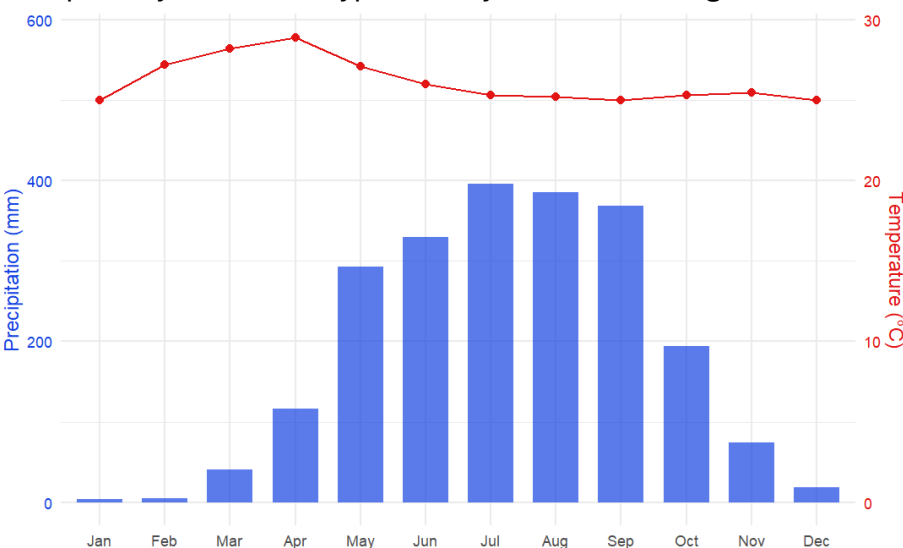


Observed and projected climate

Present Climate

Ratanakiri Province, located in northeastern Cambodia, experiences a tropical monsoon climate heavily influenced by its geography being of primarily 200–700m plateau, proximity to the Annamite Range, and the seasonality of Asian monsoon systems. Mean annual temperatures are warm, typically ranging from 24 °C to 28 °C, with relatively small seasonal variation due to its tropical latitude. However, temperatures can drop noticeably in higher elevations, especially during the cool season. Precipitation in Ratanakiri is primarily driven by the Southwest Monsoon, which brings moist air from the Indian Ocean and the Gulf of Thailand between May and October. The region experiences two primary seasons, them being a single, intense rainy season approximately from June to October and a pronounced dry season from November to May. Annual precipitation sums are high, generally ranging from 1800 mm to 2500 mm across the province, with orographic enhancement leading to slightly higher amounts on the windward slopes facing the southwest.

El Niño is a climate pattern that describes the unusual warming of surface waters in the eastern tropical Pacific Ocean. El Niño is the warm phase of the El Niño-Southern Oscillation (ENSO) phenomenon. La Niña, the cool phase of ENSO, is a pattern that describes the unusual cooling of the region’s surface waters. El Niño and La Niña are considered the ocean part of ENSO, while the Southern Oscillation is its atmospheric changes. El Niño has an impact on ocean temperatures, the speed and strength of ocean currents, the health of coastal fisheries, and local weather from Southern Africa to Southern America. El Niño events occur irregularly at two- to seven-year intervals. However, El Niño is not a regular cycle, or predictable in its amplitude. In Cambodia, El Niño events often lead to delayed monsoon onset, reduced total rainfall, and increased risk of drought and heatwaves, particularly during the dry season. Conversely, La Niña events are typically associated with an earlier or stronger monsoon, above-average rainfall, and heightened risks of flooding and landslides, especially in the hilly terrain. While ENSO events influence broader Southeast Asian climate variability, their direct impact on Ratanakiri’s precipitation extremes is less consistent than in Pacific-facing regions; however, intense La Niña phases often correlate with above-average monsoon rainfall and heightened flood risk (Fujibe *et al.* 2016). Ratanakiri is protected from the direct impacts of tropical cyclones and typhoons by the surrounding mountains and highlands, but the region has



occasionally been affected by remnants of tropical cyclones originating in the Northwest Pacific, which can bring extremely heavy rainfall and destructive winds, primarily during the late rainy season.

Figure 30: Annual precipitation and temperature averages in Ratanakiri province, Data: weatherandclimate.com

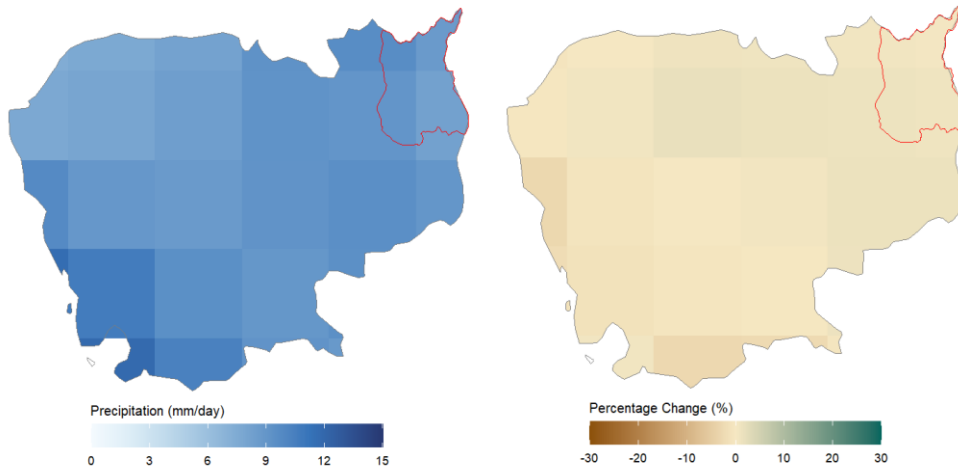
Climate trends

Analysis of available data and regional studies indicate a clear warming trend in Ratanakiri over recent decades. Mean annual temperatures have increased by approximately 0.8 °C to 1.2 °C since the mid-20th century, consistent with broader warming trends across mainland Southeast Asia (IPCC AR6). The frequency and intensity of hot days and heatwaves have increased, while cooler nights and cold spells have become less common (Fan *et al.* 2024).

