Private Infrastructure Development Group

University of Exeter

Africa Climate Solutions

Investing in Infrastructure for Climate Resilience across Africa

Endorsements

"It's obvious: Africa's sustainable development is inextricably linked with resilience to the impacts of climate change. Investing in infrastructure to ensure that the most vulnerable can adapt and even prosper in the face of climate impacts makes good sense. It is entirely doable, is emerging in pockets, and now needs to be nurtured and scaled. This work showcases public and private-sector leaders moving in the right direction, but we need to move from exceptional case studies towards a new normal – fast."
Nigel Topping, Global Ambassador, High-Level Champion

"The Current debate centres on infrastructure resilience instead of the resilience and adaptive capacities of the most vulnerable. This report aims to change that, by setting out how the two relate but are different to one another, and positioning infrastructure resilience as just one aspect of climate-resilient development."
Bogolo Kenewendo, Climate Champions' Special Adviser, Africa Director and former trade and investment minister for Botswana

"Assessing climate risk resilience is going to become a non-negotiable element in project development, particularly in infrastructure where the long-term impact of climate change cannot be overlooked. Analysis like this makes it easier for project developers to understand both climate risks and the opportunities to be found in mitigating them. This is not only valuable because it helps address the capacity gaps that undoubtedly exist, but also because it enables project developers to have an informed discussion with financiers about the true level of climate risk, and the extent to which this can mitigated, thus directly influencing the cost of finance."
Mark Napier, CEO, FSD Africa

"The most successful and exciting projects are committed to user-centred design and iterating their solutions with their customers and other stakeholders in mind – experimenting, learning and pivoting through time to ensure they deliver affordable, reliable solutions and provide relevant additional benefits. It is only with this approach that financiers will then have a real opportunity to create both people and nature focused impact and be catalyst for thriving sustainable markets, in a way that beautifully brings together climate and development, with Africa as the stage for action."
Hon. Nasra Nanda, CEO Kenya Green Building Society, Chair Africa Regional Network World Green Building Council

"For the world to succeed in meeting the SDGs, Africa must be at the forefront of a system change that supports infrastructure development that is resilient and drives the continent forward. In doing so, African countries can also lead a shift in the production and consumption patterns that have been exploitative and have left so many behind. The resilience and infrastructure investment challenges are the same and tackled together can be transformative. But, that will require a mindset shift, too - away from seeing Africa as a development challenge to the possibility of renewable energy and mineral hyperpowers and hubs of innovation for inclusion. This report is a contribution to the shifts we need to make."
Rachel Kyte, Dean Emerita of the Fletcher School and PIDG Non-Executive Director

"Getting infrastructure finance going in Africa this decade means investing in the future of the continent and of the entire planet. Sustainable development, climate adaptation and nature are profoundly interdependent. Investing in infrastructure in the countries with the largest infrastructure access gaps and the youngest population is an opportunity to reimagine the future that we cannot afford to waste. We teamed up with lead climate scientists with the aim to enable investors and partners to gain a better understanding of what kind of infrastructure can be most powerful in building communities and societies that can withstand the changing climate and unlock the continent's potential. This report also highlights clearly the cost of inaction and adapting badly to the changing climate. The Private Infrastructure Development Group's focus this decade is to accelerate action on climate resilient development through infrastructure investment and we hope this report will spur urgency and new ways to think about climate finance in Africa."
Philippe Valahu, CEO, Private Infrastructure Development Group

About PIDG

The Private Infrastructure Development Group (PIDG) PIDG is an innovative infrastructure project developer and investor which mobilises private investment in sustainable and inclusive infrastructure in sub-Saharan Africa and south and south-east Asia. PIDG investments promote socio-economic development within a just transition to net zero emissions, combat poverty and contribute to the Sustainable Development Goals (SDGs). PIDG delivers its ambition in line with its values of pioneering, partnership, safety, inclusivity and urgency.

PIDG offers Technical Assistance for upstream, early-stage activities and concessional capital; its project development arm – which includes InfraCo Africa and InfraCo Asia – invests in early-stage project development and project and corporate equity. PIDG credit solutions include EAIF (the Emerging Africa Infrastructure Fund), one of the first and more successful blended debt fund in low-income markets; GuarantCo, its guarantee arm that provides credit enhancement and local currency solutions to de-risk projects; and a growing portfolio of local credit enhancement facilities, which unlocks domestic institutional capital for infrastructure financing.

Since 2002, PIDG has supported 211 infrastructure projects to financial close, which provided an estimated 222 million people with access to new or improved infrastructure. PIDG is funded by the governments of the United Kingdom, the Netherlands, Switzerland, Australia, Sweden, Germany and the IFC. www.pidg.org

PIDG and the University of Exeter

The University of Exeter is a leading global centre for climate science, with more of the top 100 ranked climate scientists and more Intergovernmental Panel on Climate Change lead authors than any other university in the world. Exeter's Green Futures Solutions brings together 1,500 environmental researchers to work with NGOs, IGOs, businesses and governments to develop practical solutions to the earth's challenges. Exeter partners with universities and institutes across Africa on a number of environmental and climate related programmes including the Oppenheimer Programme in African Landscape Systems.

PIDG and the University of Exeter have worked in partnership to produce this report which highlights the disparate affects of climate change across different regions of Africa, and shows how investment in infrastructure can be made prudently through understanding these affects, and how that investment can – and must - play a crucial role in building resilience to climate change.

Authors

Anna Murphy, Richard Betts, Tom Powell and Peter Cook.

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We acknowledge the ETCCDI indices and heat stress indicators for CMIP6 provided through the Copernicus Climate Data Store, documented in Sillmann et al. (2013)[185], Kim et al. (2020)[2], Schwingshackl et al. (2021)[7] and Sandstad et al (2022)[186].

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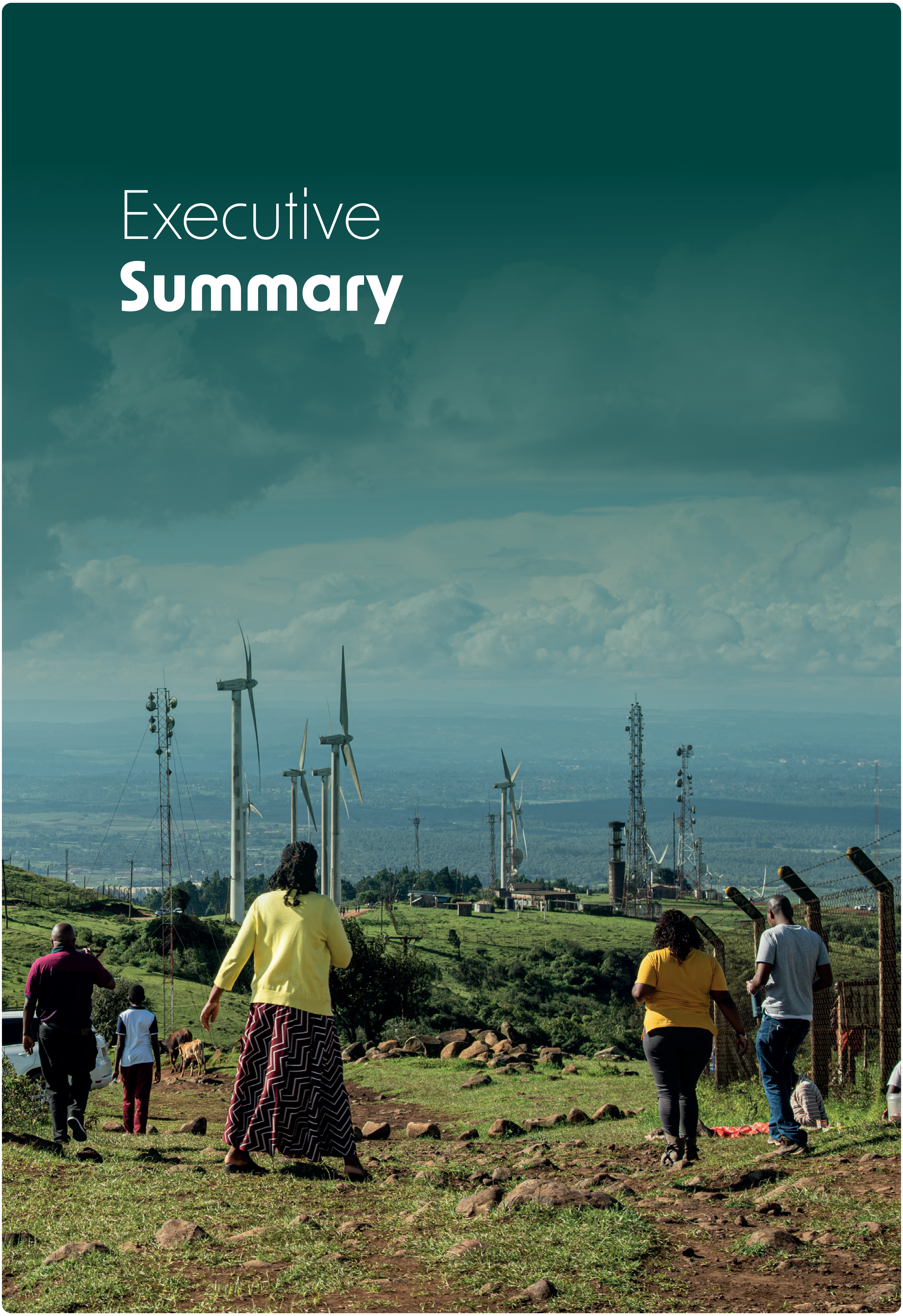
Executive **Summary**



At the inaugural Africa Climate Summit (ACS) in Nairobi in September 2023, African heads of state emphasised that: "Africa possesses both the potential and the ambition to be a vital component of the global solution to climate change. As home to the world's youngest and fastest-growing workforce, coupled with massive untapped renewable energy potential, abundant natural assets and an entrepreneurial spirit, our continent has the fundamentals to spearhead a climate-compatible pathway as a thriving, cost-competitive industrial hub with the capacity to support other regions in achieving their net-zero ambitions."

The ACS final declaration also expressed "concern that many African countries face disproportionate burdens and risks arising from climate change-related unpredictable weather events and patterns, including prolonged droughts, devastating floods, out-of-season storms and wildfires, which cause massive humanitarian crisis with detrimental impacts on economies, health, education, peace and security, among other risks". While Africa is not historically responsible for global warming, it bears the brunt of its effects, impacting lives, livelihoods and economies.

The ACS called for "climate-positive investments that catalyse a growth trajectory anchored in the industries poised to transform our planet and enable African countries to achieve stable middle-income status by 2050". The final declaration urged global leaders to seize "this unprecedented opportunity to accelerate global decarbonisation, while pursuing equality and shared prosperity".

Accelerating investment in infrastructure, which provides the services that underpin economic growth, lies at the core of seizing this unprecedented opportunity. Yet the ACS also expressed concern that "despite Africa having an estimated 40 per cent of the world's renewable energy resources, only $60bn – or 2 per cent – of US$3tn renewable energy investments in the last decade have come to Africa".

Understanding the varied effects of climate change across Africa will be essential to mitigate the risks they present and deliver sustainable returns on investment for infrastructure that is adaptable and resilient to a changing climate and – most importantly – that builds adaptation and resilience for the two billion people whose development pathway is inextricably linked to global climate outcomes.

Understanding how climate change will alter different regions of Africa is fundamental to enable investment flows, enhance viability of the infrastructure that is built, and to fully appreciate the value that such investments will unlock by building adaptation and resilience for communities and societies. Time is short and action is urgent. We need to accelerate infrastructure investment that catalyses climate-resilient development and avoids maladaptation.

This report builds a map of climate-related hazards in Africa and suggests a set of investor criteria for selecting and shaping infrastructure for climate adaptation and resilience which unlocks climate-resilient development. While not exhaustive, it builds on the latest and most robust evidence of the climate variations expected on the continent, and on evidence and case studies of investments that deliver climate-related development. The aim is to redefine what investing in climate action means in Africa, opening new avenues for investors in the continent and expanding the toolkit at their disposal to make decisions that enable and accelerate climate-resilient development.

Understanding climate impacts, and how they vary across the regions, opens up opportunity for prudent and sustainable investment in the essential infrastructure to navigate climate-compatible pathways for growth. Such investment offers the potential not only for the direct provision of resilient infrastructure, but to strengthen the resilience of economies and society. The report shows that, by appreciating the changes and risks across different regions of the continent, such investment is possible, prudent and a powerful force to drive both economic development and climate resilience.

Key Findings

Climate hazards in the form of extreme heat and humidity, drought, heavy rainfall, sea-level rise and flooding are already increasing across Africa, and will increase further in coming decades. There are also widespread, high vulnerabilities in a continent where millions of people don't yet have access to critical power, transport and water services, or are provided for only by under-invested in, aging, overstretched or informal infrastructure solutions.

Extreme temperatures projected to increase across the whole of Africa in scenarios of both 2°C and 4°C by the end of the 21st Century. **Heavy rainfall** is projected to increase across most of Africa, especially in the scenario reaching 4°C global warming by the end of the 21st Century (though in the 2°C scenario increases are less widespread and some areas are projected to see reduced heavy rainfall). **Extreme high sea water levels and shoreline retreat** are projected to increase with global warming across all coasts of Africa. Seasons conducive to fire are projected to become longer across most of Africa, except Northern East Africa.

The risk of heat stress, greatest when both temperature and humidity are high, will be most notable in Western and Central Africa. **Agricultural drought** is projected to become increasingly likely in most regions below 5° North and near the Mediterranean coast but is projected to be decreasingly likely in between. **River flooding** is projected to occur more frequently in the wetter regions of Africa, especially at higher levels of global warming.

Key regional findings demonstrate the importance of regional and local approaches to climate resilience:

- **East Southern Africa** requires resilience to increased wildfire risk, even at lower levels of global warming. Extreme drought is more likely, especially away from the eastern coasts, while coastal flooding and shoreline retreat are set to be more pronounced than in other regions.
- **West Southern Africa** needs to adapt to more frequent and pronounced drought. Heat stress is an increasing risk, but not as extreme as in other regions.
- **South Eastern Africa** needs increased resilience against flooding, especially riverine, but also coastal, heightened by population growth in high-risk areas.
- **North Eastern Africa** needs to prepare for more frequent riverine flooding, and increased heat stress risk in some areas.
- **Central Africa and West Africa** face the greatest challenges from heat stress, as extreme temperatures combine with high humidity, along with increased risks of riverine flooding. In West Africa, a particularly dense and fast growing population compounds the risk. Delivering infrastructure to provide resilience against heat stress in this region representing roughly a quarter of Africa's economy is a vital task.
- **The Sahara** region faces extreme heat stress, but diverges in impacts beyond that, with the northern Sahara set to experience extreme agricultural drought, the Sahel, riverine flooding.
- **Mediterranean North Africa** immediately faces increases in drought and wildfire risk, along with potential for extreme heat stress later.
- **Madagascar** needs increased resilience to coastal and riverine flooding, and also drought and wildfire.

From risk to opportunity: infrastructure for climate resilience

The good news is that driving sustainable development is one of the best ways of improving climate resilience, and climate resilience in turn enables and drives sustainable development: sustainable development projects delivered with a climate resilience lens can mitigate the risks of climate hazards and proactively build the climate resilience of the most vulnerable.

Our vision is that infrastructure assets and services be climate resilient themselves, increase the climate resilience of their users, and create outsized, ‘transformative’ impact. Infrastructure can be designed to drive climate-resilience and development in four ways. These are elaborated on in the Energy, Transport and Water sections.

1. Economic and social development foundations:

Access to electricity, transport and water infrastructure enable better educational outcomes, job and livelihood creation and diversification and better health and gender equality. These improve a community’s capability to adapt and respond to climate-related challenges.

2. Direct adaptation benefits:

Infrastructure can provide direct adaptation benefits, from solar-powered refrigeration preventing food loss and medicine preservation in the face of extreme heat and disrupted supply chains; to smart irrigation improving crop yields despite drought; roads designed to enable run-off and water storage for dryer spells; green infrastructure reducing the urban heat-island effect; and waste-to-energy plants removing waste from communities, in turn reducing the health risks of urban flooding.

3. Direct resilience benefits:

Infrastructure can improve the ability to cope with and respond to acute climate hazards. Power enables early-warning signals. Roads are critical for the transportation of people and emergency supplies in the event of disaster. Emergency water storage facilities are necessary to supply communities during extreme heat events.

4. Macro-economic resilience benefits:

Clean power and transport solutions reduce oil-dependency, saving countries vast sums, improving trade balances and opening up economic resources for domestic investments. Better roads can radically reduce the cost of trade, making Africa more competitive internationally. Highly efficient irrigation solutions can expand agricultural productivity, increase exports and reduce domestic food insecurity, while improved water infrastructure can attract investment into a plethora of sectors including manufacturing and tourism - supporting economic diversification and growth.

Projects are emerging and the potential is vast. Africa's entrepreneurs are building solutions which deliver development, adaptation and resilience benefits simultaneously. The continent's need for new infrastructure services creates the opportunity to leapfrog to an integrated approach which delivers on sustainability, adaptation and resilience. Nature-based 'green infrastructure' solutions are emerging and have huge potential given their effectiveness in delivering on resilience, adaptation, and development outcomes all while being typically less costly than conventional infrastructure solutions. New financial approaches are mobilising domestic finance to expand resources available and grow local economies; while blended finance and publicly funded risk-aware, 'catalytic capital' is attracting private investments into areas it previously refused to go. Iteration and collaboration are guiding solutions to complex problems in the face of uncertainty, rural development needs and rapid urbanisation.

In essence, infrastructure investors must use a resilience lens to ensure that their investments deliver on development. In essence, this requires going beyond the question "Is this infrastructure resilient?" towards asking "Will this infrastructure improve the climate resilience of the communities it serves and impacts, by nurturing change which endures and cascades across communities, sectors and economies?"

1.

Climate Hazards **across Africa**

Overview –
Climate Hazards across Africa

Climate change, and the distribution of its impacts, has deep relevance both for the resilience of infrastructure itself, and for the communities and economies infrastructure is designed to support. This report gives an overview of projected future changes in climate across Africa, focusing on aspects expected to be particularly relevant to the demand and design needs of infrastructure, especially the hazards presented by extreme weather events. These aspects are: high temperatures and risks of human heat stress; heavy rainfall and river flooding; coastal flooding; drought and wildfire risk. To support effective decision making we show projected future changes at a range of scales, beginning here with the whole of Africa, and later in the report breaking this down to regions and selected individual cities. As projecting future climate change is highly complex and requires dealing with considerable uncertainties, we also present the current level of confidence in the distribution of the climate hazards discussed.

1.1 Our approach

The future climate projections presented in this report are mostly from the latest generation of climate models produced by several climate research centres around the world. Climate models are large, highly complex computer programmes which use mathematical equations to simulate the physics of the atmosphere and oceans at global scales, along with their interactions with land and marine ecosystems. This includes equations to calculate wind flows, ocean current, the global water cycle (including the changes between ice, liquid water and water vapour, cloud formation, rain, snow, evaporation and river flows) and the carbon cycle (including plant growth taking carbon out of the atmosphere, decay in the soil returning carbon back to the atmosphere, and the uptake and release of carbon in ocean waters) (Figure 1.1). Remarkably, having simply been provided with these basic principles and other factors such as the changing angles of the sun and the shape and rotation of the Earth, these models produce highly realistic patterns of the global weather and climate.

Projections of human-caused climate change made in the past have now been shown to be remarkably accurate, and long-term averages and trends can in general be projected, albeit sometimes with large uncertainties. **However, there are still limitations** of climate models which mean their outputs and projected changes need to interpreted appropriately and not always taken at face value.