Analysis of precipitation trends between 1991–2021 points at increasing trends of consecutive dry and wet days, except on the northern Mekong area (Pen *et al.* 2024). Around Strung Tren and Ratanakiri an increasing trend of rainfall, but also at decreasing trend of consecutive dry days and consecutive wet days is detected (Pen *et al.* 2024). Furthermore, the duration and severity of droughts during the dry season, particularly during El Niño years, may have increased (Sun *et al.* 2024). On precipitation, the high natural variability, especially when driven by ENSO makes long-term trends in total annual rainfall less clear-cut (Chang *et al.* 2012, Alizadeh & Mousavizadeh 2025). Whilst the consensus on effects on climate change on ENSO vary due to its complexity, research points at ENSO's amplitude strength increasing by around 10 % since 1960's, suggesting that stronger and more frequent events are not solely due to large internal variability (Cai *et al.* 2023).

Projected precipitation

Estimates for the Mainland Southeast Asia points only at a weak increase in summer rainfall under global warming (Wang *et al.* 2025). This is due to the mutually compensating effects of the increase in atmospheric moisture caused by increasing temperatures and the weakening of summer monsoon circulation. By 2055, projected precipitation amounts under SSP3–7.0 scenario show a slight positive yearly precipitation trend on north-eastern Cambodia, including Ratanakiri province. The precipitation patterns are strongly regional, with the models' predicting a slightly wetter rainy season for western Cambodia, and in northern parts of Ratanakiri, which is one of the only regions where rainfall is expected to increase during both seasons. Decrease in rainfall in wet season is projected to be minimal, which coincides with the historical trend of intensification of rainfall (Sibinda *et al.* 2019, Sun *et al.* 2021). The models point to an increase of extremes in seasonality in western regions of the country, with projected dryer dry season and wetter wet season, in contrast to eastern provinces where the trend is towards a slightly wetter climate. This trend is especially prominent in Ratanakiri. The estimates provided by the IPCC projections point to somewhat conflicting outcomes compared to assessment of climate changes impacts on rainfall in Cambodia's third national communication on climate change, where the general short-term trend is expected to be a national increase of rainfall. Especially the regional variance is noticeable, with the data utilized on this report pointing to the wetter trend being distinctly focused on central and northern parts of the country, whilst the data used in the national communication has a distinct focus of increase on the Southeastern Koh Kong province area. This emphasizes that in the short to medium term, clear directional trends remain difficult to determine due to, among other things, model uncertainty and considerable variety caused by ENSO. Thus, the excerpts considering rainfall taken from the climate models as part of this report are to be taken as directional guidance only.



Figures 31 and 32: Projected seasonal precipitation change in wet season (June to October) and dry season (November to May), Cambodia, comparison between 1971–2000 baseline and 2050–2060 projected SSP3-7.0 average. Data: Iturbide *et al.* 2022

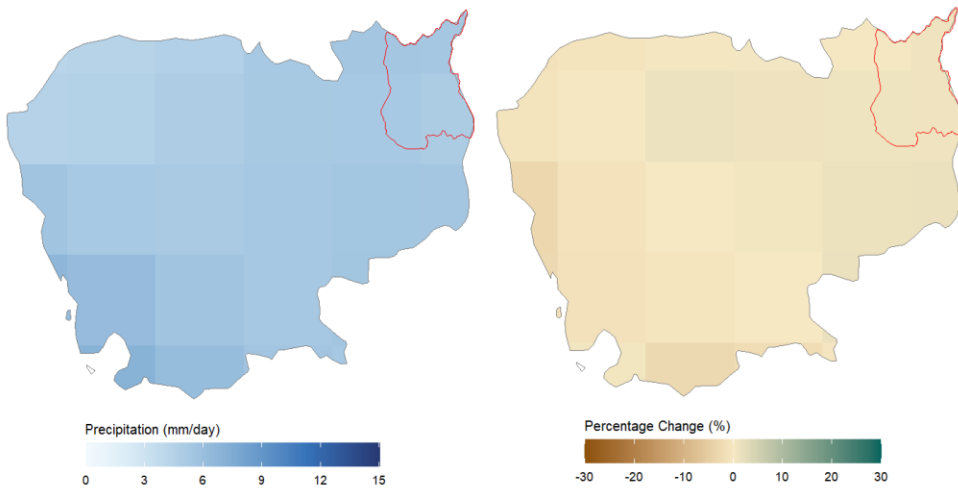
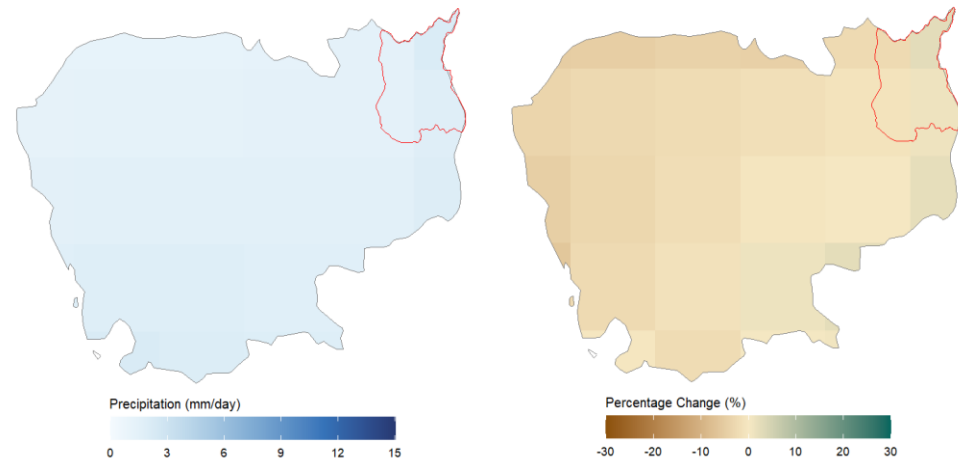