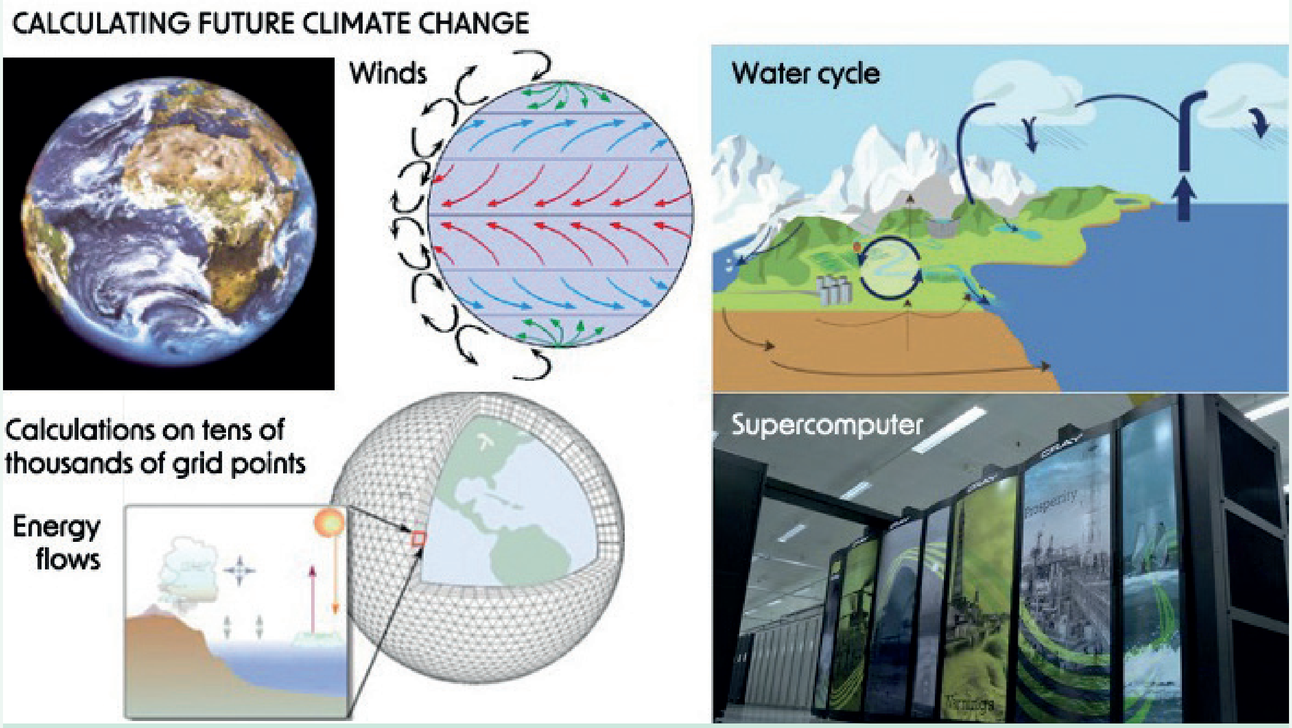


Figure 1.1 Computer modelling of weather and climate.

For example, there is often large uncertainty in future climate projections, especially when homing in on specific locations such as individual cities. Part of the uncertainty comes from the fact that we do not know what future pathway humanity will follow with greenhouse gas emissions; despite the Paris Agreement pledging to limit global warming to 'well below' 2°C above pre-industrial levels and to 'pursue efforts' to limit warming to 1.5°C, currently implemented worldwide policies on emissions cuts are nowhere near strong enough to achieve this. The exact rate of future global warming for a given emissions pathway is also uncertain, as there are many feedbacks which can either amplify or dampen the response of the climate system, and so far there has only been limited success in narrowing down the range of possibilities. Therefore, currently implemented global policies could lead to global warming of anywhere between about 2°C and 4°C by the end of the 21st Century. Of course, it is still possible that international policies could be strengthened and these high levels of warming avoided, but this is not something that can be predicted by science – therefore, **climate scientists generally examine several different emissions futures, including scenarios of ongoing or increasing emissions and scenarios of rapid and deep emissions cuts.**

The UK's Climate Change Committee recommends preparing to adapt for 2°C global warming and assessing risks for 4°C.1 This report provides information in line with that advice, presenting scenarios that reach around 2°C and 4°C by the end of the century. Most projections shown here use multiple models from the 6th Coupled Model Intercomparison Project (CMIP6) which was used in the recent IPCC 6th Assessment Report. In some cases, where relevant information is only available for other levels of global warming such as 3°C, or from other models, this is provided instead.

Another area of uncertainty is in regional and local climate responses. **At any given level of global warming, the projected local climate in a particular area could change in a range of ways,** depending on how, for example, wind patterns shift in response to warming, bring either wetter or drier conditions, or warmer or less-warm conditions. These local uncertainties are often hard to narrow down, so it can be wise to account for a range of local outcomes. We illustrate this by showing projected climate changes for individual cities from a number of different climate models that give different answers, none of which can be definitively ruled out.

There can be systematic biases in climate model simulations at the present-day which mean that, for example, the simulated temperatures in a particular region may be consistently too high or too low, or rainfall may be too high or too low. These biases often need to be accounted for when looking at model projections of whether, for example, temperatures will exceed certain levels critical for human health – if, for example, the present-day simulated temperature is too low, and this bias remains the same in the future, the model will underestimate the number of days exceeding critical levels. Techniques known as 'bias-correction' are often employed for this purpose – here, such techniques are used wherever data is available to support this. We bias-corrected projections of extreme temperatures and heavy precipitation2 with reference to either the HadEX3 observed extremes dataset3, local meteorological data or satellite data from TAMSAT.4–6 We used projections of heat stress from which had already been bias-corrected against the ERA5 climate reanalysis.7

Assessment of confidence in future climate projections is crucial for informing decision making, and the IPCC puts a very large amount of effort into distinguishing between information provided with higher and lower levels of confidence. This helps to facilitate appropriate risk management processes.

The IPCC uses both confidence and likelihood terminology. **Confidence levels** are non-quantitative and just give a relative assessment of low, medium and high confidence. In contrast, **likelihood statements** allocate a number for the likelihood which is associated with certain specific terms. Examples of these are: likely (66% – 100% chance); very likely (90% – 100% chance), extremely likely (95% – 100% chance) and virtually certain (99% – 100% chance). These terms are used here when appropriate.

1.2 The climate change picture across Africa

This section draws out key features of projected climate change, extremes and impacts, such as which regions see the most extreme examples of each trend. Deeper dives for each of the nine regions are provided in the subsequent chapters.

Extreme temperatures are projected to increase across the whole of Africa in scenarios of both 2°C and 4°C by the end of the 21st Century (Figures 1.2.1 and 1.2.2). Temperature increases are fairly similar across most of the continent, though hotter extremes are seen in regions north of about 5° North and south of about 15° South than in the equatorial region in between.

The **risk of heat stress** is greatest when both temperature and humidity are high; high humidity means that the human body cannot cool effectively through the evaporation of sweat. Heat stress risk is often indicated with a measure called 'Wet Bulb Globe Temperature' (WBGT) which considers humidity as well as temperatures.

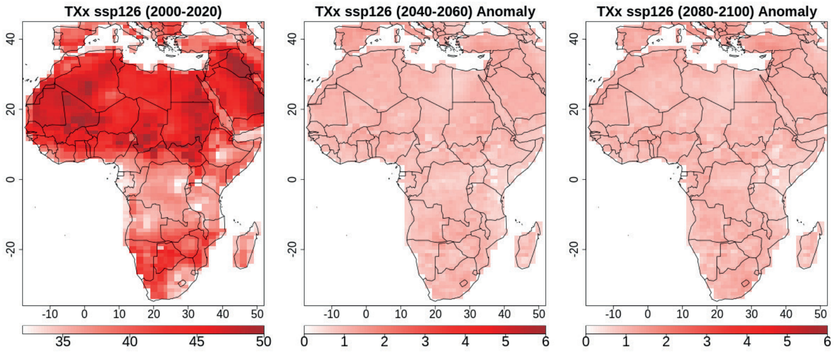


Figure 1.2.1
Average annual maximum one-day temperature for 2000-2020 and changes in the middle and end of the 21st Century in a scenario reaching approximately 2°C global warming in 2100, using the CMIP6 multi-model ensemble.[2]

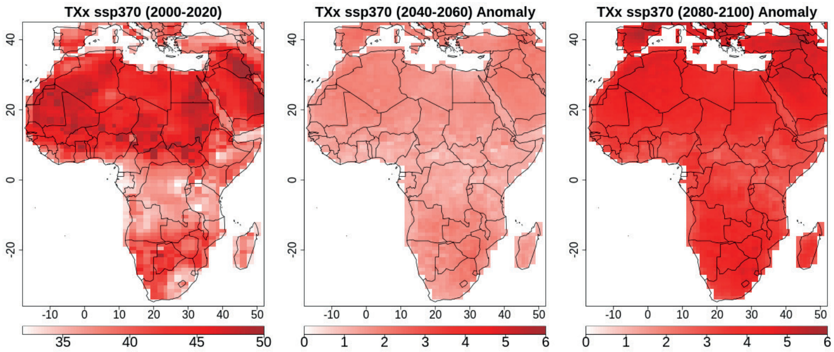


Figure 1.2.2
Average annual maximum one-day temperature for 2000 – 2020 and changes in the middle and end of the 21st Century in a scenario reaching approximately 4°C global warming in 2100, using the CMIP6 multi-model ensemble.[2]

Many parts of Western and Central Africa already see between 100 and 150 days per year with high heat stress risk, defined as days with WBGT above 28°C. The number of days per year at this level are projected to increase in these and surrounding areas, especially in the scenario reaching 4°C global warming by the end of the 21st Century (Figure 1.2.3). Extreme heat stress risk (WBGT above 32°C) is currently rare, but is projected to occur increasingly often, especially in the 4°C scenario (Figure 1.2.4).

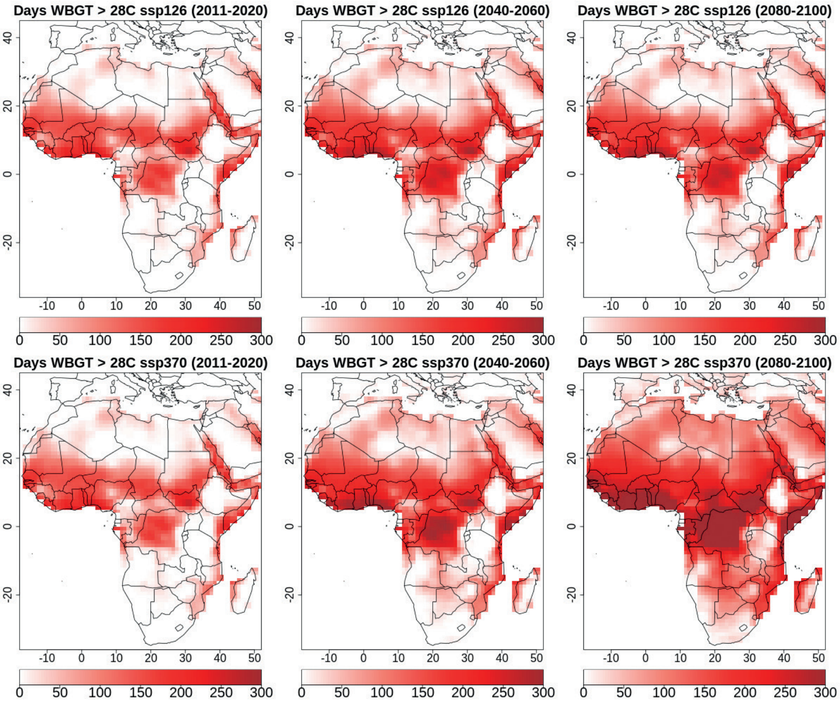


Figure 1.2.3
Average number of days per year with heat stress risk at 'high' or above (defined as WBGT above 28°C) for 2000-2020 and the middle and end of the 21st Century in scenarios reaching approximately 2°C global warming in 2100 (top row) and 4°C global warming in 2100, using the CMIP6 multi-model ensemble.[7]

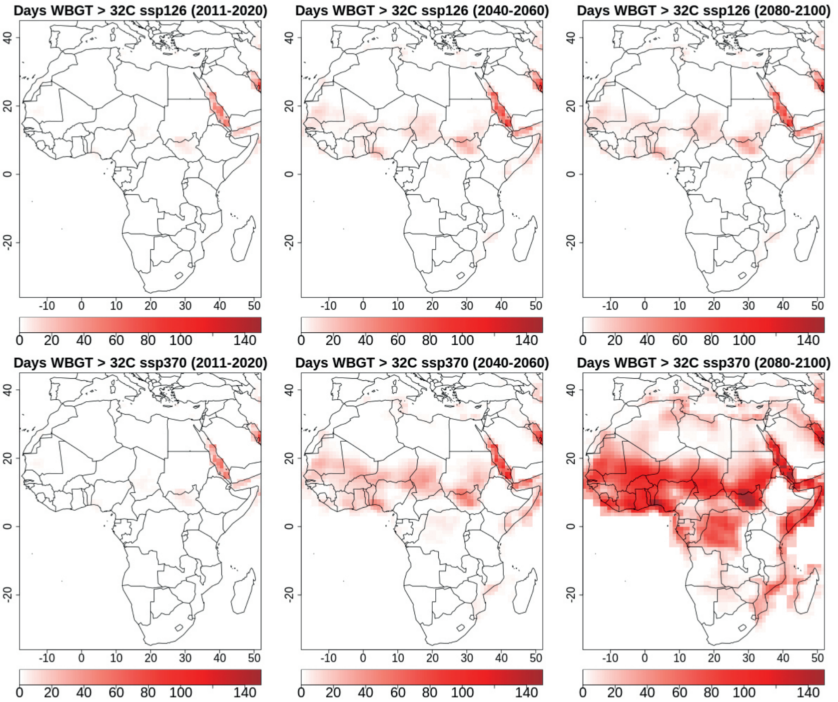


Figure 1.2.4
Average number of days per year with heat stress risk at 'extreme' or above (defined as WBGT above 32°C) for 2000-2020 and the middle and end of the 21st Century in scenarios reaching approximately 2°C global warming in 2100 (top row) and 4°C global warming in 2100, using the CMIP6 multi-model ensemble.7

Drought can be defined in several ways, either including precipitation alone (meteorological drought) or with the additional effect of evaporation drying the soil (agricultural or ecological drought) or the effect on water in rivers (hydrological drought). For simplicity, this report mainly focuses on agricultural drought. This is projected to become increasingly likely in most regions of Africa south of about 5° North and in areas near the Mediterranean coast but is projected to be decreasingly likely in the regions in between (Figure 1.2.5).

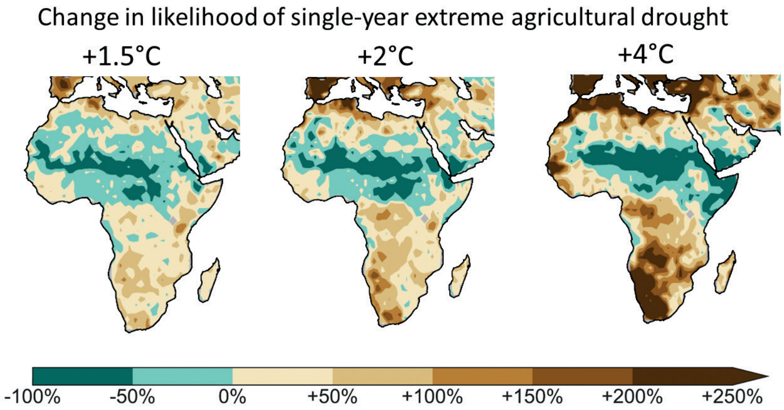


Figure 1.2.5
Projected change in likelihood of single-year extreme agricultural drought at global warming levels of 1.5°C (left), 2°C and 4.5°C (right), using the CMIP6 multi-model ensemble. Agricultural drought is defined as relatively low soil moisture levels, and is defined locally: extreme single-year agricultural drought is the driest 10% of years between 1995 and 2014 in each individual location, so the actual soil moisture during extreme drought conditions will vary according to whether the individual locations are wetter or drier in the long-term average. By definition, this level of drought would have a 10% likelihood in all locations for the baseline climate, so the present-day figure is not shown here. Figure by Ben Cook, reproduced from Caretta et al. (2022)[8]

'Fire weather' refers to weather conditions conducive to fire: hot, dry and windy. The fire weather season is projected to become longer in all of Africa except much of Northern East Africa (Figure 1.2.6), noting that this metric is not assessed in the Sahara due to lack of vegetation to burn.

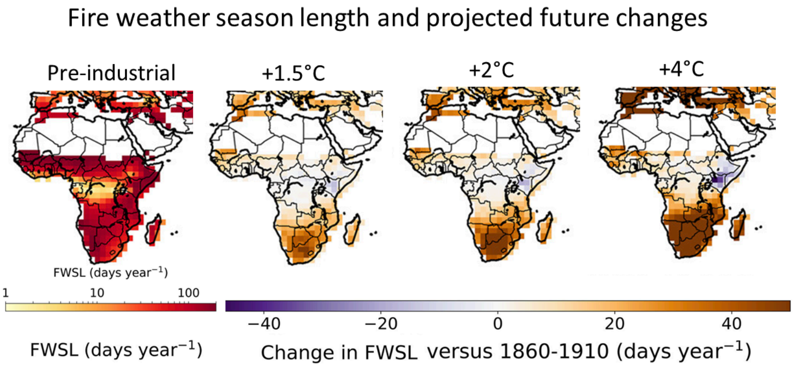


Figure 1.2.6
Fire weather season length (FWSL) in the pre-industrial climate and projected changes at 1.5°C, 2°C and 4°C global warming. Reproduced from Jones et al. (2022)[9]

Heavy rainfall is projected to increase across most of Africa, especially in the scenario reaching 4°C global warming by the end of the 21st Century. In the 2°C warming scenario, increases are less widespread and some areas are projected to see reduced heavy rainfall (Figures 1.2.7 and 1.2.8).

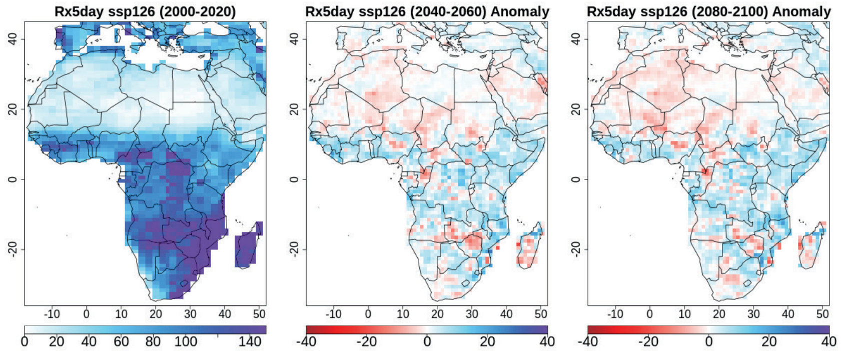


Figure 1.2.7
Average annual maximum five-day rainfall for 2000-2020 and changes in the middle and end of the 21st Century in a scenario reaching approximately 2°C global warming in 2100, using the CMIP6 multi-model ensemble.[2]

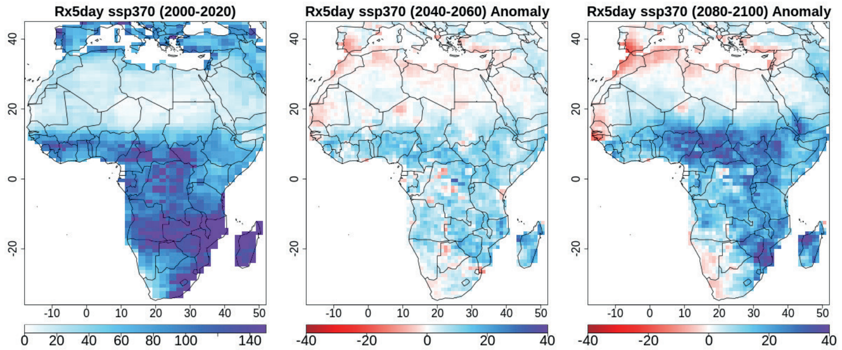


Figure 1.2.8
Average annual maximum five-day rainfall for 2000-2020 and changes in the middle and end of the 21st Century in a scenario reaching approximately 4°C global warming in 2100, using the CMIP6 multi-model ensemble.[2]

River flooding is projected to occur more frequently in the wetter regions of Africa, especially at higher levels of global warming (Figure 1.2.9). The number of people projected to be exposed to river flooding is projected to increase due to climate change at 3°C global warming, with projected changes in population also generally contributing to further increases in flood exposure, although some countries are projected to see a decrease in numbers exposed, especially with the low population-growth scenario (Figure 1.2.10).