Figure 33: Annual daily rainfall averages and projected annual precipitation change, Cambodia, comparison between 1971–2000 baseline and 2050–2060 projected SSP3-7.0 average, Data: Iturbide *et al.* 2022

Projected temperature

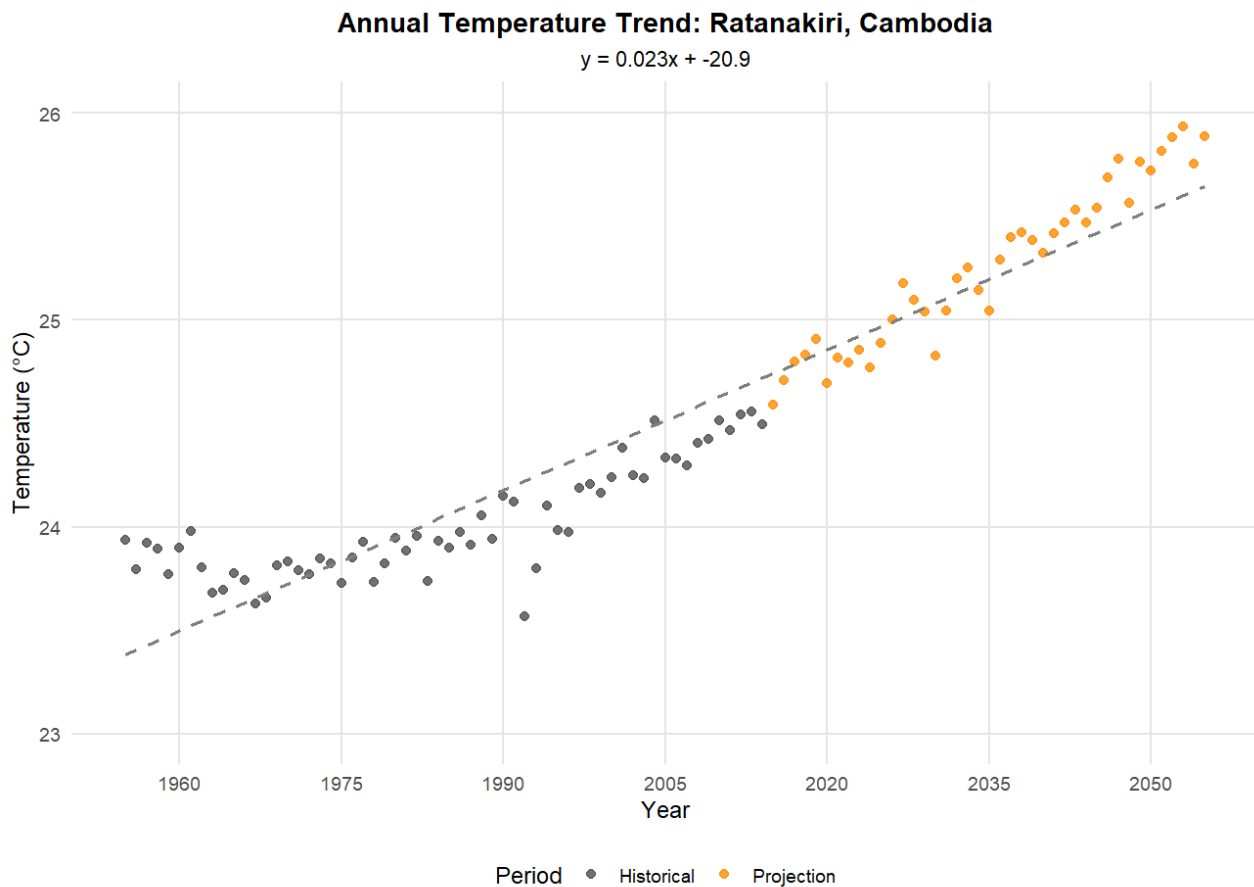


Figure 34: Annual temperature trend and future temperature projection, SSP3-7.0, Ratanakiri province. Data: Iturbide *et al.* 2022

The mean average temperature in Ratanakiri province under SSP3-7.0 scenario is projected to shift by 1,1 °C for 2055 when compared to 2015–2025 average, and by 1,95 °C when compared to 1971–2000 average (Figure 34, Iturbide *et al.* 2022). Peak temperature increases will affect the entire nation (Figure 35). However, their magnitude will vary due to Cambodia’s topography and local climates, with the expected pattern of increase of hot days following the local historical climate trends. The increase of hot days is distributed quite evenly across the nation, with northern Ratanakiri being one of the least affected areas due to the mountains of Annamite range altering local climate conditions. The general nationwide prediction by 2055 is that the prevalence of very hot days will double in most areas when compared to the 1971–2000 baseline (figure 35).

Potential evapotranspiration is the amount of water that would be evaporated and transpired if sufficient water was available at and below the land surface. Higher evapotranspiration can reduce the fraction of precipitation that flows over land and into streams and rivers. Thus, it affects the water supply and the amount of surface water available for agriculture. Long-term shifts in recharge patterns can change groundwater levels and subsequently groundwater surface water interactions and soil moisture. Since warmer air can hold more water vapor, it is expected that global warming will increase potential evapotranspiration in most regions of the world. In line with this expectation, hydrological projections for Cambodia indicate a continuous rise of potential evapotranspiration under SSP3-7.0. Potential evapotranspiration is projected to increase by up to 8 % in the northeastern

provinces, and by 4 % on Ratanakiri area. An increasing trend in potential evapotranspiration can be observed in entirety of Cambodia with high agreement from research papers (e.g. Fan *et al.* 2024). Certain regions which already experience high rates of potential evapotranspiration, such as the northwestern provinces, are expected to suffer the most from the percentual increase in evapotranspiration. The PET data is downscaled from larger raster size simulation data, and a single pixel deviance can show a large area effect on the map. The anomaly of negative evapotranspiration in Stung Treng province coincides with the location Lower Se San 2 dam. However, the water body of the reservoir is expected to lead to an increase in evapotranspiration, not decreasing it. This is an especially interesting phenomenon as the models are based on historical data, and the dam was finished in 2018.

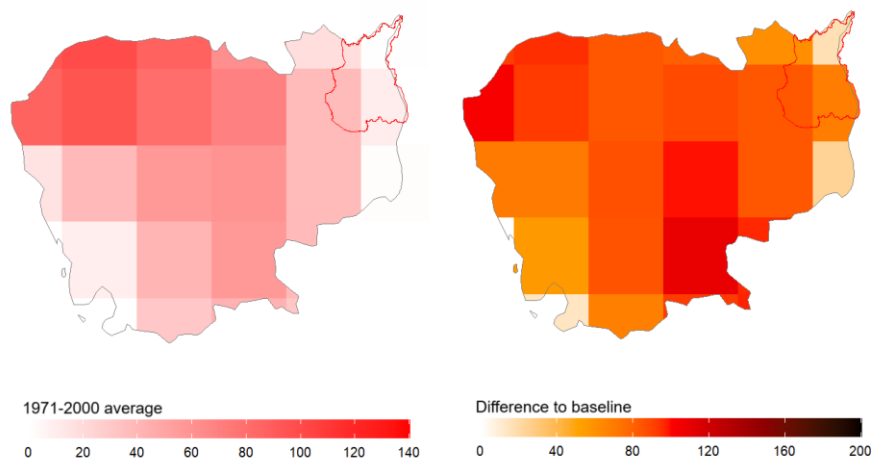


Figure 35: Projected increase in annual average of hot days (maximum temperature over 35 °C) in 2055 compared to 1971–2000 baseline, SSP3-7.0 projection. Data: Iturbide *et al.* 2022

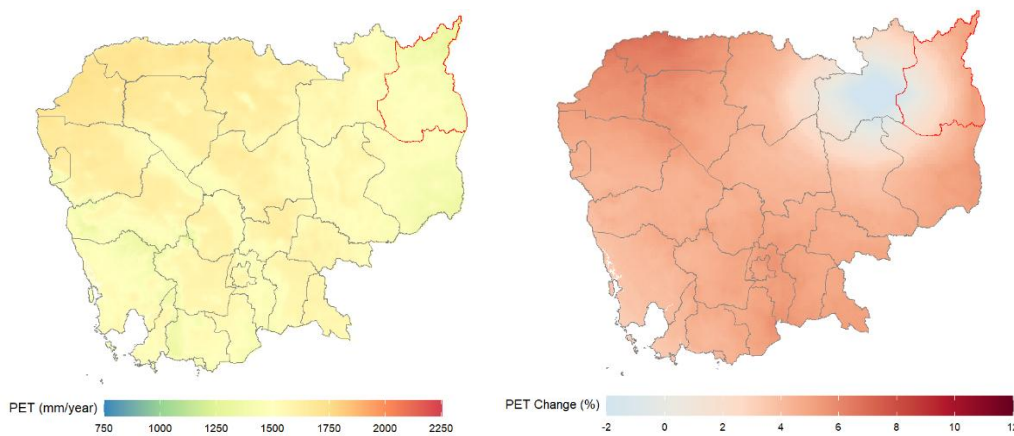


Figure 36: Projected change in potential evapotranspiration in Cambodia between 1971–2000 baseline and 2041–2060 projected SSP3-7.0 average, CMCC–ESM2 model, Data: global AI-PET database

Flooding, landslides and human displacement

Ratanakiri is cut by two rivers feeding into Mekong, Sesan and Srepok. Both rivers originate from Vietnam, with Sesan being regulated right over the border by Sesan 4 dam. The banks of these rivers are primarily affected by flash floods, which usually happen after heavy rainfall in the monsoon season. In addition to flooding brought by Southwest Monsoon, which delivers most of its annual rainfall between May and October, this phenomenon can be compounded by occasional tropical depressions and typhoon remnants from the South China Sea (MRC 2023). Intense La Niña phases often correlate with heightened flood risk (Fujibe *et al.* 2016).