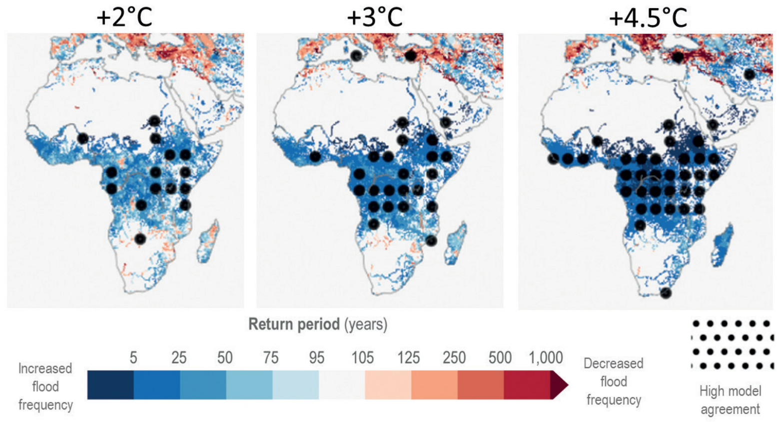


Figure 1.2.9
Projected return period of 20th-century 100-year flood in 2071-2100 with global warming of approximately 2°C (left), 3°C and 4.5°C (right). The 100-year flood refers to the flood level that would be expected to occur once per hundred years on average, ie: a 100-year return period. The actual flood level in a 100-year flood varies from place to place. Reproduced from Caretta et al. (2022)[8]

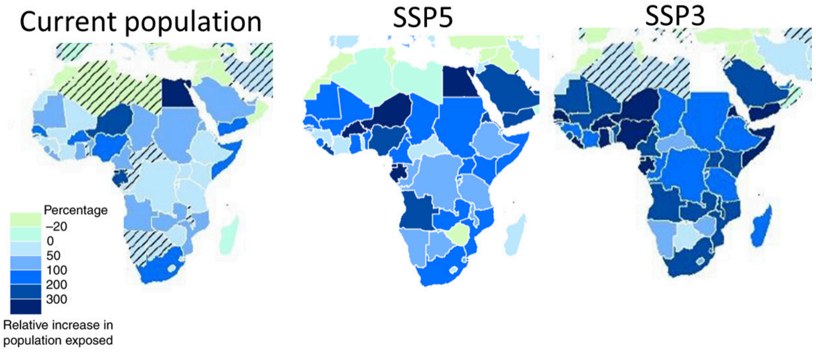


Figure 1.2.10
Relative increase in number of people exposed to river flooding in countries in Africa with 3°C global warming and three different population scenarios: current population (left), low population growth (scenario SSP5: middle), and high population growth (scenarios SSP3: right). Reproduced from Dottori et al (2018).[10] Hatching indicates less than 90% agreement across models in average change.

Extreme high sea water levels and shoreline retreat are projected to increase with global warming around all coasts of Africa (Figures 1.2.11 and 1.2.12).

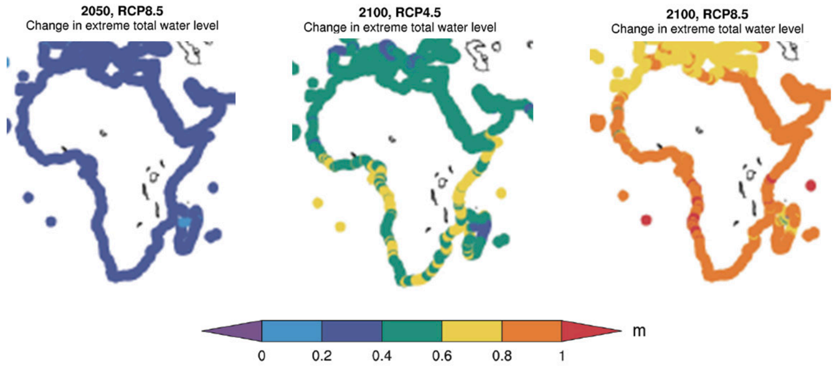


Figure 1.2.11
Projected changes in extreme total water levels (including relative sea level, storm surges, tides and high waves) around African coasts by 2050 with a very high emissions scenario (left), 2100 with a medium emissions scenario (middle) and 2100 with a very high emissions scenario (right). Reproduced from Ranasinghe et al. (2021)[11].

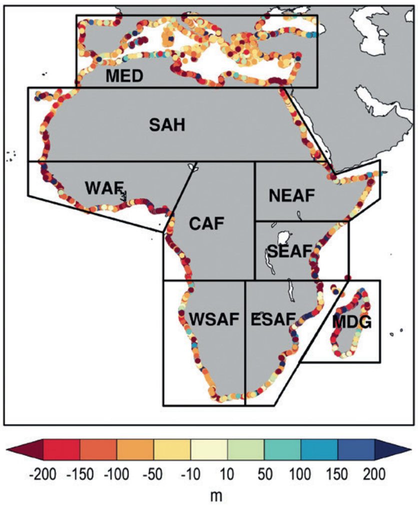
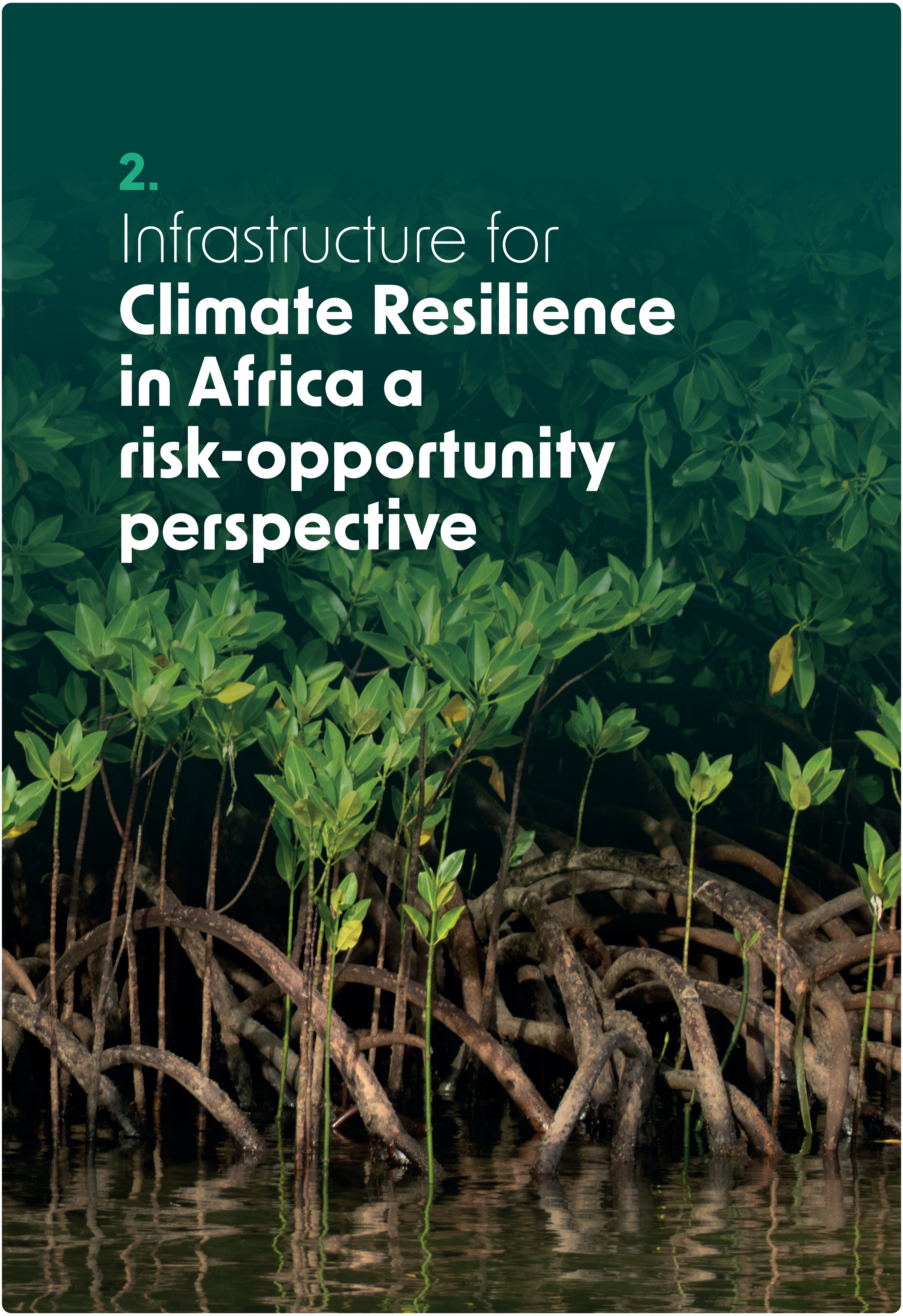


Figure 1.2.12
Projected shoreline position change around the coasts of Africa by 2100 with a very high emissions scenario. MED: Mediterranean; SAH: Sahara; WAF: Western Africa; CAF: Central Africa; NEAF: North Eastern Africa; SEAF: South Eastern Africa; WSAF: West Southern Africa; ESAF: East Southern Africa; MDG: Madagascar. Reproduced from Ranasinghe et al (2021)[11].



2.

Infrastructure for Climate Resilience in Africa a risk-opportunity perspective

2.1 From vulnerability to resilience

Africa already faces considerable impacts from climate change which will intensify in the coming decades, including heatwaves, droughts, floods and sea-level rise. These impacts pose serious, sometimes unprecedented, risks that will exacerbate existing vulnerabilities. Africa's particular vulnerability to climate change is not only driven by the increasing likelihood of direct impacts, but because they manifest on a continent in which tens of millions of people do not have access to critical services provided by reliable, resilient infrastructure.[12] Africa has a fast-growing, youthful population, and is experiencing the fastest urbanisation rates in the world; resilient food systems (and the rural livelihoods which enable them) will be essential to support the cities of the future, while a high proportion of Africans remain dependent on subsistence livelihoods. The capacity to adapt or build resilience to climate risks is therefore deeply connected with wider goals for sustainable development, and with location-specific climate impacts.

The synergies between adaptation, resilience and sustainable development present huge opportunities for developing infrastructure projects with the potential to transform lives, livelihoods and national economies. Africa possesses **globally critical mineral resources and capacity for renewable energy generation,** and needs investment to unlock these opportunities. The continent's young, educated and **entrepreneurial population is developing and scaling solutions** which deliver development, adaptation and resilience benefits simultaneously. **New digital and financial approaches** are increasing the affordability of solutions to users and companies alike, expanding resources available and growing local economies; while blended finance and publicly funded, risk-aware 'catalytic capital' is attracting private and domestic investment into new areas. The question facing development and infrastructure investors is **how to identify investment opportunities that maximise these synergies to deliver ambitious and appropriate solutions for Africa's unique contexts.**

A systems lens can help to identify low-risk, high-opportunity solutions. We use this perspective to explore how infrastructure investments can deliver climate resilience gains for Africa's most vulnerable communities, focusing on energy provision; transport; and water and sanitation. A systems perspective requires the examination of dynamics such as unintended consequences, undesirable and desirable feedbacks, cascading impacts, and the potential for transformative change. **We argue that this approach can encourage more humility, care and ambition in decision making, and unlock insights for lower-risk, higher-opportunity interventions.**

Climate-resilient development: Combines adaptation and mitigation development strategies, and reduces exposure and vulnerability to climate hazards, thereby supporting sustainable development for all.[13]

Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities.[13]

Resilience: The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or re-organising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation.[14]

Infrastructure: The basic systems and services, such as transport, power supplies, communications, ecosystem services, school and health facilities, that a country, city or area uses/needs (in order to work effectively) – including the processes, rules and behaviours which sustain them.[15]

Maladaptation: Interventions which lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change or diminished welfare in the present or future.[16]

The economic case for investing in climate resilience has never been stronger. World Bank modelling suggests that the benefit of investing in more resilient infrastructure in low and middle income countries is US$4.2 trillion, with US$4 in benefit for each US$1 invested, and that investing in energy system resilience can cost up to 12 times less than disaster relief measures.[17] While the economic opportunity of investing in climate resilience through infrastructure is under-researched, we do know that infrastructure projects are among the most bankable in Africa,[18] the risk of investment is typically far lower than perceived,[19] and from its young, determined and entrepreneurial population, inspiring companies and projects are everywhere.

In this report, we categorise adaptation processes largely as the processes which improve robustness to the long-term impacts of slow-onset climate events, and resilience as the resourcefulness and recovery capabilities when an extreme weather event occurs.

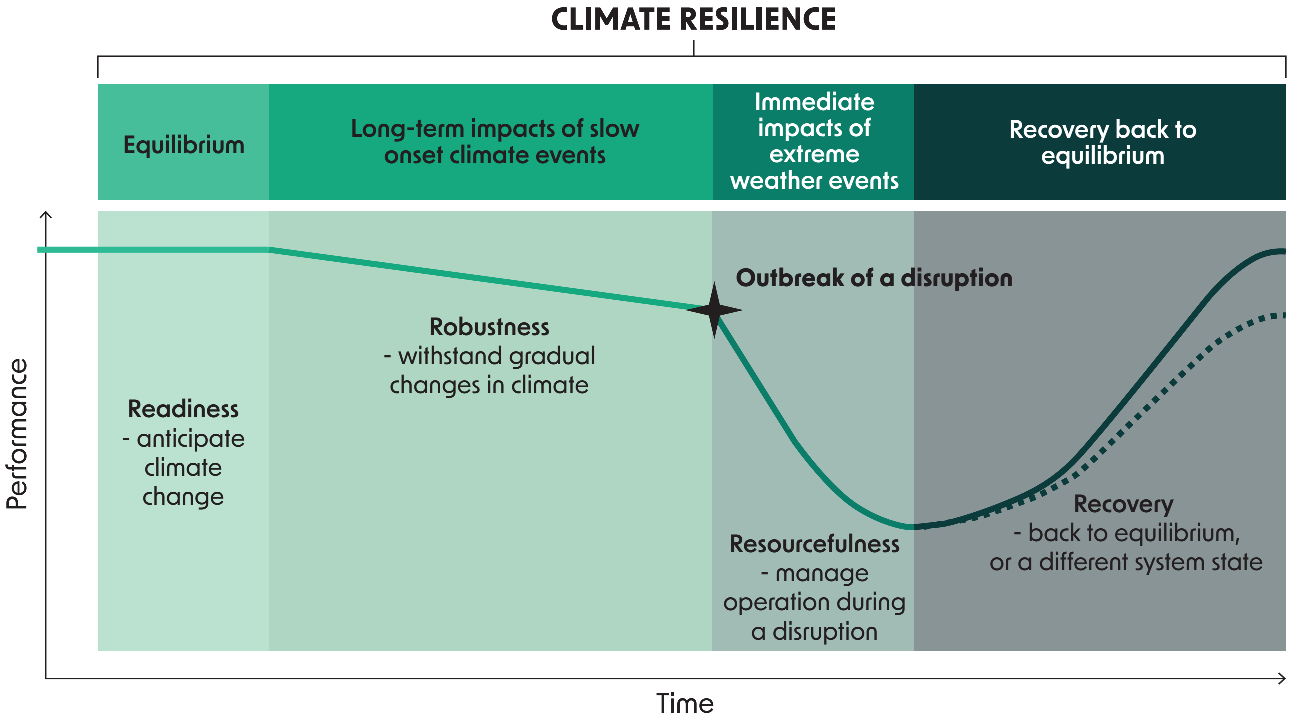
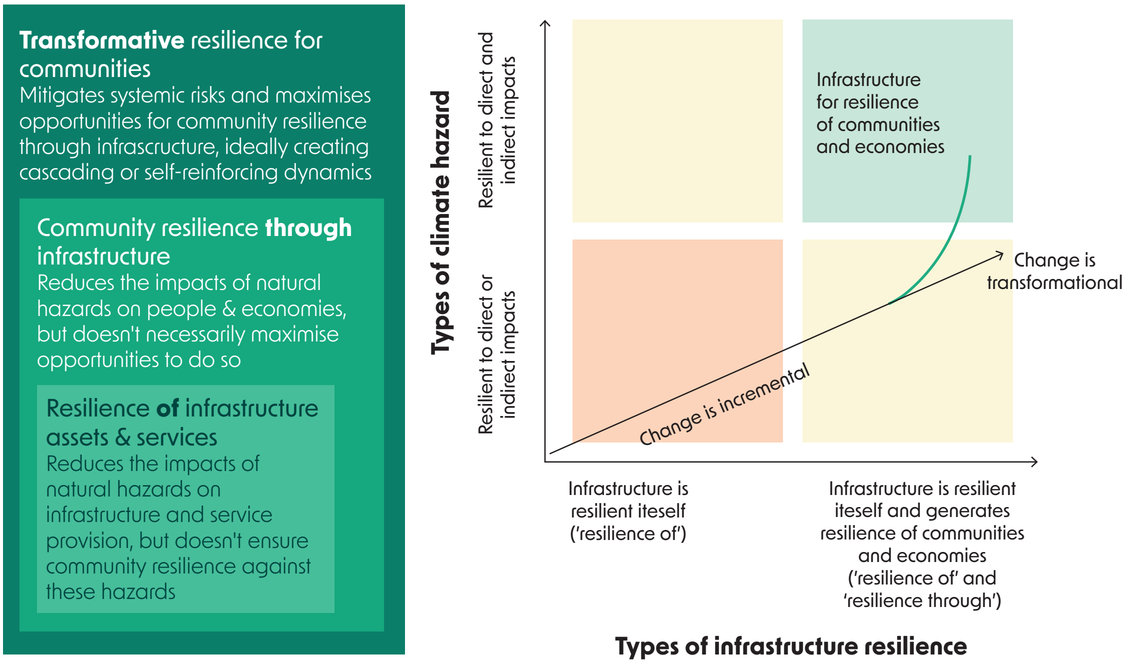


Figure 2.1.1 Illustrating different elements of climate resilience. Source: IEA (2020)[20].

Our vision for catalysing climate-resilient development through infrastructure



Figures 2.1.2 Resilience matters at the scale of individual infrastructure investments, but is also critical to consider at the scale of the communities and economies that depend on the services infrastructure provides. Sources: World Bank (2019) and authors.[17]

Infrastructure investments in Africa are not yet, on the whole, driving climate-resilient development, and we have not found a clear vision, framework or series of case studies to help investors identify and prioritise projects to fund climate resilience for vulnerable populations in Africa through infrastructure.

We believe that climate-resilient development through infrastructure should take into account three key elements:

1. Infrastructure assets and services should be climate resilient (resilience of)[17]

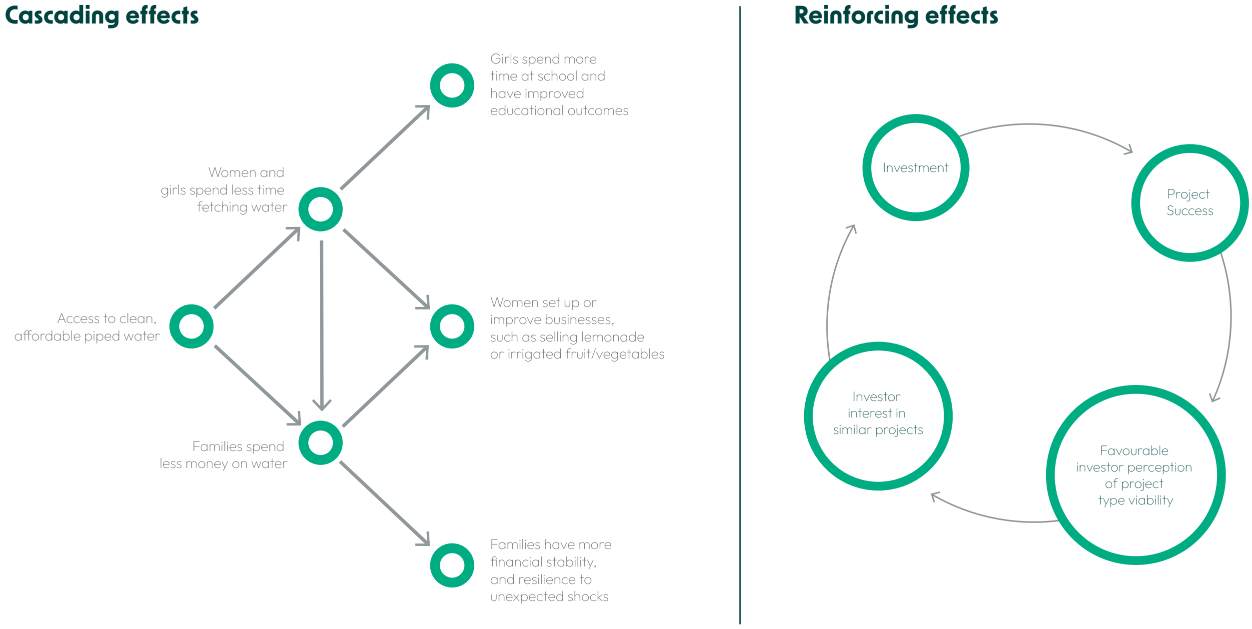
(a) They are resilient to current and future direct climate hazards, such as extreme heat, flooding and drought, and have the ability to be adapted to maintain resilience over time;
(b) They ensure the resilience of the infrastructure network they are part of; and
(c) They are resilient to likely indirect impacts of climate change, such as changing global supply chains, workforce and lifestyle changes and climate-induced population movements.

2. Infrastructure assets and services should increase the climate resilience of their users (resilience through)[17,21]

This especially includes the communities most exposed to climate harm and least able to cope with it. Infrastructure can support development, equipping people to adapt and bounce back from direct and indirect climate impacts. This can be understood as expanding resources available to poor and vulnerable populations, and ensuring continuous access to essential services (e.g. energy, food, water, healthcare and transport) through climate disruption.

3. Infrastructure and investment approaches create outsized ('transformative') impact[22]

This might be done by initiating cascading benefits of development (e.g. driving gender empowerment, improved education, economic and climate resilience outcomes which reinforce one another); through sparking or strengthening processes of positive change (e.g. through a demonstration effect, crowding-in further investments or stimulating public-private partnerships); or by improving the enabling environment (e.g. improving policy, lowering the barrier for further investments).


Cascading effects

Reinforcing effects

Figures 2.1.3 Examples of reinforcing feedbacks and cascades.

Below we outline some of the key resilience opportunities posed by infrastructure investments:

1. By providing affordable access to basic needs like energy, transport and water, infrastructure enables people to access education, information, communications, opportunities for entrepreneurship and diversified livelihoods. Resulting economic development strengthens resilience; when people have more assets, more education and more ways to earn an income, they are better able to weather shocks.

2. By directly addressing adaptation challenges, for example by powering cooling during heat stress or shaping safe settlement patterns in the face of flood risk.

3. By enabling response to or recovery from climate shocks, for example by providing early warning systems or safe routes for emergency support or evacuation.

4. By building economic resilience at national scale, for example by developing domestic capacity which reduces dependence on imports and vulnerability to global market fluctuations.

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1. Infrastructure resilience minimises the impacts of direct climate hazards, for both chronic stresses and extreme shocks, such as changes in extreme heat, water-related risks (i.e. drought, heavy flood) and extreme wind (e.g. tropical cyclones, windstorms). These can manifest as more extreme stresses (e.g. hotter temperatures), more extreme fluctuations of stresses (e.g. greater variation in rainfall between wet and dry seasons), more extreme magnitudes of shocks (e.g. more extreme hurricane events) and more frequent shocks (e.g. more frequent hurricane events).

The risk

Globally, Africa is the most vulnerable to climate change

Extreme weather events affected 19 million people in the continent in 2022 alone and up to 95% of the population is at risk of becoming malnourished in regions such as West Africa by 2050, even under some 1.2°C to 1.9°C warming scenarios. Climate-related damages are projected to be higher in Africa than anywhere else in the world.[23]

By one estimate, Sudan, Mauritania, Mali, Niger, Burkina Faso, Chad, Djibouti and Nigeria may each see their economic growth reduced by at least 25% by 2050, according to current policies.[24] However, GDP estimates typically grossly underestimate both the economic and human risks of climate impacts by not incorporating systemic or cascading impacts such as large-scale migrations and climate-induced conflict, which are extremely difficult to model but whose linkage with climate change is well established.[25] People and regions with high rates of natural resource-use, ecosystem degradation and poverty will suffer the most as a result of their vulnerability, compounding development challenges where it matters most.[17]

Africa's infrastructure gap for climate resilience risks counterproductive development efforts

According to the African Development Bank, the continent requires up to US$170bn per year by 2025 to develop its infrastructure, with the annual financing gap sitting at about US$100 billion.[26] This infrastructure is essential to economic growth and poverty reduction: the current infrastructure gap constrains Africa's growth by 2% every year,[27] reduces competitiveness as exports remain costly due to road and port inefficiency and makes people's lives harder by undermining their ability to work or access education.[28] Natural disasters cost about US$18bn per year in low and middle-income countries through direct damage to power generation and transport infrastructure, straining public budgets and reducing investment attractiveness to private investors.[17] New infrastructure poses a risk and an opportunity: its long lifecycle (often 50-120 years) and the development patterns it locks-in mean that decisions made this decade have significant long-term impacts.[29] Maladaptation - when a measure implemented for climate-adaptation purposes backfires, causing communities to become more vulnerable than they were before that intervention[30] - risks negatively impacting economies through physical damage to infrastructure and economic impacts, creating new or exacerbated vulnerabilities, transferring vulnerabilities towards already-vulnerable groups, damaging ecosystems and driving conflict.[31,32]

Climate resilience must therefore be incorporated into retrofit, maintenance and construction decision making, particularly as haphazard approaches will undermine progress: no level of investment in flood defences can contain or reduce economic losses from floods if urbanisation in flood zones continues.[33] Roads constructed to enable mobility for education, jobs and supply chains may damage local ecosystems upon which local, regional or national communities depend. Infrastructure built to be climate resilient can still undermine the climate resilience of the communities it aims to serve – even compounding vulnerabilities to climate impacts. A lack of thoughtful decision making to maximise synergies between national and community development, ecosystem integrity and adaptation risks unnecessary trade-offs between them – ultimately costing livelihoods and lives.

Resilient roads compared with resilience through roads

Roads interact with surface and groundwater flows, redistributing water-related hazards and resources, with possible consequences on crops, homes, people and livelihoods. A focus on 'resilient roads' might entail using innovative materials to make roads less vulnerable to the damage caused by flooding (e.g. faster cracking) to keep maintenance needs down, but this still risks negatively impacting its surroundings.[34]

Roads can be used to improve community climate resilience, by enabling direct surface run-off for the collection and retaining of water, and even aquifer recharge.[35] Road design can include secondary-purpose flood dykes (ditches), supporting water flow away from areas where people live.[36] Such techniques can reduce flood risks and enable water storage and irrigation for resilience to drought, therefore protecting rural dwellers, farmers and herders from multiple hazards.[36] Building multifunctional roads can deliver on the development gains of improved mobility and build resilience to water-related climate hazards.

Early evidence suggests that the gains from incorporating climate-resilient designs into transport infrastructure projects outweighs the costs and need not be capital intensive. For one project in India, initial adaptation costs were just 3% of the total project costs. Indeed, climate adaptive designs can be low-cost, nature based, use locally available materials and created work opportunities for local people. One of their benefits is lower maintenance costs too, as maintenance costs can be 25% lower for climate-resilient roads.[37]

The current approach and tools on infrastructure for climate resilience are inadequate

Although they are related, the current focus of infrastructure and climate resilience is on climate-resilient infrastructure (resilience of), not climate-resilient people, livelihoods and communities in Africa (resilience through). Most of the 100+ pieces of guidance, tools and standards available to support embedding resilience and sustainability across stages of the infrastructure lifecycle focus on infrastructure resilience – not the resilience of the people the infrastructure serves.[38] This has created a knowledge gap in how to create a pipeline of bankable projects guided by strategic thinking for the users' resilience. There are a lack of decision-making frameworks and case studies built for or drawing on the African context.[2] And tools and principles such as the UN's Principles for Resilient Infrastructure, developed in 2022, calls for a focus on net rather than transformative resilience gains.[39] Tools for more systemic change – whereby small interventions make an outsized impact – are needed, so that scarce financial resources can be used for maximum impact.[22] Failure to shift the analytical approach towards resilience through, to centre the African context, and to seek transformative change by nurturing self-amplifying feedbacks. Inaction risks well-intentioned pro-resilience infrastructure investments at worst undermining resilience of the communities it aims to serve, and at best driving less impact than what was possible.

We need a greater focus on the most vulnerable

It is those in poverty, with very limited or no access to energy, transport and water infrastructure, who are often the most vulnerable to climate hazards. Those in poverty pay the most in time and/or money for the least-regulated services, and their service provision or access is most likely to be disrupted by climate change. In Nairobi, Mukuri settlement residents pay 172% more for less and lower-quality water than in Nairobi's formal settlements with access to public kiosks. [40]

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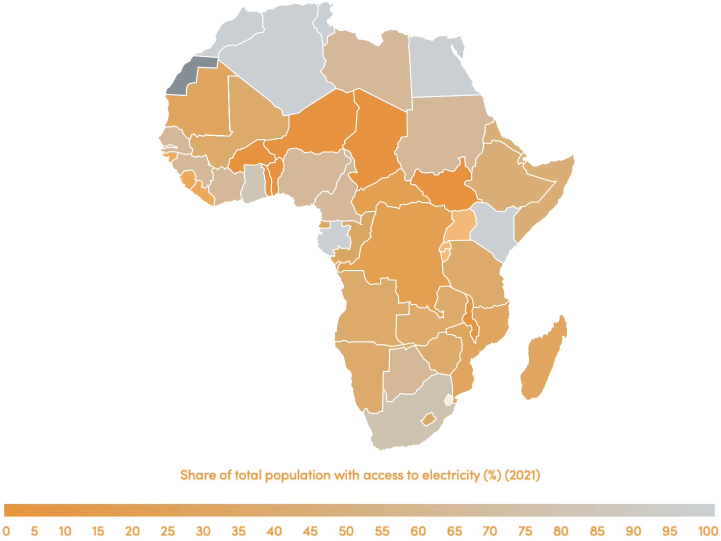
[2] The geographic distribution of the tools within the Resilience Toolbox leaves Africa largely absent. The International Coalition for Sustainable Infrastructure's project tracking innovations in sustainable and resilient infrastructure practices and solutions – which aims to establish an overview of global climate adaptation and sustainability best practices – features no African example.

Figure 2.1.4 illustrates the overlap between the countries with lowest energy access and vulnerability to climate impacts. Across different types of infrastructure, there is a deep urban/rural divide in access on the continent, with an 84% electrification rate in urban areas compared with 29% in rural areas, with much access in rural areas limited to basic electricity for lighting and mobile charging, and with insufficient power for productive, income-generating activities that drive wider development.[41] Of urban populations, 56% live in informal settlements which typically have extremely limited and ad hoc infrastructure available. [42] Those in informal settlements are more likely to suffer heat stress given the materials of their homes and lack of access to powered cooling; any transport systems which do exist are most disrupted by floods given narrow, unpaved surfaces; while informal sanitation solutions are more likely to overflow in the case of flooding.[43]



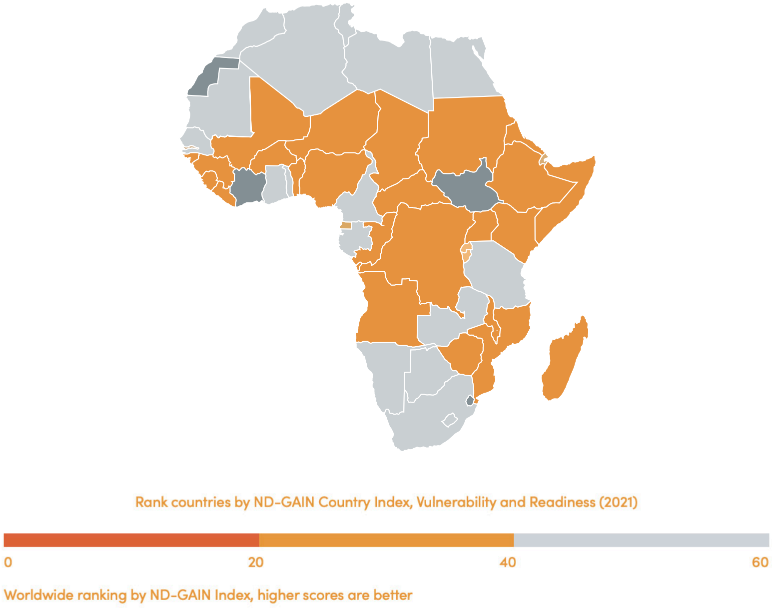


Figure 2.1.4 Populations living without electricity are often those most vulnerable to climate change, illustrating the vital interaction between climate vulnerability and access to critical services. Images source: GOGLA (2023).[79]

The opportunity

A systems lens to investing in infrastructure for climate resilience in Africa can enable infrastructure investments with greater benefits and lower risks.

There are strong synergies between climate resilience and sustainable development through access to infrastructure assets and services for power, transport and water. Power enables access to early warning signals and cooling during heatwaves, and refrigeration for food and medicine. Transport enables mobility and livelihood diversification, and access to diversified food supply chains. Reliable water access in the face of climate shocks like flooding mitigates sanitation challenges and avoids diarrhoea and cholera outbreak. If such infrastructure is resilient to climate impacts, direct coping and indirect impacts and associated costs are avoided. In sum, having enough power, transport and water infrastructure to meet demand is important for overall societal resilience. This infrastructure needs to be resilient itself, and must be designed to increase societal resilience across relevant vulnerabilities.

Most infrastructure projects will have a combination of desired and undesired, expected and unexpected, direct and indirect consequences. This is because they are interventions into our societies, which are complex and unpredictable. South Africa's Gautrain, the first high-speed train in Africa, alleviated traffic congestion and air pollution, spurred economic development in the region, created jobs and stimulated growth across multiple sectors.[44,45] Yet Egypt's Aswan High Dam, constructed to manage the Nile River's annual flooding, enable year-round irrigation and provide hydroelectric power, caused nutrient-rich sediment to flow downstream, leading to increased use of chemical fertilisers, coastal erosion, stagnant reservoir water and significant health issues.[46,47]

To design interventions that have more of the intended, positive consequences, it is necessary to understand the characteristics of 'complex systems' and build these into our decision-making approach.[48,49] The behaviour of complex systems is different to the behaviour of their individual parts, and they are always evolving in response to internal and external pressures (i.e. humans behave differently to individual cells, and human societies behave differently to individual humans). Their behaviour depends on many interrelated dynamics, and is difficult to predict. Cause and effect can be disproportionate: sometimes one small change can trigger many larger effects, both positive and negative (consider the impact of the invention of the mobile phone on global society, or the impacts of COVID-19); while some large interventions may have minimal effects (i.e. many costly development projects fail to drive sustained change).[48,50]

The inherent **uncertainty** about how complex systems will respond to an intervention means that analysis of investment choices should consider direct and indirect, quantifiable and unquantifiable risks and opportunities.[48] Given uncertainty, projects should be designed to be adaptable.

Feedbacks – both reinforcing (e.g. the snowball effect, where it becomes larger and larger as it rolls), and balancing (e.g. a thermostat, which activates to bring the temperature back to a desired state) are key dynamics. Feedbacks can be harnessed to drive change, and to avoid actions that are unintentionally self-defeating. They mean that small, interventions targeted to can – if done well – make a big difference.[51] When assessing risks and opportunities, looking for feedbacks (e.g. through system mapping) can help identify where an intervention can be self-amplifying (therefore rapidly increasing an undesirable or desirable impact).[48,49]

Nature-based solutions (NbS) are an integral part of a systems approach, not least due to their adaptability, cost-effectiveness, and capacity to provide multiple development benefits. The role of NbS as part of the solution to reduce vulnerability to climate hazards and build resilience across energy, transport and water is integrated throughout the report, and for all infrastructure investments the impacts on nature should be considered (see box on p.28). Often, outcomes can be synergistic; for example infrastructure that guides safe and efficient patterns of urbanisation is a key pathway to protecting biodiversity and other ecosystem functions including carbon sequestration from unplanned urban sprawl, as well as ensuring that people have access to vital services. [52,53]

Reinforcing feedbacks examples:

- Oyster reefs have been used as cost-effective coastal protection strategies instead of hard infrastructure seawalls, given reefs' self-repairing quality and adaptability to changing climates. While man-made seawalls degrade and require maintenance, these natural solutions repair, adapt and grow even through changing climates.[54]
- Providing first-time energy access to a household or community can enable one single-mother household to grow her own food even in drought, start her own business for additional income, keep her child in school and eventually employ other women in her community – building a self-strengthening dynamic of individual and community economic and gender empowerment.[55]
- Catalytic finance, with a 'demonstration effect', is when a small amount of finance sparks another investment, and another, resulting in much larger sums being deployed for a given solution. By creating a new pattern of investment, one investment has an outsized impact by changing the behaviour of other investors.[56]

A systems approach creates the opportunity to drive rapid, nonlinear change to accelerate progress in the desired direction, as well as to avoid high-impact unintended consequences. Such an approach is crucial for this challenge given the need for transformational rather than incremental change – particularly in light of vast development needs, urgent climate adaptation needs and limited finance.

Investing in nature-positive development

Healthy functioning ecosystems provide services which are critical to sustainable development, like food provision, freshwater cycling, climate change mitigation and resilience, natural pest-control and flood protection. Africa has among the most intact ecosystems in the world,[57] which provide significant opportunities for 'ecosystem-based adaptation' (EbA) and nature-based solutions (NbS), but which face considerable pressures from economic development. Currently, the continent lags behind others in terms of infrastructure development.[58] This means that there is enormous pressure to accelerate infrastructure critical to develop industries to employ the continent's young population, provide basic services such as energy and water, increase productivity in agriculture and enhance technological connectivity. The development of large-scale infrastructure projects (See The African Development Corridors Database for information on African projects)[59] can provide great benefits for people, but depending on their design, could also produce great negative impacts on the environment, on which people depend for a range of basic and development needs.[59,60]

In the coming decades, rapid urbanisation and economic development require a pipeline of infrastructure development, much of which is likely to be 'nature-negative'.[61] Efforts to counter nature-eroding infrastructure development need to be developed through guidelines, policies and even loan covenants where borrowers put specific conditions on the development of nature-positive infrastructure designs. Considering the ecosystem and biodiversity impacts of new infrastructure can enable investors to limit or mitigate negative impacts. For example, when considering investments for energy access, large-scale hydropower has a significant construction footprint and involves replacing and altering ecosystems at the scale of whole landscapes or river systems; utility-scale solar PV or wind power development can have degrading impacts, but can co-exist or even enhance some existing ecosystems (e.g. agri-photovoltaics can benefit agro-ecosystem productivity); off-grid solar systems may replace other nature-degrading activities like collecting firewood, but may also support un-regulated water extraction. A key mechanism through which this consideration is made is the Environmental Impact Assessment, which, while critical, still has shortcomings of its own.[62] Other emerging tools for disclosure of nature-related impacts of business (e.g. Science-based Targets for Nature, Task-force for Nature-Related Disclosure)[63,64] are supporting consideration of nature in business and investment decision making.

In some cases, infrastructure developers can work to incorporate EbA or NbS approaches to strengthen co-benefits for infrastructure users, nature, and financial return. EbA features strongly in most African countries' Nationally Determined Contributions to the Paris Agreement (NDCs), with particular opportunities in water management to reduce costs and risks to infrastructure (e.g. through integrated water management and sustainable catchment management), as well as in agriculture and forestry.[9] Further work remains to provide systematic evaluation of these opportunities, but many case studies exist that demonstrate how effective these solutions can be.

2.2 Investment criteria

As an approach to identifying infrastructure investments with the greatest potential gains for resilience, we propose the following framework. This is structured as a set of questions for investors to consider, addressing both the resilience of the infrastructure and its effect on societal resilience. In the table below, these questions are accompanied by examples of resilience strategies, indicators and outcomes. An applied example of SunCulture, a solar irrigation company, is on p.73.

Theme	Question	Strategies / indicators	Examples
Physical resilience of infrastructure assets and systems	**Is the project robust and/or adaptable to the physical hazards posed by current and future climate impacts of its location (even under a wide range of climate scenarios)?** **Can additional actions be taken to ensure high performance under climate extremes, at reasonable cost?**	• Technology choice for resilience. • Physical design measures. • Adaptability/reversibility (e.g. shorter lifecycle). • Safety margins (reduce vulnerabilities at low upfront cost).	• Solar infrastructure more resilient to drought than gas/oil. • Elevated infrastructure for flood resilience. • Wind/solar have 25-year lifespan, enabling iterative decision making. • Some nature-based solutions are self-adapting to climate impacts.
	Does the project improve the resilience of the infrastructure network of which it is a part?	• Diversification of inputs or system decentralisation. • Prioritisation of critical infrastructure and vulnerable populations when recovering from failure.	• Solar/wind diversifies a grid dependent on hydropower. • Off-grid renewables avoid putting additional pressure on grid and may prevent outages for critical infrastructure. • Centralised solutions which prioritise hospitals for service provision/improvement/recovery.
	Is the project designed to mitigate or be resilient to behavioural shifts driven by climate impacts (e.g. increased demand for power for cooling or increased water consumption)?	• Redundancy is built in. • Demand-mitigation measures (e.g. nature based solutions). • Alignment with government adaptation.	• Water storage sufficient for increased water consumption during drought and heatwave. • Urban tree-planting to reduce urban heat-island effect. • Investment aligns with a city's urban plans for climate resilience.