Cambodia has a long history of extreme flood damage, with major floods affecting 10–20 provinces and the lives of hundreds of thousands of people. Examples of these which also have affected Ratanakiri have been the 2013 flash floods and 2009 typhoon Ketsana's aftermath. Storm related events and flash floods are the primary factor for internal displacement in Cambodia, with estimated countrywide number of 15000 displaced by 2021. However, no systematic reporting or databases exist of displaced people, which makes regional analysis of the effects difficult and reliant on news reports or local interviews (internal-displacement.org). Based on interviews with Pich Yek from Felm's partner organization ICC and local news reports, floods in the area can affect hundreds per event, causing damage by not just directly affecting property, but also via contaminating groundwater in the affected areas.

Wang *et al.* (2025) estimated based on climate models that the summertime rainfall in Mainland Southeast Asia is not expected to have major increases due to climate change. This is due to the mutually compensating effect result of the increase in atmospheric moisture caused by increasing temperatures and the weakening in summer monsoon circulation. Similar effects are presented by figure 30. Based on these projections and the local trend of dispersing rainfall, it is unlikely that climate change will have a major impact on riverine flood hazard in the area.

Global landslide map by World Bank categorizes Ratanakiri province to have a rainfall induced landslide risk on the slopes of northwestern parts of the province. Pich Yek confirms that Ratanakiri has a history of minor landslides, with land clearance next to rivers creating additional hazards and landslide events. The risk escalates during prolonged or intense rainfall, significantly exacerbated by widespread deforestation for plantation agriculture, unregulated land clearing, and settlement on the slopes (Seng *et al.* 2021). While comprehensive national landslide inventories are limited, studies in Cambodia's highlands indicate precipitation, particularly cumulative rainfall over days or weeks, is the primary trigger for slope failures, with land cover change being a critical amplifying factor (Auer *et al.* 2016). Analysis of precipitation trends between 1991–2021 on northern Mekong area in Stung Tren points at an increasing trend of rainfall, but also at decreasing trend of consecutive dry days and consecutive wet days (Pen *et al.* 2024). This fits with the trend showcased in figures 30 and 31 for the area, whilst also pointing at a potential reduction in extreme rainfall and droughts. Even if the change is small, it is still considered positive against the backdrop of worldwide trend of increase of extremities in rainfall. On medium term considered by this report, the increase in landslides due to climate change can be considered minimal, though research suggests total waterfall matters more than rainfall intensity (Ceron *et al.* 2022).

Ratanakiri vulnerability to both riverine flooding and landslides is exacerbated by the projected population growth in the area, escalated due to settlement initiatives. Its population is heavily concentrated along the Sesan and Srepok rivers due to agricultural dependence and limited road access in the hinterlands (figure 39). Population growth projections suggest continued expansion in these high-risk zones, mirroring current settlement patterns (figure 38). Villages and towns with inadequate drainage, freshwater access and housing construction are disproportionately vulnerable. The most vulnerable areas to flooding can also suffer repeated inundation, worsening vulnerability. Rural communities lacking sanitation and safe water sources face heightened health risks post-flooding due to water contamination (WHO 2019).

As the projections and current trends point to rainfall during the monsoon season following historical trends without considerable intensification being detected by research, it is expected that climate change has only an insignificant effect on possible intensification of flash floods and landslides in Ratanakiri region during the next 30 years. However, the projected population growth and the trend of increasing damages to natural land cover from plantation agriculture will lead to more people and property being at risk to rainfall induced hazards in the future.