Theme	Question	Strategies / indicators	Examples
Economic and social development foundations	**Does the project provide accessible, reliable and affordable energy, transport or water access for the first time?**	• Expands water, energy, transport infrastructure.	• See case studies throughout. For a project to qualify as 'no regrets', it should provide these benefits across a wide range of future uncertainties and be adaptable.
	Does the project deliver co-benefits such as health, food or water security, or access to information?	• User-centred design. • Multi-purpose infrastructure. • Nature-based solutions.	• User centred design in one case study to expanding energy access sufficient for refrigeration, which is often not considered as a 'basic need' by energy access projects. • Roads designed for water harvesting. • Fruit trees reduce urban heat-island effects and improve food security.
	Does the project enhance the economic resilience of users?	• Solutions are affordable/ cheaper/more time-efficient than existing options. • Solutions enable new/improved economic.	• Piped water which improves access and reduce price of water compared with kiosks and reduces time needed. • Powered refrigeration which creates new business.
Direct adaptation benefits	**Does the infrastructure provide direct adaptation benefits to extreme heat, drought and flooding?**	• Reduced vulnerabilities to heat stress, drought or flooding.	• Investments which power r eliable cooling solutions or deliver reliable water provision and sanitation.
	Does the project deliver adaptation benefits for all impacted communities (users, upstream/downstream communities, future generations)?	• Stakeholder consultation/user-centred design. • Actively shape safe settlement patterns/align with urban plans for adaptation.	• Roads which deliver water storage for local farm irrigation. • Nature-based solutions which create local, sustainable jobs. • Engagement which shapes local/gov. policy.
Direct resilience benefits	**Does the infrastructure improve people's ability to cope with/ recover from acute climate hazards?**	• Enables early warning signals. • Enables delivery of emergency supplies. • Enables financial resilience.	• Powers early warning signals (e.g. radio/TVs). • Climate-resilient roads. • Asset insurance for climate-related incidents.

Theme	Question	Strategies / indicators	Examples
Macroeconomic resilience benefits	**Does the project help decrease dependence on fossil-fuel imports (and ideally other imports too)?**	• Clean energy/transport solutions. • Circular business models. • Nature based solutions.	• Electric motorbike service, ideally locally manufactured. • Waste-to-energy plant delivering heat as a service.
	Does the project avoid environmental harm, by reducing emissions, air pollution and/or biodiversity loss (ideally enhancing local ecosystems)?	• Clean energy/transport solutions. • Circular business models. • Nature based solutions.	• Bus Rapid Transport systems. • Roads built to mitigate impact on animal migration patterns. • Wetlands water treatment solutions.
	Does the solution maximise how it can strengthen local and national economies?	• Creates local industry at assembly/manufacturing level appropriate to development stage.	• Creates local supply chains. • Trains/employs more vulnerable groups.
Mitigating risks	**Have possible negative consequences (e.g. how desired impacts might backfire) of proposed solutions been considered – and is there a process to regularly review this?** **Are there challenging trade-offs to consider?**	• Systems mapping and stakeholder consultation to identify new dependencies/ possible cascading impacts / self-amplifying effects. • Case study analysis and comparison.	• Adaptation efforts can inadvertently introduce longer-term risks and/or improve the vulnerability of some communities, at the expense of increasing it for others, or create a false sense of security. Systems mapping and stakeholder consultation can elicit these risks. • Difficult trade-offs, where negative impacts may occur under some scenarios, probably mean the project is not low-regrets.
Maximising opportunities	**Does the project drive progress towards desirable positive tipping points and cascades, or nurture desirable feedback loops?** **This might be by improving the enabling environment, delivering an innovative financial solution, or working with partners.**	• Self-strengthening nature based solutions. • Funding with a demonstration effect. • Risk-aware capital which crowds-in private finance. • Align with government adaptation strategies, lobby for policy change or work with local organisations to ensure most vulnerable are centred.	• Adaptive oyster reefs for coastal flood protection. • Public Private Partnership for water treatment plant the first of its kind in SSA, demonstrating viability of the blended finance approach. • Solar-irrigation company which partners with others to make solar panels exempt from VAT. • Waste-to-energy plant which works with governments on their water adaptation strategies, and works closely with utility companies and local organisations to deliver user-centred solutions.

Table 2.2.1 Prototype Investment Criteria for climate resilience through infrastructure.

3.

Sector **Applications**

3.1 Energy

Using a structured systems thinking approach allows investors and developers to rigorously explore the highly contextual risks and opportunities presented by projects across different sectors and in different geographies. Many sectors are vital to development, and in the next sections we apply this thinking to three of the most critical: Energy, transport and water infrastructure. The challenge, opportunity and the types of adaptation and resilience benefits are outlined for each sector.

Key Messages

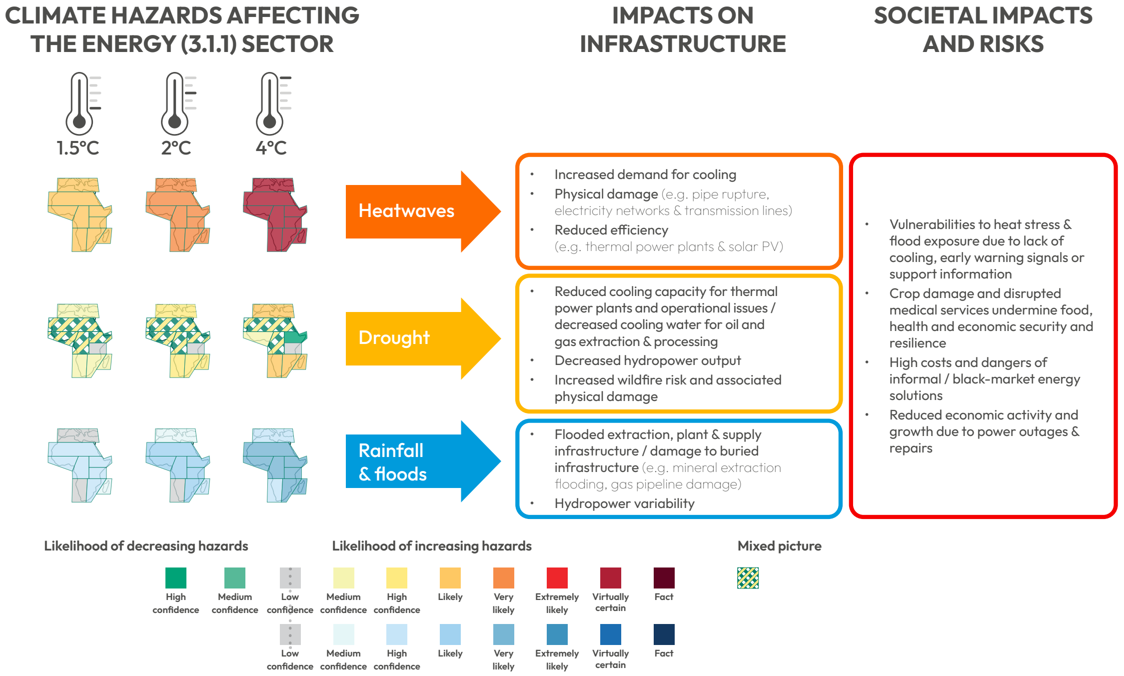
- Access to clean, affordable and resilient energy systems is foundational for development, yet much of Africa's energy infrastructure is highly vulnerable to climate hazards.
- Although climate-resilient infrastructure is a good start, it does not create climate-resilient communities by default.
- There are ways to invest in energy infrastructure to reduce future economic losses from physical damage, reap economic benefits, and improve socioeconomic and environmental benefits of development and habitat protection.
- The key benefits are outlined in the following section – many of which are most effectively achieved through off-grid solar projects.
- Investments remain focused on utility-scale projects and in few major markets, implying the need for a focus on off-grid systems for the most vulnerable (largely outside) these markets.

The challenge

Access to clean, affordable, resilient energy systems is foundational for development.

Energy infrastructure powers access to cooling and heating, extra hours for studying or work, machinery to power agricultural and other economic activities, clean water, communications and information through the use of mobile phones, and reduces health issues associated with biomass-fuelled cooking. It plays a critical role in healthcare, sanitation, telecommunications and resilient livelihoods. Nearly 600 million people in Sub-Saharan Africa do nothave access to electricity, though many more who do do nothave enough to live an economically productive life.[55,65]

Yet much of Africa's energy infrastructure is highly vulnerable to extreme weather (Fig 3.1.1). Power systems in developing countries are more vulnerable to natural shocks than those in richer countries due to lack of maintenance, rapid grid expansion and insufficient generation capacity.[66] Over 60% of Africa's thermal power plants are at high or very high risk of being disrupted by water stress due to reduced availability of water for cooling or transporting fuel.[66] A significant portion of its refining and liquefied natural gas capacity is exposed to medium or high water-stress risk.66 Hydropower output is suffering from both drought and flooding.[66] According to some scenarios, hydropower generation could decline by over 60% by 2050 in the Zambezi basin and drought in 2014-2015 already led to a 50% decline in Zambia's hydroelectric generation.[67] Higher temperatures are increasing transmission losses due to the increased resistance of power lines.[68] Electricity systems in Africa are already witnessing increasing climate resilience challenges, which threatens energy security at household, community and national levels, with resulting economic and social losses.[66]



- Increased demand for cooling
- Physical damage (e.g. pipe rupture, electricity networks & transmission lines)
- Reduced efficiency (e.g. thermal power plants & solar PV)

- Reduced cooling capacity for thermal power plants and operational issues / decreased cooling water for oil and gas extraction & processing
- Decreased hydropower output
- Increased wildfire risk and associated physical damage

- Flooded extraction, plant & supply infrastructure / damage to buried infrastructure (e.g. mineral extraction flooding, gas pipeline damage)
- Hydropower variability

- Vulnerabilities to heat stress & flood exposure due to lack of cooling, early warning signals or support information
- Crop damage and disrupted medical services undermine food, health and economic security and resilience
- High costs and dangers of informal / black-market energy solutions
- Reduced economic activity and growth due to power outages & repairs

Figure 3.1.1 Vulnerabilities to energy infrastructure and associated societal impacts of projected climate change in Africa under 1.5°C, 2°C and 4°C scenarios.

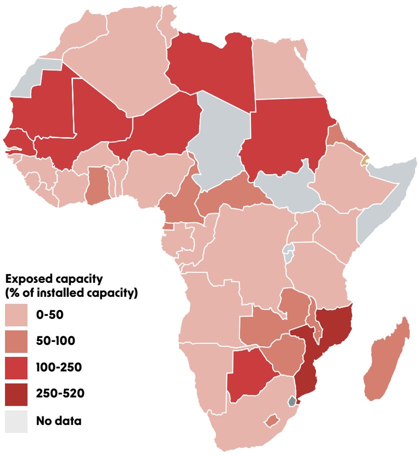


Figure 3.1.2 Exposure of African power generation to multiple hazards. Colour intensity shows total exposed capacity for all hazards by the total installed capacity in each country. Values may exceed 100% because one power plant can be exposed to more than one hazard. Power plants are considered to be exposed to a hazard when they are in an area in which the hazard level is 'high' in the ThinkHazard. Hazards considered are: coastal flooding, earthquakes, floods, water scarcity, cyclones, volcanic eruptions, tsunamis, extreme heat and wildfires. Source: Koks et al (2019)[69].

Date	Location	Type of climate impact	Affected segment	Impacts
Jan 2023	Zambia and Zimbabwe	Drought	Hydropower plants	Lack of water in dams required load shedding and power limited to 12 hours per day for several weeks.[70]
Apr 2021	Central African Republic	Torrential rains	Electricity towers	Power supply interrupted for weeks, impacted water supply and health.[71]
Jan 2021	Mozambique, South Africa	Tropical cyclone and associated flooding	Electricity grid and coal power plants (wet coal)	Falling trees and poles caused power outages. Eskom lost 14GW generation and had to implement contingency measures.[72]
Dec 2019	Uganda	Drought	Hydropower plants	20% grid capacity suddenly went offline, causing a blackout, because two of Uganda's hydropower plants were blocked by flood debris caught in turbines.[72]
Mar 2019	Mozambique, Madagascar, Malawi, Zimbabwe	Cyclone and flooding	Electricity grids and hydropower plants	Two major hydropower plants in Malawi went offline, reducing capacity from 320MW to 50MW and causing blackouts and loss of hydro export revenue. Power returned six weeks later.[72]

Table 3.1.1 Selected climate events and their impact on energy infrastructure in Africa.

Energy infrastructure types and risks to climate hazards

Type	**Coal**	**Gas**	**Oil**	**Nuclear**	**Hydro**	**Solar**	**Wind**	**Grid**
Extreme heat	🟨	🟥	🟨	🟥	🟨	🟥	🟨	🟥
Drought	🟩	🟧	🟥	🟨	🟧	▨	🟩	🟩
Rainfall and floods	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟥
Sea level rise	🟩	🟨	🟧	▨	🟩	⬜	⬜	⬜
Wind (cyclones)	🟨	▨	🟨	🟨	🟨	🟨	🟥	🟨

Table 3.1.2 Source: IEA (2022)[73]. Key: Very high, High, Medium, Low, Very low, No data[3]

🟥 *Very high*
🟧 *High*
🟨 *Medium*
🟩 *Low*
▨ *Very low*
⬜ *No data*

Yet energy infrastructure does not create climate resilience by default, and there is risk of maladaptation.[74] Cold-chain solutions – critical to food security – may emit gases such as HFCs, with high global warming potential, in turn accelerating climate change. Infrastructure system interdependencies can amplify the impacts of a shock as disruptions within interdependent systems cascade: power grids, for example, often linked to water supply and ICT infrastructure, mean that one disruption in a given component causes outages across systems.[17]

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[3] The table shows climate change risks to refineries and mines globally. SSP1-2.6 and SSP5-8.5 are used for the low-emissions and high-emissions scenarios respectively. Climate risks are divided into five categories, from dark green for low risks to red for high risks. Grey indicates a lack of data. The levels are determined based on the combination of hazard, exposure and vulnerability. See original IEA source for full methodology.

The opportunity

Investment into energy systems which are climate resilient themselves and deliver climate resilience for the most vulnerable have the opportunity to reap a 'triple dividend' of reduced future economic losses from physical damage, economic benefits of increased productivity and innovation, and the socio-economic and environmental benefits of development and habitat protection.[75]

Climate resilience of energy infrastructure

Measures to improve the resilience of energy infrastructure include physical system hardening (e.g. elevated infrastructure, heat/humidity/salt-resistant materials, robust solar panel mounts and substations to protect from extreme winds, strengthened wind turbine structures, hydropower plant reinforcement and improved outlets/spillways), switching to water and heat-resilient production, diversifying energy supply chains and introducing climate-monitoring systems for early warning and emergency response.[73] Nature-based solutions such as tree-planting in upstream catchment areas can also protect against risks such as wildfires and landslide-related damage, while integrated solutions such as floating solar PV in existing reservoirs can help to reduce evaporation and increase efficiency and resilience of water resources for both drinking and hydropower generation.[77,78]

Yet while adaptation measures may be necessary for any power generation, off-grid technologies are typically some of the most resilient to climate risks. Their small, distributed nature makes them portable if climate events drive migration. They do notrely on long-distance cables and infrastructure, which create vulnerabilities to floods, high winds and cyclones. Heatwaves do not cause blackouts. They are not affected by high rainfall or drought, unlike large-scale hydropower. With no fuel supply chain, they still function and are unaffected by fuel cost rises or fuel supply chain disruptions.[79] Even larger off-grid solutions, such as walk-in cold rooms, cold storage for transportation and agriculture processing, though less portable than smaller lighting and home system kits, are delinked from grid-scale infrastructure. They are still less vulnerable to blackouts and fluctuating fuel prices, supporting communities to build the health and agricultural infrastructure they need to increase resilience to extreme weather.[79] Decentralised solutions can also reduce increasing pressure on on-grid services, protecting against large scale outages. Digital solutions such as smart grids are a key part of the on-grid solution needed for enabling access to affordable, reliable electricity.[80]

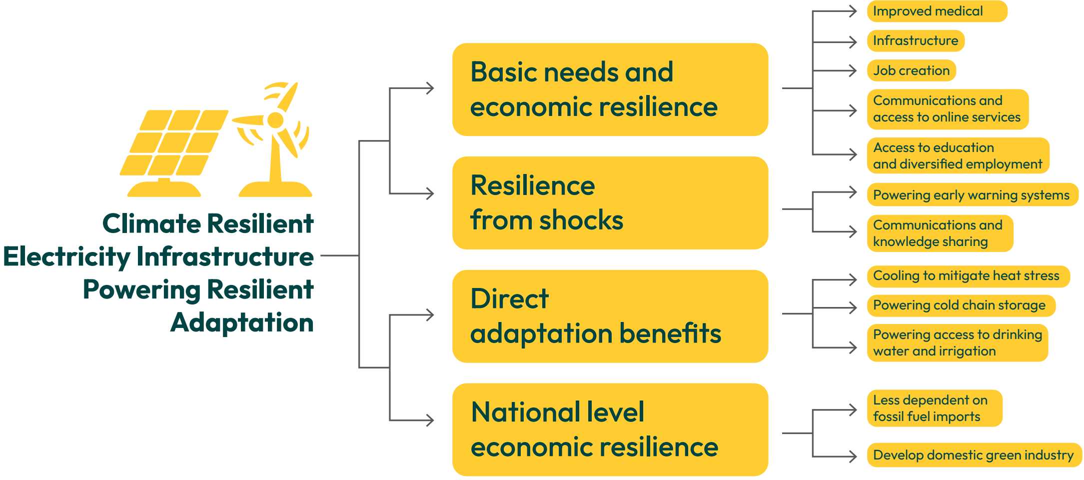


Figure 3.1.3 Pathways for resilience and adaptation through clean energy infrastructure development.

Sustainable development and climate resilience benefits can be provided by a wide range of energy solutions in different contexts. In general, access to electricity brings economic benefits that enhance resilience through increased productivity, alternative livelihoods, access to information and communications. Both utility-scale and off-grid renewables are a crucial part of the shift away from fossil-fuel dependence. The examples below primarily focus on off-grid solar technologies. This is because they should be the primary way to power modern electricity services for those who lack it today, both for domestic and productive uses, according to the IEA, World Bank, IPCC and others.[84] Over 80% of the electricity-deprived live in rural areas, where mini-grids and standalone systems are estimated to be the most viable given the speed, ease and affordability of installation. Indeed, they are estimated to be the least costly and most viable way to electrify 55% of those who lack modern electricity.[72]

Case study 1:
National scale diversification of Kenya's energy system

Context and risk: In 1996, hydropower constituted almost two-thirds of energy generated, energy supply was being affected by droughts, and energy demand was growing.[68,81] This drove recurrent load shedding and forced the country to rely on expensive rental generation.[81] Given droughts, the service reliability and economic stability of Kenya's future energy system was at risk.

Interventions: The country championed a diversified least-cost, local, climate-resilient solution, pursuing geothermal and other renewables which were less vulnerable to drought. Over several decades, it built a well-diversified mix, now constituting nearly 85% energy generated from geothermal (about 50%), hydropower and wind, including the expansion of off-grid solutions as it expanded energy access.[82]

Climate resilience outcomes: While expanding energy to 75%, Kenya's energy supply is also now less vulnerable to increasing drought and rainfall variability, reducing climate hazard-related outages and associated economic and social impacts.

Systems thinking prompt

Avoiding maladaptation through stakeholder engagement: At a project level, the Lake Turkana Wind Project, the largest wind-power project in Africa, biggest private investment in Kenyan history and a key element of the diversification strategy, caused controversy given significant impacts on social dynamics in an area already subject to high poverty and drought, and in a country where drought is already exacerbating conflicts over scarce water and pasture. By giving concessions to the Sarima tribe, the project raised the stakes of belonging to this group, reanimated conflicting versions of local history and belonging, and crystallised ethnic identification. More in-depth participation to understand the local context and potential cascading impacts may have revealed this risk and led to an alternative design of concessions.[83]

1. Socio-economic development foundations

Poverty reduction, the delivery of basic needs and the creation of a financial safety net improves people's ability to invest in adaptation and recover from chronic and sudden climate impacts.