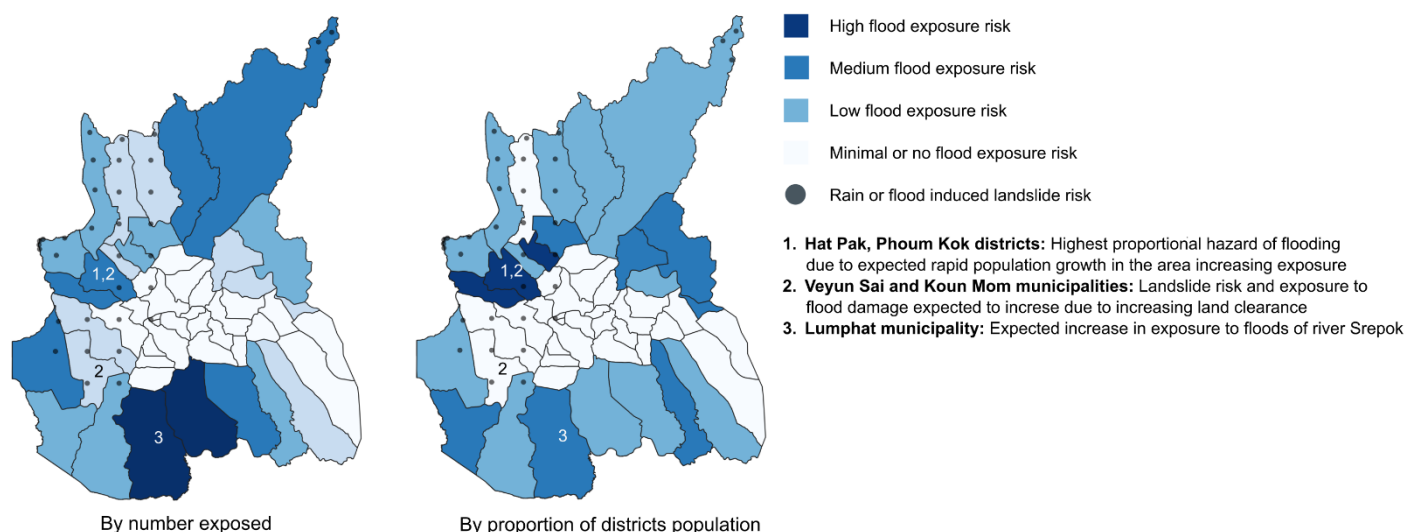


Figure 37: Flood exposure and landslide risk under SSP3-7.0 in 2055, two-year flood extent. Riverine and coastal flood risk ranked by percentage of affected population per municipality. Landslide risk by areas affected by rain-initiated landslide hazard, classes by natural breaks (Jenks). Data: Aqueduct flood hazard maps, Zhuang *et al.* 2024, Pich Yek ICC, World Bank landslide dataset

Critical infrastructure, agriculture, and economy

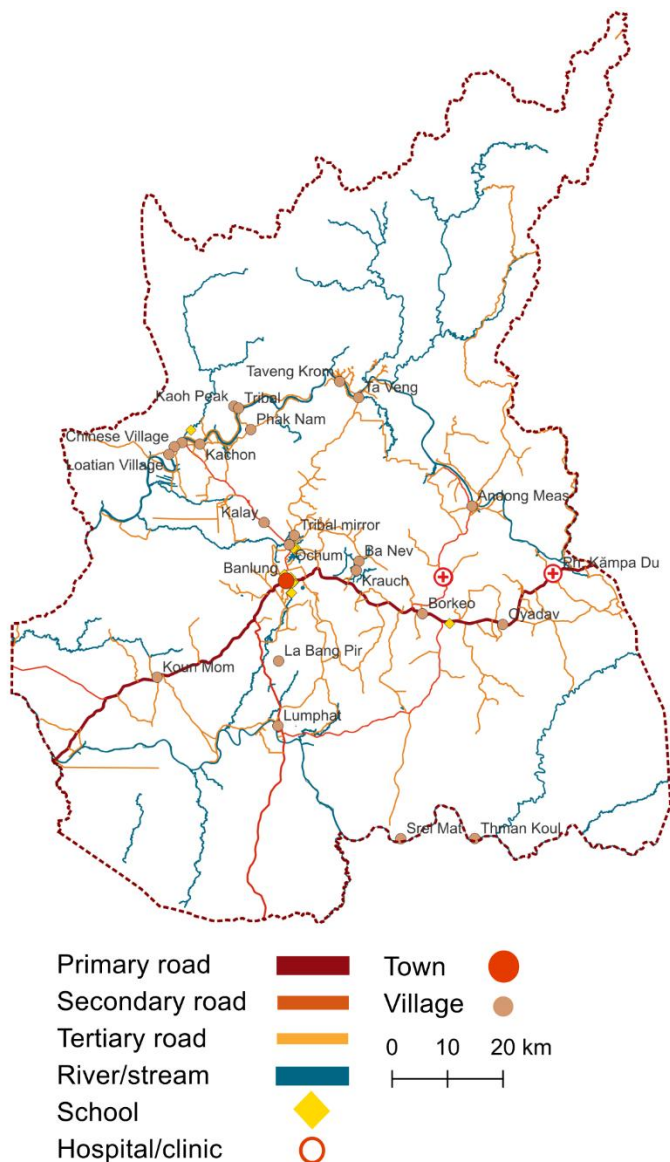


Figure 38: Infrastructure in Ratanakiri, Data: OSM

As 90 % of the area's population is employed in agriculture and other vulnerable sectors with subsistence farming being very common, the impacts of climate change get directly translated into insecurity of local way of life (Census 2019). Ratanakiri being one of the poorer provinces in Cambodia with 25 % living under the national poverty line emphasizes vulnerability (IDpoor). The generally positive economic trend of the country is expected to reduce some of the risk brought by rural poverty and help with adaptation to rising temperatures, even if the benefits are heavily skewed towards larger cities. Since the increase of drought due to lack of rainfall in the region is unlikely, the main strain on agriculture is the expected increase of hot days and evapotranspiration. The staple crop of the area is rice, with diversification to other crops such as maize being common.

Process based models such as AgMIP projections, using experimental farms for data and researcher-defined adaptation rules, generally tend to predict global increases in

yields as temperatures increase (Hultgren *et al.* 2025). The expected long-term impacts of climate change on global and East Asian yields also vary considerably between different research (Rosenzweig *et al.* 2014). Whilst the previous estimates are theoretically possible, Hultgren *et al.* (2025) aimed to reflect actual conditions across diverse socioeconomic contexts and capacities for adaptation with their research. This approach has produced considerably different results, with an estimated decline of 4,4 % in calory supply per 1°C of global temperature increase, even when accounting for adaptation and Co2 fertilization (Hultgren *et al.* 2025). Li *et al.* (2025) also observed a trend of declining national calory supplies, with the damage rapidly scaling between heating scenarios. The study expects the decline in rice yields to vary from -2,7 % under SSP1-2.6, to -9 % under SSP5-8.5 by 2100 when compared to 2015 average. Li *et al.* (2017) studied rice yields in Mainland Southeast Asia, and projects a 10,26 % decrease in yields per 1°C increase in temperature. According to the study, in Cambodia the yields are estimated to decrease between 10,1-12,2 % between medium and high heating scenarios by 2041-2050 when compared to 1991-2000 baseline, with Co2 fertilization considered (Li *et al.* 2017).