Off-grid clean energy systems are particularly effective. A 2021 Uganda Poverty Report found that new electricity access, including via solar home systems and kits, had the highest impact of any public good on the reduction of poverty levels within the country, leading to a decrease in poverty of over 10%.84 Savings generated by owners of small solar products who no longer needed to pay for kerosene were redeployed as investments into livelihoods, allowing vulnerable populations to bounce back faster from the economic shocks created by climate hazards, while also supporting economic growth. Clean cooking solutions, too, have multiple benefits, enabling women and children to save time collecting firewood, boosting economic and educational outcomes. Off-grid solar technologies help families avoid illness and contribute to improvements in medical infrastructure. About 90% of solar home system customers in East Africa report that the technologies improve health and safety, while solar irrigation and cooling systems improve access to clean water and food, in turn reducing water-borne illness and malnutrition.85 In India, primary health centres in the state of Chhattisgarh with off-grid solar supply admitted over 60% more patients and conducted almost twice the number of child deliveries in a month than those operating without solar.86

The off-grid sector has also unlocked many jobs and entrepreneurial opportunities.
In East Africa, an estimated 21 FTE roles are created for each 100 solar homes systems sold, with 8 FTE roles being created per 100 in West Africa.85 With off-grid solutions, communities can often access the power and appliances they need to modernise agriculture, boost food and water security, sustain health infrastructure and create clean energy businesses and jobs. Business models can enable multiple solutions, through sales of low-carbon, high-impact products such as clean cookstoves, water purification systems, smartphones, TVs and radios, thereby enabling access to clean cooking and drinking water as well as news, emergency announcements and adaptation knowledge. Off-grid solutions particularly improve the welfare of communities through the creation of job opportunities, health and agricultural infrastructure, creating economic prosperity: a core foundation of resilience.

Case study 2.

Data-driven solar home systems with Bboxx

Context and risk: Electricity access was low in Bboxx's target countries (e.g. 19% in DRC, 19% in Burkina Faso and 47% in Rwanda) and while the solar home systems market was relatively well proven in Kenya, Nigeria, and Rwanda, it was not proven in others such as DRC or Burkina Faso.

Interventions: Bboxx provides a 'plug and play' solar home system (SHS) designed for rural off-grid customers typically using candles and kerosene lamps. Once connected, the smart system powers lights, radios and TVs, and mobile phones for households and micro-businesses – as well as enabling access to clean cooking, smartphones and e-mobility, often for the first time.[87,88] The off-grid pay-as-you-go (PAYG) model allows users to pay for energy services on a pay-as-you-use basis, rather than upfront, making the solution more affordable. Bboxx gained government subsidies in multiple countries to expand its service and, in 2022, accepted an investment from InfraCo Africa among others to expand access to less-served populations such as those in the DRC, rural Rwanda and Nigeria, and Burkina Faso.[89]

Climate resilience outcomes: InfraCo Africa's investment helped Bboxx expand into higher-risk markets in the DRC, aiming to provide confidence to other solar home system companies and their investors. Evidence of a demonstration effect may emerge in the next 2-4 years. At a company level, Bboxx's decentralised renewable energy systems make power supply more resilient for consumers and businesses in the event of extreme weather events which impact grid supply. [90] Its SHSs improve energy independence (due to decreased dependence on national grids more vulnerable to outages; and decreased fuel costs for customers); enhance education and communication (the radio which comes with standards SHSs can be used for early warning signals; and the smartphone charging facilitates improve their uptake and usage, improving access to the internet); and have reduced indoor air pollution through the replacement of 80,000 kerosene lamps. At least 10,000 direct jobs have been created, for Bboxx staff, sales agents or indirectly from small enterprises enabled on the Bboxx platform (e.g. barber shops, powered TVs for movie stations and solar-irrigation for farmers). According to Global Off-Grid Lighting Association (GOGLA)'s methodology, it is estimated that 980,000 lives have been improved.[91]

Systems thinking prompts

Avoiding maladaptation: A key resilience risk for the SHS businesses and customers is non-payment, given low income and resilience to economic shocks resulting in default. Bboxx's smart, PAYG system aggregates vast data, enabling granular Know-Your-Customer (KYC) checks and monitoring, enabling the company to propose cheaper solutions at the outset for more at-risk customers. This reduces the likelihood of overextension and indebtedness.[91]

Physical resilience for future scenarios: In Kenya's Homa Bay, April 2023, unusually torrential rains and winds affected some customers as roofs were blown off houses. Bboxx replaced the SHSs – but does not currently have insurance for itself or customers should a climate-induced hazard have more significant impacts. The key trends expected in Kenya and Rwanda include increases in high temperatures and risk of heat stress and increased river flood frequency. In the DRC, longer and more intense heatwaves will be particularly dangerous given humidity, while increased landslides have also been observed. In Nigeria, Togo and Burkina Faso, increased rainfall and flooding is projected. The company is currently developing a climate resilience action plan, which will need to account not only for historical climate trends but these projections – including uncertainties.[91]

2. Direct climate adaptation benefits

Climate impact	Climate adaptation and resilience opportunities of energy infrastructure access
Heatwaves	• Cooling solutions mitigate heat stress. • Cold-chain and refrigeration solutions preserve food and vaccines. • Clean cooking solutions / powered irrigation solutions reduce exposure to heat when seeking firewood or undertaking manual irrigation.
Drought	• Powered irrigation solutions prevent or lessen crop failures or yield declines.
Rainfall and floods	• Clean cooking and heating solutions reduce reliance on wood and charcoal, reducing deforestation and desertification, and in turn reducing flood risks and associated impacts. • Provision of energy infrastructure in safe urban expansion zones can shaping safe urbanisation patterns away from high-risk flood zones.
Sea level rise and floods	
Crosscutting	• Off-grid solutions can ensure healthcare infrastructure operate under increased pressure, powering lighting, equipment, and refrigeration. • Electricity-powered digital devices enable access to early warnings about approaching climate hazards. • Avenues for e-commerce/digital opportunities enable people to engage in economic opportunities not dependent on specific weather conditions.

Table 3.1.3 Direct climate adaptation benefits of energy infrastructure

Beyond creating economic resilience, energy systems provide direct adaptation benefits. First, solar space cooling, for example, has the potential to benefit 318 million people globally who lack electricity and live in countries at highest risk of extreme heat.[92] Second, Qandu Qandu's SHS solution for rural off-grid customers showcases refrigeration solutions that are delivering multiple forms of climate resilience to informal settlement dwellers in South Africa. Third, Freetown's initiative showcases the role of nature-based solutions in reducing potential pressure on power infrastructure, by reducing flood and landslide risk (which risks physical damage to power infrastructure) and by reducing the urban island heat effect (mitigating increased cooling needs during extreme heat).

Nature-based solutions for electricity-free cooling

The combination of the urban heat-island effect with climate change makes Africa's rapidly urbanising population particularly vulnerable to extreme heat stress.95 The presence of trees and other green spaces in urban environments is an important buffer of heat stress, by providing shade and cooling through increased transpiration.[96] Cities across the Global South tend to have significantly less green space than those in wealthier countries, and African cities are the least green compared to other continents. Consequently, their citizens experience less temperature amelioration benefit. For example, Douala (Cameroon) and Fes (Morocco) both experience on average only around 0.1°C of cooling by vegetation, while cities such as Lyon (France), Sydney (Australia) or Kansas City (US) all experience over 5°C of cooling.[96]

Enhancing the quantity and quality of green spaces in African cities, for example through urban tree-planting, parks and roof-top gardens could provide cooling of several °C, making a significant contribution to improving resilience to heat stress. In turn this can reduce the need for expensive and energy-intensive solutions. The 'Freetown is Tree-town' initiative offers an example of a strategic, holistic approach to building urban resilience through increasing green spaces.

Case study 3.

Microgrids for energy access and refrigeration in the informal settlement of Qandu-Qandu, Khayelitsha, Cape Town South Africa

Context and risk: Qandu-Qandu, an informal settlement of 3,500 self-built households, is not connected to the electricity grid, the settlement is located on land prone to regular flooding, and energy sources used include illegal (and therefore often unstable/unsafe) grid connections, charcoal, paraffin and diesel for use in portable generators, posing risks to personal and community safety from shack fires, high costs and health risks such as asthma.[93,94]

Interventions: Through in-person surveys, the project identified lack of safe, reliable and stable electricity; lack of an electricity source powerful and affordable enough to power fridges; and lack of a finance model ensuring that a utility would provide affordable energy over the long term. Deep engagement across 48 settlements enabled researchers to identify common characteristics of the settlements compared with context-specific differences – deepening their understanding about how the solution might be scaled and/or tailored to new contexts. A modular solar mini-grid technology based on solar towers with a solar PV panel, some of which had battery units below for storage, was designed to be powerful enough to run fridges. Through an energy utility, different energy packages were offered to residents for affordable energy provision for lighting, phone charging etc, and others were offered in conjunction with training for women to run businesses based on refrigeration, enabling it to generate income.[93,94]

Climate resilience outcomes: The user-centred approach (deep stakeholder engagement among settlement dwellers, municipality and national government employees), resulted in an infrastructure solution tailored to the users – including refrigeration often deprioritised by development agencies. This enabled women to set up microenterprises such as lemonade stands. In the face of projected increases in heatwaves, food and medicine can also be preserved. It also addressed the safety hazards of unclean and illegal solutions.[93,94] The project design processes, including construction and pricing, were highly iterative, demonstrating capacity to adapt for new (e.g. climate vulnerable) contexts.

Systems thinking prompts

Avoiding maladaptation: The project is a direct solution to immediate challenges faced by settlers, but did not appear to engage with how it might risk encouraging urbanisation into increasingly high flood-risk areas, which result in winter floodings and contamination with sewage.[91]

Case study 4.

Nature-based cooling solutions to heat stress in Freetown, Sierra Leone

Context and risk: Freetown endures intensifying heatwaves and humidity, compounded by the urban heat island effect, which is itself intensifying due to deforestation and urban expansion. The combination of heat and humidity is a particular danger for heat stress – and is especially dangerous for the young, elderly, those working in exposed conditions like farmers, market vendors and street traders, and the 35% (and growing) residents who live in informal settlements of sheet metal houses which trap heat and lack cooling mechanisms. Intense heat has already resulted in lost worker productivity as a share of output of 3.5%,[97] and has health impacts including increased malaria and heat-related hospitalisations and mortalities.[98]

Interventions: The city council's 'Freetown the Treetown' nature-based solutions initiative is a tree-planting, growing, mapping and tracking approach to mitigate heat stress, flooding and landslide risks for residents. It aims to increase the city's tree canopy by 50%.[99] Early projects focused on the highest-risk areas, with 35% of areas targeted for new trees in informal settlements, where the poorest, most vulnerable populations live and which has the lowest tree coverage.[100] It is a community-led model: reforestation is co-designed and co-managed by the community and city government, with Freetown residents involved in decision making on where trees are planted and receiving micro payments for tree planting and maintenance. The council has proactively procured from local tree nurseries and other businesses to ensure the project economically supports local economies.[100,101] An initial US$1.8m from the World Bank kickstarted the project, which is now gaining private capital investment through a natural capital approach by selling 'impact tokens' generated from the trees.[102] Local growers use a tree-tracker app to track planting and growth (with a geotag per tree); tree IDs are turned into 'impact tokens,' which are bought, sold and traded by corporations to offset their carbon and support net-zero pledges, generating revenue to fund more tree-planting.[100,102] Revenue from access to carbon markets will eventually fund further climate resilience infrastructure (e.g. large-scale urban drainage and housing construction/retrofits).[91]

Climate resilience outcomes: The project's trees will provide shade and a cooling effect particularly alongside roadsides, schools and in residential areas, as well as improving biodiversity and air quality and helping address food insecurity (e.g. by planting fruit trees) – thereby addressing multiple ecosystem, health and food resilience risks simultaneously.[100,102] Early modelling is indicating improved slope stabilisation (i.e. resilience to landslides driven by increased rainfall) and data is being collected to measure heat mapping and the reduced impacts of heat stress among those without access to affordable, reliable power for cooling. Second, it is expected that the cooling impact of the trees will reduce pressure on the power system during heatwaves. Third, more than 550 direct and 1,000 indirect jobs were created, with a focus on the marginalised, vulnerable and underemployed.[103] Fourth, by improving air quality, it increases people's health, making them more resilient when faced with the health consequences of extreme heat. Fifth, the development of a private-sector revenue stream in the form of impact-tokens improves the economic sustainability of the project and aims to raise the revenue for the more expensive grey infrastructure solutions needed to further urban cooling.[104,105]

Systems thinking prompts

Avoiding maladaptation: A potential risk was that the project became a victim of its own success, increasing the rate of informal urbanisation, a key driver of landslides, flooding and urban island heat.[91]

Partnership and collaboration: A critical element of this initiative is that it's not a single project, but rather a wide-scale portfolio directly designed to deliver the city's adaptation plan (which, for example, includes green roofs, pocket parks and water features too). Interventions are designed to intentionally reinforce one another's benefits. The city council is also supporting another three cities by September 2024 year to have published climate actions plans inspired by the Treetown initiative.[91]

3. Direct climate resilience benefits

Climate impact	**Climate adaptation and resilience opportunities of energy infrastructure access**
Heatwaves	• Powered public buildings can become cooling centres during extreme heat events, providing refuge for those without home-cooling solutions.
Drought	• Ensure ongoing access to clean water through electricity (e.g. solar) powered water pumps, particularly crucial during periods of drought and extreme heat.
Rainfall and floods	• Power water from drain-flooded areas and manage water levels in waterways. • Increased infrastructure options such as automated flood gates and barriers.
Sea level rise and floods	
Crosscutting	• Access to information through charging mobile phones, radios or TV, enabling information and robust communication networks about upcoming or recent hazards and gaining health advice. • Community centres with energy access as hubs during and after disasters, offering shelter, communication and essential services.

Table 3.1.4 Direct climate resilience benefits of energy infrastructure.

Energy systems improve people's ability to respond to and recover from chronic and acute climate impacts. One key benefit is knowledge transfer. An estimated 4.3m solar-powered radios, 1.9m solar TVs and 30m off-grid solar energy kits with phone-charging capacity have been sold to date; the majority to rural customers who struggle to access basic connectivity services. East and West Africa found that having a solar home system enabled the vast majority to use their phone more (89% and 93% respectively).[106] A study in Cote d'Ivoire found that mobile internet penetration jumped by 31% when customers had access to PAYGo solar.[107] Such access to phones and media can provide advance warning of climate impacts and share advice on appropriate responses. Powering of early warning signals are also critical resilience benefits. Compact, portable solar energy technologies can aid communications to connect aid agencies with communities in affected regions, provide cold storage for medical supplies and supply light and phone-charging services for emergency shelters, supporting response to disaster. To respond to Mozambique's cyclone Idai when the grid stopped operating for several days, solar energy kits with lighting and phone-charging capabilities were provided to NGOs by off-grid companies to support response efforts.[108]

4. National-level economic resilience

The transition away from fossil fuels not only contributes to mitigating climate change, but increasingly provides economic opportunities and resilience benefits for fossil fuel-importing countries, increasing their capability to invest in climate-resilient development. Most African countries do nothave domestic fossil fuel resources, and the critical minerals needed for the green transition abound on the continent. Renewables are already passing price-parity tipping points that make them more cost-competitive than fossil-fuel options in most markets.[109] The shift from fossil fuel to renewable-powered economies could save African countries huge sums on avoided fossil fuel imports.[110] The export of critical minerals for international renewables growth can support national and regional economies, while the creation of domestic manufacturing renewables industries has huge potential to create opportunities for jobs and industrial development.[111] All of these can contribute to long-term economic resilience and capability to invest in specific adaptation and resilience efforts. Key challenges include the perceived risks of investing in countries in Africa driving high costs of capital, lack of grid infrastructure and the need for deeper regional integration of power systems.

The infrastructure investment gap

Despite these findings, Africa currently remains heavily dependent on fossil fuels. Clean energy investment in Africa in 2021 sunk to an 11-year low, and the COVID-19-driven economic downturn worst affected the installation of new stand-alone off-grid systems.[112] Nearly three-quarters of renewables investment in the continent is concentrated in a handful of major markets (South Africa, Egypt, Morocco and Kenya).[113] In essence, investments in clean energy solutions which deliver on climate resilience are needed across the continent.

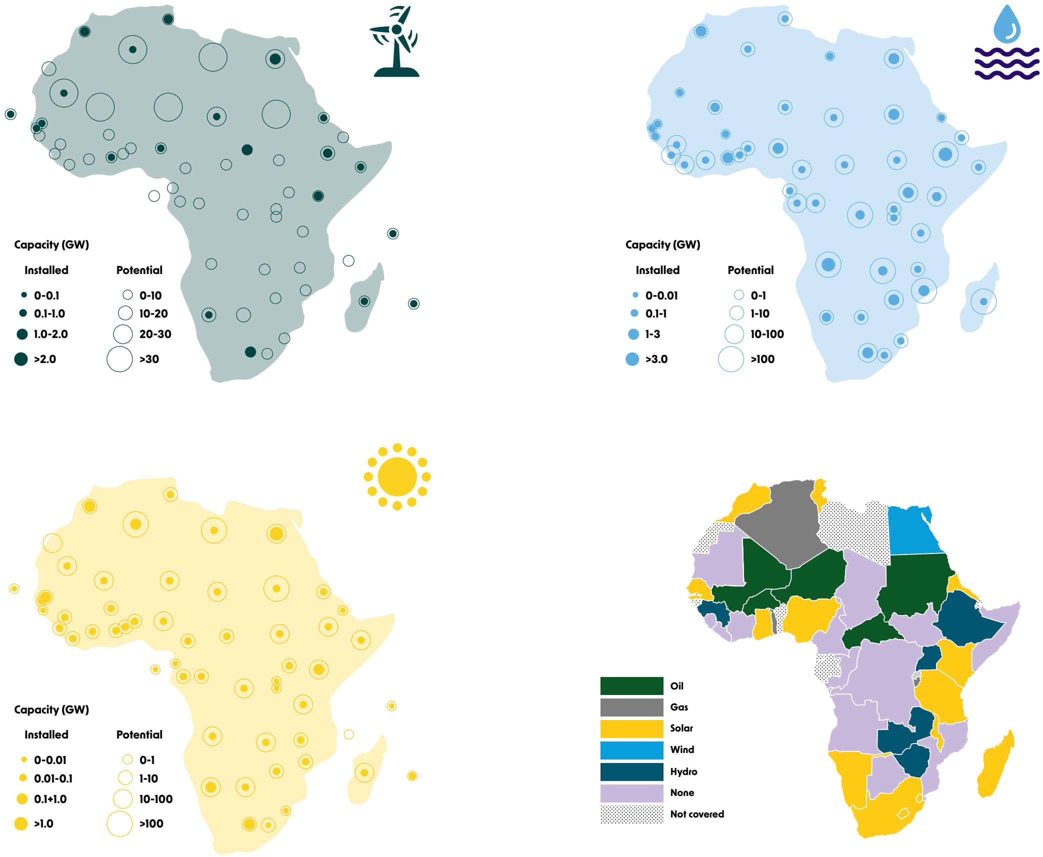


Figure 3.1.4 The infrastructure investment gap, showing potential compared to installed capacity for hydropower, solar PV and wind generation. The final map shows the top power generation technology for each country, as measured in new capacity additions in 2021. Images source: BNEF (2022)[113]

3.2 Transport

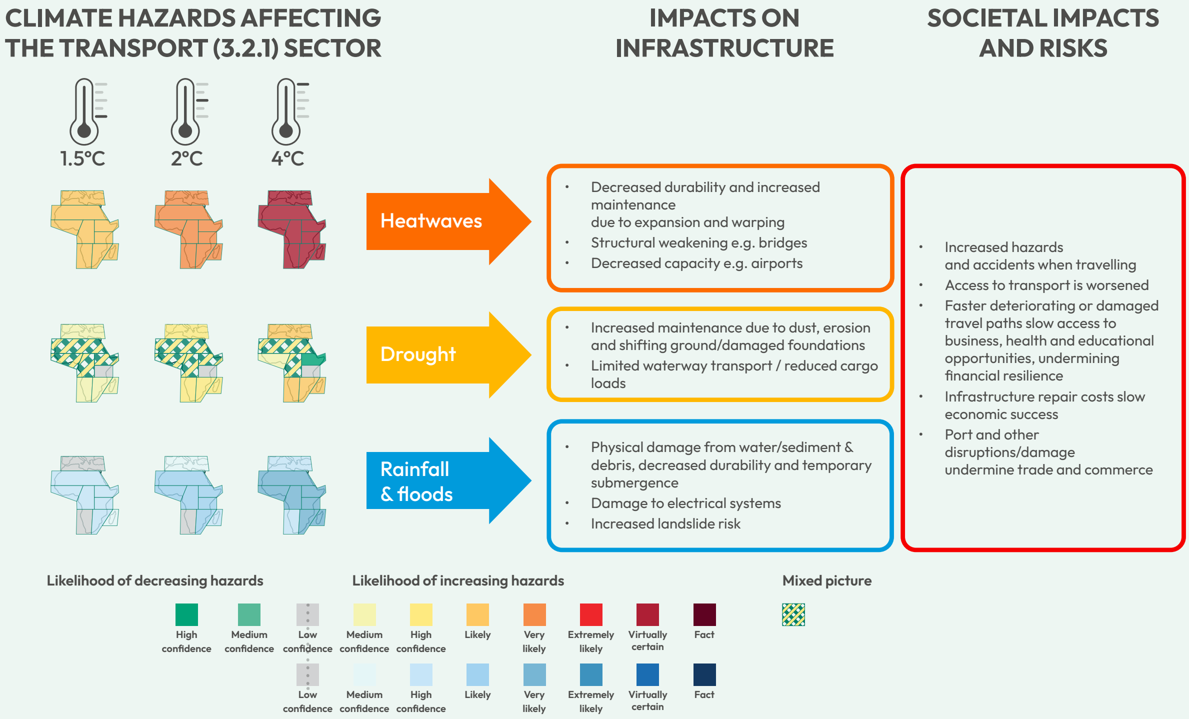
Key Messages

- Transport systems are critical to development, and Africa's transport infrastructure, largely made up of roads, is vulnerable to climate hazards.
- Although transport supports development, it can undermine climate resilience, for example by changing flooding patterns and creating new dependencies.
- There are exciting opportunities to deliver on socioeconomic development and climate resilience through transport investments – from electric motorbikes decreasing fuel costs for the riders and customers, reducing air pollution and emissions, and the use of reflecting coatings on buses to reduce the urban island heat effect, to nature-based solutions for city streets to mitigate the impact of floods.
- With transportation projects heavily focused on mitigation, there is a huge need for a greater focus on adaptation and resilience in this sector.