As climate change in Mainland Southeast Asia and Cambodia is characterized by delay to the commencement and end of the wet season, adaptation to the phenomenon by altering the planting dates has been the primary mean of combatting the effects. This form of adaptation largely negates negative effects climate change has on yields (Li *et al.* 2017). Adoption of rice variety that is tolerant to a 2°C increase in temperature has minor impact (less than 0.5 %) on rice yield for all countries in the area, suggesting that temperatures themselves have little effect (Li *et al.* 2017). Water stress is the most major contributing factor, with irrigation systems considered to lead to additional 7,9–19,8 % increases in rice yields. However, even if yields are not expected to decline, the increase of average temperatures and hot extremes is expected to have a negative impact on efficiency of manual labor in agriculture.

This effect is due to the extreme heat enforcing limits on working hours or even days (de Lima *et al.* 2021). The effect of the decline in productivity of manual labor by 2010's was already ~ 10 % on peak months when compared to pre-industrial era (Dunne *et al.* 2013). Areas such as Cambodia will be most affected in the future due to the high baseline temperatures of the area combined high humidity, which further increases heat stress (Dunne *et al.* 2013, de Lima *et al.* 2021). Proposed solutions are increased mechanization of agriculture, or adoption of crops which require less manual work hours to cultivate in comparison to rice (de Lima *et al.* 2021). Long term projections (2090's and beyond) generally support adaptation by switching from rice to maize on medium and high heating scenarios (Hultgren *et al.* 2025). Maize yields are expected to have a slight positive long-term trend in the area, with rice yields declining. Additionally, maize production is considered easier to mechanize and requires generally less manual labor, thus easing the adaptation to heat stress caused by high average temperatures in the area.

The continuing trend of increase in the number of hot days will further emphasize electricity access. The energy demand for cooling is expected to double by 2050's, due to an increase of extreme heat, currently rapid national economic growth of 7,7 % per year and the nation's population being expected to increase by four million for 2050 (KHM cooling action plan). Cambodian government has set a goal of achieving 100% rural electrification, with steady progress being achieved. Rural electricity access has increased from under 10 % in 2004 to 93,4 % as of 2024, according to World Bank. Additionally, the national power grid development master plan for 2020–2040 aims to link Ratanakiri to national high voltage network in period 2022–2025 (Asian development bank). Energy lab (Energylab.asia) working on solar-based rural electrification projects sees Ratanakiri having 85,6 % grid access as of 2021, with remaining villages relying on solar power-based solutions or not having electricity. The non-connected communities are usually the most remote and vulnerable ones, which would benefit the most from electrification (Siciliano *et al.* 2022). The most vulnerable not being able to afford electricity is also an observed issue, with solar powered projects pursued by aid agencies seen as a bridging solution (Siciliano *et al.* 2022).

Ratanakiri has been under renewed focus of investment from the central government during recent decades. However, the provinces' road infrastructure outside the provincial capital of Bandung and main roads are still largely unpaved and susceptible to damage from heavy rainfall, limiting rural accessibility (Figure 39). Climate changes impact on the amount of wet season precipitation on the area is expected to be insignificant on the timescale of the report, so main strain on road infrastructure is expected to be from population growth. The access index presented on figure 39

indicates that the current infrastructure is insufficient to provide around the year accessibility outside the vicinity of Banlung and the surroundings of major roadways. The tertiary road network covers the countryside sparsely, with the rainy season further reducing accessibility via both vehicle and foot. Whilst Srepok provides a transport route in the southern parts of the region, the accessibility is still considerably poor compared to the projected increase in population density.

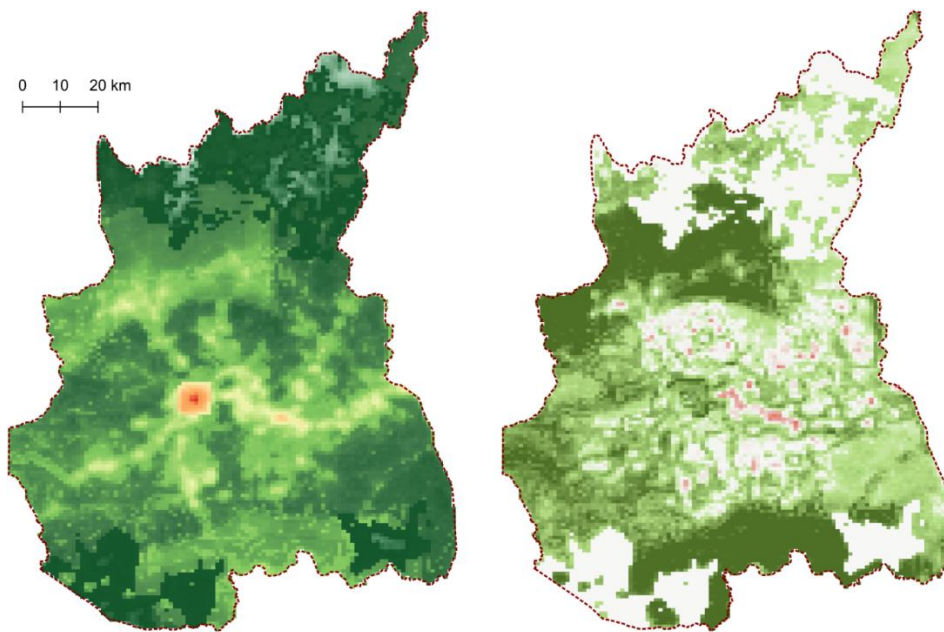


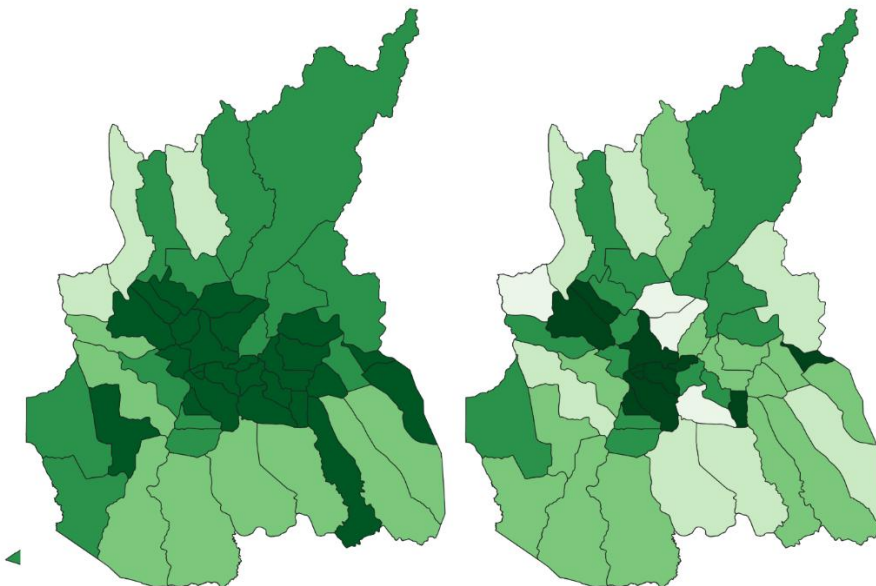
Figure 39: Current population distribution in Ratanakiri and expected population change by 2050. Data: Zhuang *et al.* 2024

Gridded 2020 population estimate

Expected percentage change by 2050

Pop per tile: 1 10 25 50 100 150 250

Change /%: -50 -25 0 25 100 150+



Optimal scenario

Tracks and pathways not usable

Accessibility /%: 0-20 20-40 40-60 60-80 80-100

Figure 40: Access index calculated on current road and waterways, population inside distance of 2 km or less of a road or a waterway, 2055 population estimate. Best case scenario with no impediments to movement, expected scenario with impediments outside main roadways. Data: Zhuang *et al.* 2024, OSM, utilizing World Bank Rural Access Index (RAI) method

Human health and water resources

The countrywide impact of rising average temperatures and increase in hot days is expected to have an especially pronounced impact on Ratanakiri. As the vast majority (90 %) of Ratanakiri's population are employed in farming, the effects of extreme temperatures are not only expected to affect the livelihoods via decrease in productivity, but also negatively affecting health and further compromising stability of livelihoods. Heat related mortalities are projected to increase on the area by up to 10 % for 2055 under SSP3-7.0 scenario, when compared to 1990–2019 baseline (Amnuaylojaroen *et al.* 2024). This follows the broader patterns projected for entirety of Mainland Southeast Asia.

The direct impacts of increased temperatures on human health and the potential increase in diseases on the region are expected to have substantial impact in increase of local risk factors. Rural poor without electricity or improved water sources are at the highest risk. The traditional lifestyles that many indigenous people of Ratanakiri practice are especially vulnerable to these hazards. Many of the effective measures to increase local resilience to temperatures require an increase in rural incomes, living standards or increased public spending. These include rural electrification, mechanization of labor in agriculture, improved access to healthcare and improvements to water infrastructure.

Ratanakiri trails behind the rest of the nation on health metrics such as child mortality (43 by 1000), children being vaccinated (27 %), and access to healthcare facilities (60 % over 30 minutes travel away with 5 % at over 2 hours) (Cambodia DHS 2021–22). Studies point that the increase in temperature creates more optimal conditions for tropical diseases, but long-term scenarios are difficult to predict and cannot be utilized to base accurate planning upon (Klepac *et al.* 2024). However, research and current knowledge give some directional insights on climate impacts on disease patterns.

Mosquitoes as the vector for malaria and the parasitic agent, Plasmodium group, rely on optimally warm temperatures with them being in the upper 20–30 °C range. Based on temperature projections for Ratanakiri, the conditions for mosquitoes are expected to be within the optimum range by the 2050's. The expected effects are shortening duration of incubation, and mosquitoes becoming infective much sooner (Rahmani *et al.* 2023).

Ratanakiri has the poorest water and sanitation service coverage in the nation. Water contamination by flooding or by human actions is a severe issue, due to 53 % not having access to basic water services during dry season, and 31 % are reliant only on surface water (Cambodia DHS 2021–22). Pich Yek (ICC) also remarked during the interview that one of the most major impacts of flooding in the area is contamination of water sources. Sanitation follows similar patterns, with only 42 % having access to basic services. Outside Banlung these numbers are expected to be even higher.

Temperatures in 25-30 °C range, constantly wet conditions created by steady precipitation and bad sanitation are generally expected to increase the prevalence of vector born tropical diseases (Houang *et al.* 2025). Periods of increased rainfall are found out to be linked to the increase of prevalence of diseases such as dengue fever (Houang *et al.* 2025). However, the impact of increasingly optimal conditions for tropical diseases in the area is difficult to judge, since assessing impacts of disease patterns should also take improvements in treatment and control strategies into account, but this is considered to be very difficult due to the unpredictable nature of research advances and public interventions (Klepac *et al.* 2024).

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