The challenge

Development requires access to clean, affordable and resilient transport systems.

Roads, railways, ports and airports enable the distribution of goods and services, facilitate access to jobs, markets, schools and hospitals and support communities and countries' efforts to rebound from disasters and high-impact climate events.[114] Roads are essential lifelines for rural communities to gain economic opportunities and basic services.[67] Yet in Africa, about 450 million people, and more than 70% of the rural population, are estimated to be unconnected to transport infrastructure systems. Living in this isolation is associated with higher mortality rates, lower health, education and poverty outcomes and lower agricultural productivity.[114]



- Decreased durability and increased maintenance due to expansion and warping
- Structural weakening e.g. bridges
- Decreased capacity e.g. airports

- Increased maintenance due to dust, erosion and shifting ground/damaged foundations
- Limited waterway transport / reduced cargo loads

- Physical damage from water/sediment & debris, decreased durability and temporary submergence
- Damage to electrical systems
- Increased landslide risk

- Increased hazards and accidents when travelling
- Access to transport is worsened
- Faster deteriorating or damaged travel paths slow access to business, health and educational opportunities, undermining financial resilience
- Infrastructure repair costs slow economic success
- Port and other disruptions/damage undermine trade and commerce

Figure 3.2.1 Vulnerabilities to transport infrastructure and associated societal impacts of projected climate change in Africa under 1.5°C, 2°C and 4°C scenarios.

Transportation infrastructure such as roads and railway systems are one of the sectors most threatened by climate change in Africa. Globally, an estimated 27% of road and rail assets are exposed to at least one cyclone, earthquake or flooding hazard; and 86% of ports are estimated to be exposed to three or more hazards.[43] Without adaptation and resilience measures, sea level rise and coastal flooding will damage ports and disrupt operations and shipping, flood airports, damage or isolate roads and railways, and impair or destroy natural coastal defences; droughts and floods will damage and obstruct bridges and other infrastructure and result in loss of protective vegetation; and increasing temperatures may lead to rail deformation, expanded bridge joints, and cause health risks for transport workers and users.[43] Vulnerabilities are particularly high in developing countries as the transport infrastructure is ageing, underfunded, poorly maintained and under increasing pressure due to urbanisation. Many studies suggest that climate-related damages to roads, the most frequently used means of transportation, will be higher in Africa than in any other region in the world, relative to population and GDP.[115]

Date	Location	Type of climate impact	Affected segment	Impacts
October 2023 and April 2022	South Africa	Floods	Roads	Recent floods which killed 11 people also resulted in closure of 80 roads and damage to rail lines.[67] Previous flooding and landslides in April 2023 which killed 448 people and displaced over 40,000 also severely damaged infrastructure, including roads.[116]
October 2022	Mozambique	Cyclones and flooding	Roads and bridges	Two bridges washed away, 300km roads made impassable and 580km more damaged.[117]
July-August 2021	Accra, Ghana	Floods	Urban mobility	Floods significantly increased time spent in daily transport due to severe traffic congestion; increased inability for people to travel in and out of neighbourhoods due to road erosion or damage. This resulted in reduced work time, likely loss of income particularly for self-employed and casual workers.[118]
Annual	Lagos, Nigeria	Floods	Roads and other infrastructure	Annual flooding in Lagos, including to roads, expected to cost US$22.2m every year.[119]

Table 3.2.1 Selected climate events and their impact on transport infrastructure in Africa.

Natural hazards cause an estimated US$15bn per year in direct damage to transport systems worldwide, US$8bn of which occurs in low and middle-income countries, which experience the highest costs relative to their GDP.[65] The social consequences are also greater as damage to a single transport link can exacerbate existing or introduce new risks associated with poverty.[120] Mozambique's high vulnerability to extreme weather was demonstrated by floods in 2000, 2001, 2012 and 2013, whose restoration cost is estimated at US$400m, while both river and coastal flooding are projected to increase.[121] A recent study of Tanzania found that worst-case disruptions to its multi-modal transport networks could cause losses of up to US$1.4m per day, which will threaten livelihoods and lower economic productivity by disrupting the flow of goods and people.[122] One report on Ghana estimates that, by 2050, climate risks could cause damage worth US$3.9bn in the country's transport sector, due to hundreds of kilometres of flooded roads and other transport infrastructure.[123] The economic and social consequences of transport systems vulnerable to climate impacts are clear.

While transport infrastructure can be transformative for development, for example through connecting remote areas to new markets, it can also pose risks to climate resilience. Thoughtfully constructed roads can act as dikes, but a maladapted road might negatively impact flood patterns, for example by dividing flood plains into two, concentrating flooding on one side.[124] The trend to electrify transport systems also risks making them more vulnerable to energy disruptions:[43] in 2019, an electricity outage due to a power failure affected three Indonesian provinces, rendering the mass rapid transport system and electric train inoperable.[40] A resilient transport system must ensure resilience to disruptions in other sectors – and vice versa.

The opportunity

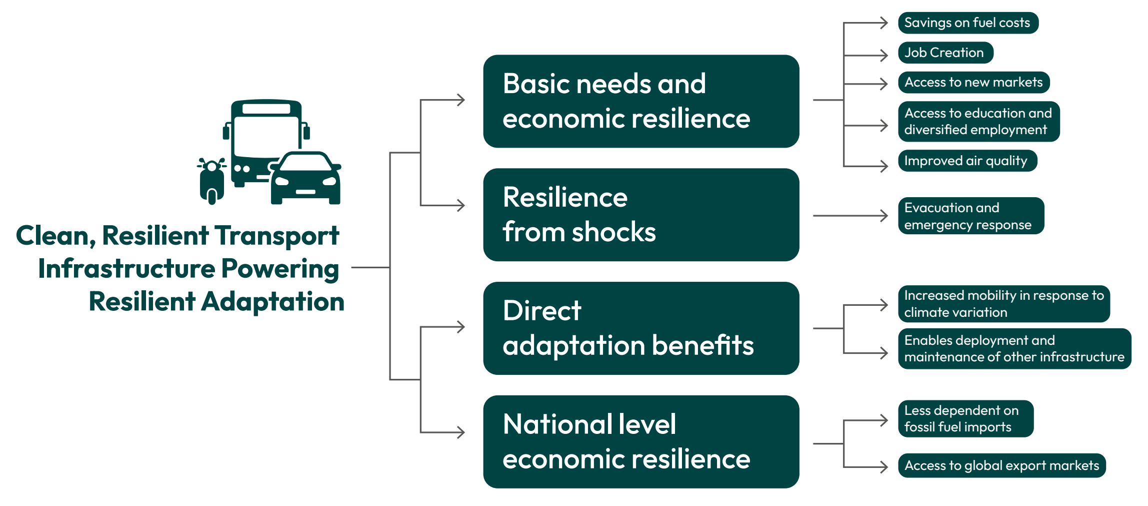


Figure 3.2.2 Pathways for resilience and adaptation through clean transport infrastructure development.

The momentum to invest in transport systems for climate resilience is growing. While the SDGs focus on expanding access, the Race to Resilience campaign seeks that "transport infrastructure be resilient to climate hazards through adoption of new technology, design and materials" and the COP27 Transport Implementation Lab has called for action to mobilise the global engineering community – including key transport industry bodies, the private sector, professional associations, academia and civil society, to work together with representatives from the policymaker and investor communities on the target for climate-resilient transport systems by COP28. The World Bank, among others, increasingly incorporates adaptation and resilience into project evaluations, and is scaling investments and technical assistance for climate-resilient transport systems in Sub-Saharan Africa.[125]

The economic case for climate resilient roads is particularly strong.[126] Poor quality, climate-vulnerable roads decrease agricultural productivity and increase the costs of regional and international trade, with the cost of transporting goods up to five times higher per unit distance in some Sub-Saharan African countries compared with in the US.[127] Better road infrastructure makes it easier for businesses to access more goods at lower prices, increases business sales and productivity, improving profits and wages, and giving households higher income and lower prices, resulting in greater purchasing power.[128] The World Bank estimates that the modernisation of the Dakar-Lagos regional road corridor delivers a benefit-cost ratio of 3:1, in relation to investment costs.[128]

Harder-to-quantify socio-economic and environmental benefits include habitat protection and development.[129] Isolation of rural populations is associated with higher mortality rates and lower health, education and poverty outcomes, meaning that better connectivity has wide-ranging development benefits.[43] Transportation systems can be designed to avoid harm to ecosystems, for example by integrating ecological corridors which support wildlife pathways and ecosystem services.130 Kenyan regulations, specifically the Lamu County Spatial Plan, for example, positively influenced the location of Lamu port, and designated some areas as off-limits for construction to account for existing habitats such as mangroves, and the critical ecosystem services they provide. Access for wildlife was retained by moving certain developments 10km east of a reserve known to be a crucial dry season watering spot. Specific infrastructure choices can also be made in consideration of land and ecosystems: light rail transport, for example, is much less land-intensive than conventional roads, therefore decreasing the burden on ecosystems.[131]

Case study 5.

Diversifying mobility options: Cameroon's Douala Urban Mobility Project

Context and risk: Douala, the main economic hub of Cameroon, is vulnerable to high rainfall and flooding given its location at an estuary. Between 2015 and 2020, the city experienced annual high-impact rainfall levels and flood events. These are projected to become more intense in the coming decades (see Chapter 4.4). This vulnerability is exacerbated by uncontrolled urban development in flood-prone areas, and increasing sea levels. Douala's transport infrastructure is low quality, underdeveloped and vulnerable to these climate impacts.[135]

Interventions: The Douala Urban Mobility Project is designing actions to increase the climate adaptation capacity of the city's urban transport infrastructure. Proposals including the expansion of walkways, cycle lanes and a Bus Rapid Transport system are being informed by technical studies including a flood modelling study, flood danger maps and the identification of critical vulnerability points along key corridors. The studies will inform and prioritise grey and green solutions including drainage systems, bioswales (a ditch filled with soil, allowing rainwater into the earth), sewer and water supplies, stormwater-retention vegetation and traffic diversion routes, and will identify solutions to mitigate flood risks.

Climate resilience outcomes: The project's key indicators include that feeder road, pedestrian and cycle paths and BRT be retrofitted and built to climate resilience standards.[136] It also involves a review of transport infrastructure construction codes and standards to assess how climate-related risks can be better integrated within them.[137]

Systems thinking prompts

Driving transformation in the enabling environment: The project also involves the training of local stakeholders in urban mobility and climate change issues to better incorporate climate resilience considerations in urban transport planning and management, thereby improving capabilities to continually adapt, refine and improve the city's approach and ensure safer settlement design.

Climate resilience of transport

Innovative solutions to improve the resilience of multiple transportation systems are emerging and being deployed. Most focus on engineering or structural approaches, and are designed to address issues like subsurface conditions, material specifications and drainage and erosion.[43] New materials have been used in Tanzania, where after gravel roads of Bagomoyo District were damaged by flooding, the district invested in a new paving system, where materials were water-resistant, locally sourced and produced, and cheaper than the recommended upgrade for heavily trafficked highways; and the method is now under consideration for use across Sub-Saharan Africa. Uganda's railway is being climate-proofed through grey and green adaptation investment, including tree-planting, to enhance the climate resilience of the tracks while bringing more affordable transport to 1.2 million people.[132] For the expansion of the Gambia's Banjul Port, adaptation and resilience options included the regeneration and preservation of mangroves as an important coastal defence.[133]

Building infrastructure which enables diversification towards active modes of mobility, as is being championed in Addis Ababa, can also create a more resilient transport system not dependent solely on large-scale fixed infrastructure: with more than 75% urban journeys potentially short enough for active travel, this presents an opportunity for system resilience – as long as it can be enabled in alignment with increasing climate stressors like extreme heat.[43]

Nature-based 'green infrastructure' solutions provide many cross-cutting opportunities too. Green drainage solutions such as permeable pavements, bioswales, retention basins, rain gardens and engineered wetlands can mitigate flooding hazards and support ecosystems, allowing a more natural water cycle – and are being explored by cities including Accra, Nairobi, Mombasa and Durban.[43,134] Planting trees and other vegetation along urban infrastructure, exemplified in Freetown, can help combat heat island effects, reducing peak summer temperatures by 1-5°C and surface temperatures by 11-25°C, which eases heat stress not only on road users but also on the assets themselves.[43] The Douala Urban Mobility Project is a good example of where technical and feasibility studies have informed the type and combination of urban resilience measures.

Climate resilience through transport infrastructure

1. Socio-economic development foundations

By delivering on core development outcomes, transport systems make people more capable of responding to climate-related challenges. Transportation networks unlock benefits including increased access to markets and enhanced business efficiency, productivity and opportunities. In Ethiopia, connection to a rural road was associated with a 10.4% decrease in residents' likelihood of being in poverty and a 2.8% increase in waged employment over a four-year period.[43] In Madagascar, which has one of the least-developed road networks in the world, one ongoing road project financed in response to cyclone damage reduced an eight-hour journey to just three, driving improvements in access to schools and hospitals, while farmers were able to sell produce at two to three times higher prices.[138] Meanwhile, Zembo helps boda-boda drivers save on fuel costs through their electric motorbike model – another example of a project delivering multiple economic, social and community benefits. Fuel savings create more economic flexibility of drivers, their service enables mobility for those in flood-prone areas, and the reduction of air pollution contributes to reducing the urban island heat effect – all while supporting the wider economic transition away from oil imports.

Case study 6:

The indirect climate resilience gains of e-mobility solutions with Zembo

Context and risk: In Uganda, motorbikes ('boda-bodas') provide transport for 60% of the population, and over 600,000 self-employed drivers are vulnerable to fuel price fluctuations.[135] Rapid urbanisation and growing transportation demand is degrading air quality. Kampala is expected to reach a population of 4.1m by 2024 and poor air quality and traffic congestion are the norm, but the viability of the electric vehicle market has not yet been clearly demonstrated.[91]

Intervention: Zembo is a Ugandan e-mobility solutions company which provides affordable electric motorcycles, with a solar-powered battery-swap offering across solar charging stations in the country, supported by financing from InfraCo Africa, among others.

Climate resilience outcomes: While the most obvious climate-related benefit is avoided emissions, reduced air pollution increases health outcomes, and the heat-island effect of pollution is decreased. At an economy-wide level, reduced fuel dependence for most countries improves trade balances and frees up economic budget. For the boda-boda drivers themselves, the biggest benefit is reduced exposure to fuel prices. The average boda-boda bike costs about US$4 in fuel to travel 100km, compared with only US$0.20 for an electric equivalent.[136] Furthermore, the company has charging stations located close to and within informal settlements prone to flooding, such as Bwaise. The physical climate risk assessment deemed the threat to charging stations was low, implying that adequate measures were taken to ensure that the charging station itself would not be vulnerable to climate hazards, but that vulnerable communities could be served.[91]

Systems thinking prompts

Strengthening local economies: While components are assembled in Uganda, there may be further economic opportunity to develop local supply chains and reap the indirect economic and job-creation benefits of doing so.[91]

2. Direct climate adaptation benefits

Climate impact	Climate adaptation and resilience opportunities of transport infrastructure access
Heatwaves	• Material innovation (e.g. reflective materials on buses and/or pavements, and the incorporation of green spaces) can reduce urban heat islands. • Reliable roads and other transportation systems enable rapid transportation and sale of perishable produce affected by heat.
Drought	• Road water harvesting and storage techniques enable farmers who experience droughts at other points in the year to maintain their livelihoods. • Enable installation of water-saving technologies, like efficient irrigation systems, by moving equipment and experts to drought-prone areas.
Flooding	• Enable construction of flood defence mechanisms through transportation of skilled labour and materials.
Crosscutting	• Guide settlement away from high-risk areas. Integrated transportation and urban planning can guide development and movement patterns away from high-risk areas prone to specific climate hazards. • Enables mobility to work, healthcare and education without exacerbating health or economic impacts, maintaining livelihoods. • Enables access to necessities such as water, food and other supplies, crucial if supply chains are disrupted due to extreme heat or other climate hazards.

Table 3.2.2 Direct climate adaptation benefits of transportation infrastructure.

Transport systems also provide direct adaptation benefits. The use of reflective coatings on buses, pavements and other surfaces are one strategy to reduce the urban island heat effect – particularly in areas of high drought, where green space solutions are less available.[141] Meta-Meta's road water harvesting solution in Ethiopia has enabled farmers to use water from roads that previously would cause flood damage, by intercepting the water and guiding it to recharge areas, surface storage places or distributing it over farmland, enabling livelihoods in areas where many were considering migrating due to lack of livelihood opportunities in the face of worsening droughts.[142] Similarly, a project to expand the climate resilience impacts of Mozambique's roads highlights the opportunities to help manage droughts by connecting road-side trenches to farmland, and making use of road drifts for water storage.

Transport systems can also be designed to actively steer settlement patterns over time to reduce vulnerabilities, because people migrate towards better-connected areas.[4] Multiple cities are using new transport infrastructure to shape safe mobility and settlement patterns as such. Dar es Salaam, as part of the Metropolitan Development Project, is improving urban services including transport, such as with a Bus Rapid Transport system, designed to make specific areas accessible and attractive for settlement.[143] Accra, Ghana, has multiple projects integrating transport, drainage and spatial planning to reduce vulnerabilities.[144] In Maputo, Mozambique, a coastal city vulnerable to sea level rise and storm surges, the city has undertaken significant urban planning efforts to guide development away from high-risk areas, such as improving road networks and drainage systems between safe areas. In Addis Ababa, Ethiopia, the urban planning and infrastructure development, including a Light Rail Transport system launched in 2015, has played a key role in shaping the city's development, making certain areas more accessible and attractive compared with those more vulnerable to landslides (see Chapter 4.5 for more description of climate hazards facing Addis Ababa).[131]

3. Direct climate resilience benefits

Climate impact	Climate adaptation and resilience opportunities of transport infrastructure access
Heat stress	• Access to efficient cooling systems (e.g. cold chain). • Temporary relief by provision of a cool environment for those who do nothave it at home or work (e.g. cool trains/buses).
Drought	• Enable pastoralists to move livestock to areas with better water and pasture availability in the case of extreme drought.
Flooding	• Enable rapid movement of people, repair teams, supplies and equipment to remove accumulated waste and reduce stagnant water, reducing the spread of disease in the case of flooding and damage to sanitation infrastructure.
Crosscutting	• Enable access to healthcare in aftermath of climate-induced events. • Facilitates rapid evacuation before or after extreme weather events and aids emergency services and aid (food, medical supplies and reconstruction materials) distribution in reaching affected areas. • Mobility can also support improved communication, ensuring communities receive warnings about impending or recent climate hazards. • Multiple transportation routes ensure that, if one route is compromised, there are alternative routes to ensure movement of people and goods. This redundancy is critical during emergencies.

Table 3.2.3 Direct climate resilience benefits of transport infrastructure.

Transport plays a critical role in enabling resilience and recovery to climate-related shocks, both from a humanitarian perspective, and in facilitating responses from other damaged sectors such as energy, water and trade. For example, a functional transportation network can drastically reduce the time taken to evacuate threatened populations or deliver vital supplies. During the 2015 Malawi floods, damaged roads and bridges hampered relief efforts, leaving thousands isolated and without immediate assistance. Conversely, the upgrading of the transportation systems in Mozambique after catastrophic floods in 2000 played an instrumental role in the more effective response to Cyclone Idai in 2019, as did the Dakar-Djibouti railway relief operations across the Sahel during recurrent droughts.[145]

4. National-level economic resilience

Investing in clean transport is helping countries reduce their oil dependence and improve their trade balances.[110] Emerging markets currently face a choice between importing expensive oil at rising prices – and growing this dependency – or domestic electricity produced by renewable sources where prices fall over time with cumulative global deployment.[148] Emerging market oil importers currently spend around 2% of GDP on oil imports and these markets, with growing transportation demand, have high and rising dependency on imported oil.[149] Globally, the electrification of transport has passed tipping points in at least two major markets (China and Europe) and electric vehicle (EV) mandates in these markets and the US are likely to accelerate the transition.[150] Improving technology and falling battery prices can enable EVs to compete directly on price in Africa, reducing the cost of energy imports per vehicle by at least 90%, lowering costs to consumers by at least two-thirds, and cutting premature deaths from air pollution linked to transport.[110] Such efforts contribute to a country's long-term economic prosperity, resilience and capability to invest in specific adaptation and resilience efforts.

Case study 7.

Expanding climate-resilient rural road access in Mozambique

Context and risk: Mozambique has been experiencing more frequent, more extreme weather including longer dry spells, severe floods and frequent coastal storms. Heavy rainfall and river flooding is projected to become more frequent in the East Southern Africa region, with the current 100-year flood projected to become a 25 to a 50-year flood at 2°C and 3°C warming. In January 2013, catastrophic floods hit the lower Limpopo valley and other parts of southern Mozambique, ruining nearly 90k hectares of cultivated land, resulting in high food costs. The floods damaged at least 18 stretches of paved roads and bridges, many flooded villages were cut off entirely, and others had to be accessed by boat. About 70% of the province's road network was damaged (2,200km) including 30 bridges and 62 aqueducts. Before the floods, the government of Mozambique had targeted basic infrastructure investments as the single most important contribution to growth and to improving the lives of the poor.[142] A key tension faced was that, "the more quickly crews rebuild roads and bridges after a flood, the faster people can get moving, back to work, back to markets, back to school, back home. But a road that's built quickly is often a road that is just as vulnerable to flooding as the one it replaces."[146]

Intervention: Since the floods, the World Bank, with financing from others, started supporting a long-term project aiming to improve access to markets via secondary and tertiary roads, as well as supporting trade and tourism via other roads.[146] The government temporarily restored major critically damaged links – and attention turned to 'building back better'.[146] Since the floods, the project's goals have layered adaptation into work already in progress. It includes looking at the national design and build specifications to ensure they're resilient in the face of extreme weather; carrying out vulnerability assessments of existing roads in pilot projects; and retrofitting and adding resilience to existing infrastructure.[146] Part of the Safer Roads for Economic Integration project involves restoring nearly 300km of roads and other vital infrastructure with climate-resilient upgrades. One example is the use of 'geocells' or high-density plastic webbing, which more evenly distributes road stresses while reducing cracking or water seepage.[147]

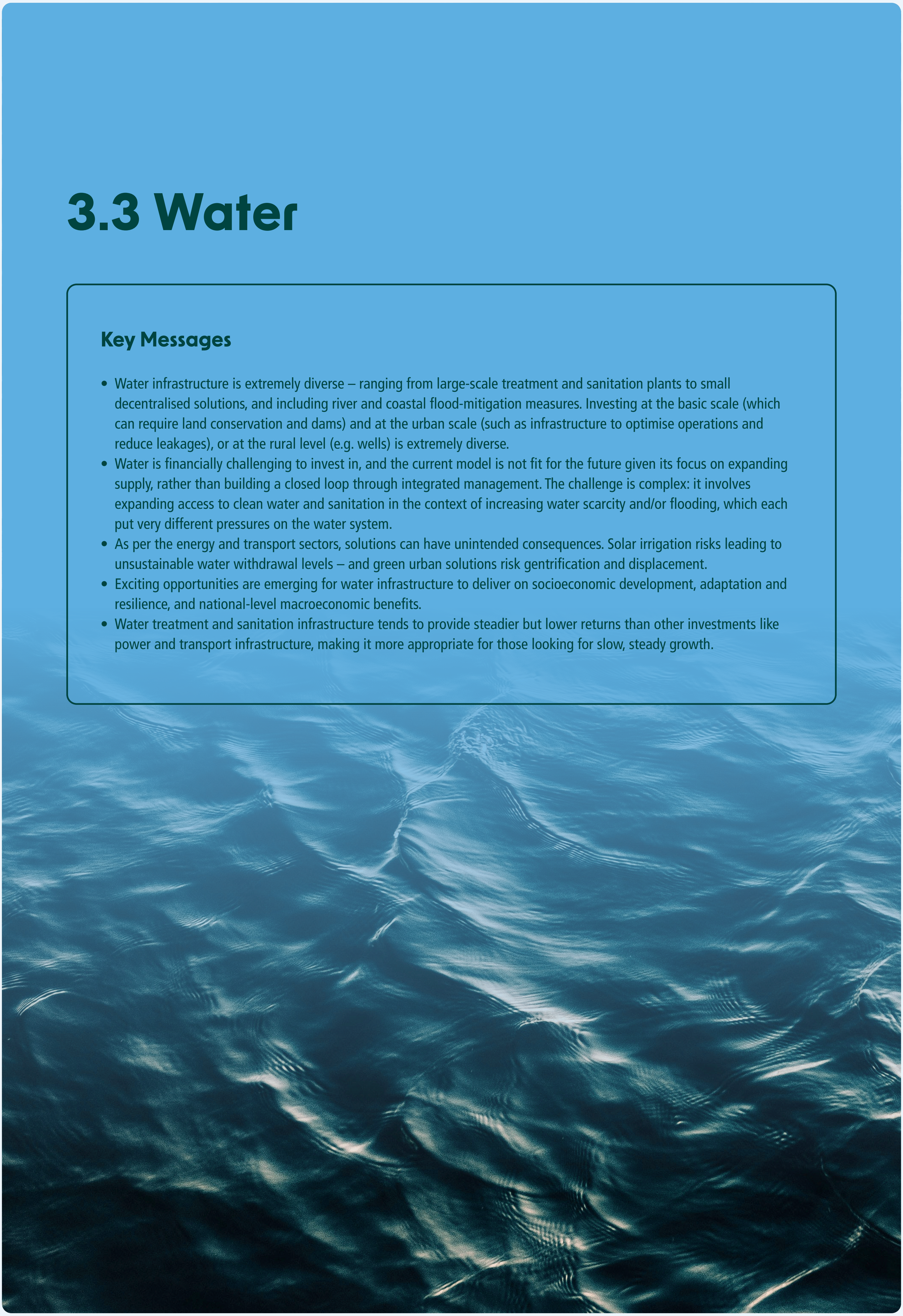
Climate resilience outcomes: 72% of roads were classified as in good or fair condition by the end of the project, with benefits reaching 4.66 million rural inhabitants by 2015.

Systems thinking prompts

Increasing co-benefits through multi-purpose infrastructure: Road systems can interact with the water cycle. A 2017 report by the World Bank Group, Roads for Water and others, explored opportunities to integrate climate change adaptation and water management into the design and construction of roads. It highlighted that a range of climate impacts could be managed through road infrastructure, proposing that: in arid and semi-arid areas road water harvesting can help manage drought (for example by converting borrow pits for water storage, connecting roadside trenches to farmland, using water bars on unpaved roads, making use of road drifts for water storage and other water-harvesting measures), while in lowlands and floodplains roads can be used to manage water flow, primarily by considering low embankment roads with overflow areas to guide floods (including with trees).[124]

The infrastructure investment gap

The investment gap for transport in Africa is huge. In 2021-2022, for example, 16 cities from Sub-Saharan Africa reported 27 transport-related projects aiming to improve urban mobility and rural connectivity which are in need of US$1.5bn in investment.[151] With a rising population and higher levels of road congestion and pollution, the Ghanaian capital of Accra is seeking additional funding as part of a vast US$102 million transport management project that aims to increase urban mobility and reduce transport-related GHG emissions, notably through a climate-resilient Bus Rapid Transit (BRT) system. With limited road capacity for the development of dedicated bus lanes or railway infrastructure, Freetown seeks funding to conduct a feasibility study and cost evaluation of a cable car system as a potentially better-suited mode of mass transportation for the city.[151] Yet even of these 16 proposed projects, nearly 70% focus explicitly on mitigation, revealing the wider pattern that adaptation and resilience investment remains on the fringes of transport projects in Africa.[151]



3.3 Water

Key Messages

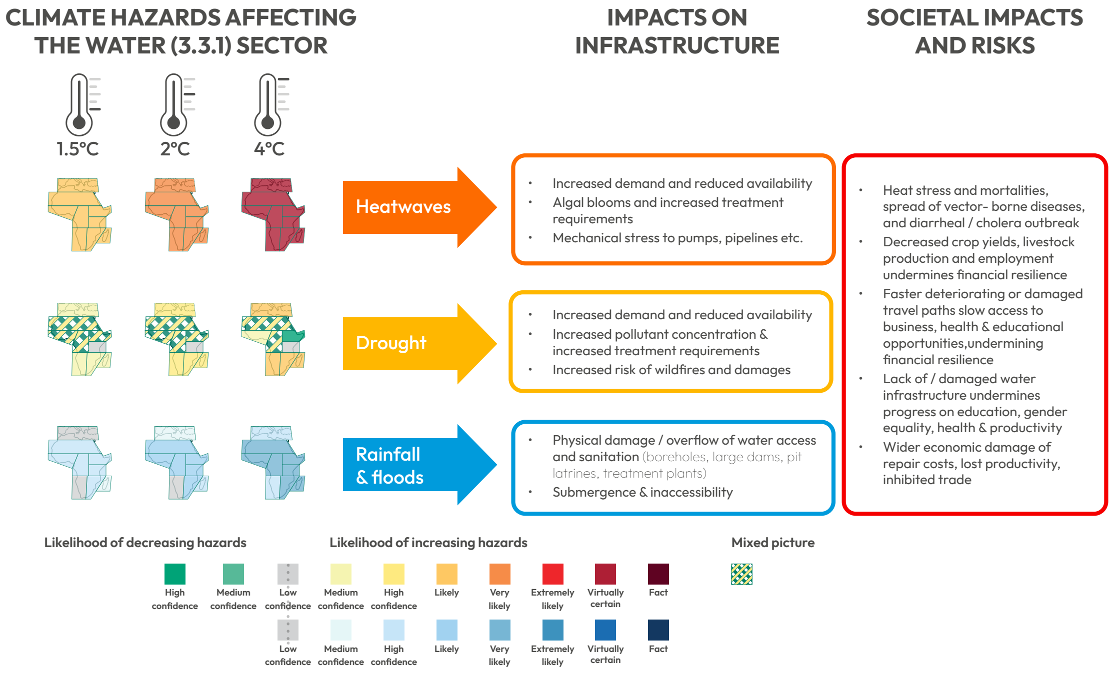
- Water infrastructure is extremely diverse – ranging from large-scale treatment and sanitation plants to small decentralised solutions, and including river and coastal flood-mitigation measures. Investing at the basic scale (which can require land conservation and dams) and at the urban scale (such as infrastructure to optimise operations and reduce leakages), or at the rural level (e.g. wells) is extremely diverse.
- Water is financially challenging to invest in, and the current model is not fit for the future given its focus on expanding supply, rather than building a closed loop through integrated management. The challenge is complex: it involves expanding access to clean water and sanitation in the context of increasing water scarcity and/or flooding, which each put very different pressures on the water system.
- As per the energy and transport sectors, solutions can have unintended consequences. Solar irrigation risks leading to unsustainable water withdrawal levels – and green urban solutions risk gentrification and displacement.
- Exciting opportunities are emerging for water infrastructure to deliver on socioeconomic development, adaptation and resilience, and national-level macroeconomic benefits.
- Water treatment and sanitation infrastructure tends to provide steadier but lower returns than other investments like power and transport infrastructure, making it more appropriate for those looking for slow, steady growth.

The challenge

Water infrastructure stores, treats and distributes water needed for human consumption, sanitation, and agricultural and industrial uses across multiple sectors – as well as protecting people from floods and sea level rise.

It delivers critical services to the power sector, is deeply tied to the provision of healthcare, is essential to irrigation-driven agriculture, and enables transportation routes. Without it, communities face water scarcity, contamination and associated health risks, they are at greater risk of food insecurity, have fewer livelihood opportunities and are more vulnerable to water-related climate hazards. Yet about 400m Africans lack even basic water supply services, 700m have no access to decent sanitation, and about 200m people are forced to practise open defecation.[152] This is down to a lack of infrastructure easing water scarcity when supply is limited, not a lack of water (sometimes defined as economic rather than physical water scarcity). That which does exist is often stretched, ageing and insufficient in the context of rapid urbanisation and climate hazards.

Africa's current water infrastructure is exceptionally vulnerable to climate impacts.[152] Reduced precipitation will negatively impact surface water and groundwater availability, causing drought, and affecting quality, through increased temperature and higher concentrations of pollutants. Increased storms and precipitation will cause physical damage and flooding, and higher sediment, nutrient and pollutant loadings. Sea level rise and exacerbated floods threaten coastal structures, causing undesired salinisation.



- Increased demand and reduced availability
- Algal blooms and increased treatment requirements
- Mechanical stress to pumps, pipelines etc.

- Increased demand and reduced availability
- Increased pollutant concentration & increased treatment requirements
- Increased risk of wildfires and damages

- Physical damage / overflow of water access and sanitation (boreholes, large dams, pit latrines, treatment plants)
- Submergence & inaccessibility

- Heat stress and mortalities, spread of vector- borne diseases, and diarrheal / cholera outbreak
- Decreased crop yields, livestock production and employment undermines financial resilience
- Faster deteriorating or damaged travel paths slow access to business, health & educational opportunities,undermining financial resilience
- Lack of / damaged water infrastructure undermines progress on education, gender equality, health & productivity
- Wider economic damage of repair costs, lost productivity, inhibited trade

Figure 3.3.1 Vulnerabilities to water infrastructure and associated societal impacts of projected climate change in Africa under 1.5°C, 2°C and 4°C scenarios.

One driver of vulnerability is the current development model, which focuses more on expanding supply than on integrated water management. Business-as-usual approaches are characterised by a centralised, supply-focused network of grey infrastructure, reliant on large dams and aquifers, linked to bulk treatment facilities which distribute water services to fee-paying customers, often at a deficit to the utility – while a few large-scale sanitation treatments plants are developed at high cost, only to serve limited parts of cities; maintenance is compromised due to restrained budgets, creating a cycle of underinvestment, water leakages, untreated sewage, intermittent access, contaminated storage and cuts – while maintaining dependency on increasingly unpredictable natural resources and climate patterns.[40] However, more climate-resilient decentralising water provision has so far run up against the financial challenges of economies of scale, making it challenging to investors seeking to recoup CAPEX investments.[91]

The challenge is therefore to identify solutions across the range of water infrastructure types to expand water and sanitation access and resilience to climate hazards, without contributing to water scarcity. Answers will be highly context-dependent, given the issue's complexity and geographic specificity. Uncertainties add a further challenge: decision makers need to invest to expand access to water and sanitation, in the context of high uncertainty about whether certain regions will face more or less extreme droughts or heavy rainfall. These uncertainties are dependent on natural variabilities, scientific uncertainties and the temperature scenarios which unfold. Developing effective water infrastructure requires integrated thinking across spatial, temporal and solutions spaces.[91]

Date	Location	Type of climate impact	Affected segment	Impacts
2022	Mozambique, Madagascar and Malawi	Tropical storm	Sanitation and water supply facilities	In Malawi, the storm destroyed an estimated 1,000 boreholes and 20 larger water supply facilities upon which at least 500,000 people depended. In Mozambique, sanitation and water resources were contaminated or completely destroyed. Madagascar's capital's water systems were also affected.[153]
2018-2019	Mozambique	Cyclone and flooding	Multiple	Caused total infrastructure damage totalling more than US$1bn. Heavy rains and flooding severely impacted sanitation and access to safe drinking water in most affected areas, with homes destroyed and latrines overflowing, contaminating water supply, resulting in a cholera outbreak.[154]
2011	Idaban, Nigeria	Flooding	Multiple	All-time high of 187.mm rainfall led to 'indiscriminate' dumping of solid wastes on water channels, with devastating human health consequences and property damage.[155]

Table 3.3.1 Selected climate events and their impact on water infrastructure in Africa.

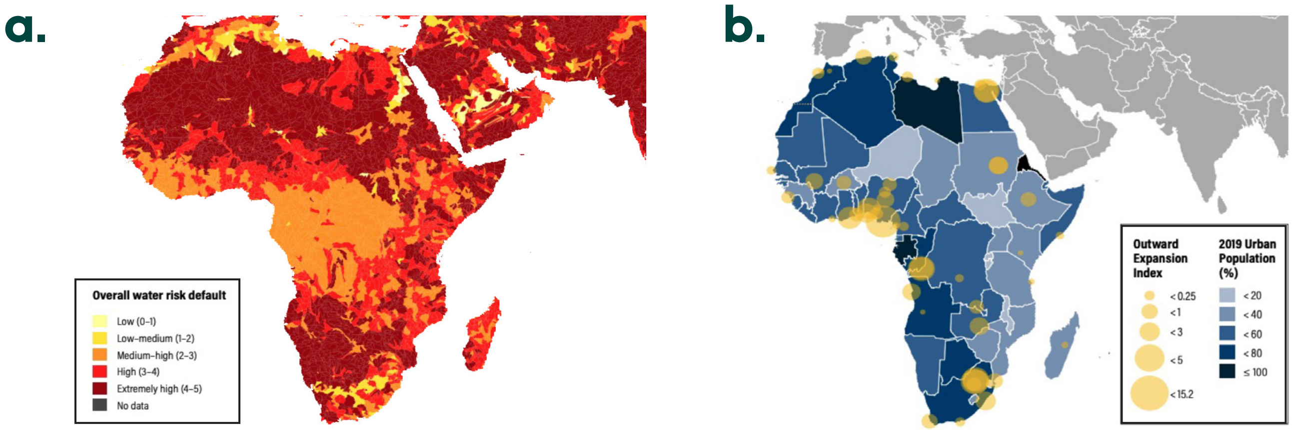


Figure 3.3.2 Most catchments in Africa face a medium or higher level of water risk (a), including areas with high levels of urbanisation (b). Water risk measures all water-related risks at basin level by aggregating indicators including physical quality, quality, and regulatory and reputational risk categories. This does not necessarily reflect water risk at the city or household level; for example a city or settlement could be in a 'low' risk basin, but lack of infrastructure could still mean the settlement itself has low access to water and sanitation services. Source: WRI[40]

Failure to build resilience to the changing climate risks vast economic and human costs. Already, in Lagos, frequent flooding causes damage to critical infrastructure including water facilities, causing an estimated $22.2 million worth of damage each year.[119] A single water outage for an urban business can reduce its monthly revenue by more than 8%. For businesses in the informal sector, monthly revenue can decline by 35%, given they suffer more frequent outages due to poorer services, in turn ruining livelihoods of the more vulnerable and stagnating economic growth.[40] In Senegal, water pollution associated with untreated domestic wastewater discharges, taking into consideration the impacts on the environment and health, impacts an estimated 3.8% GDP, while the government has spent millions on emergency measures to meet demand gaps for water supply and to remedy flood damages to people, infrastructure and the environment.[156] In Beira, Cyclone Idai led to a severe cholera outbreak, indicating how cities without proactive approaches to climate resilience will experience more climate-induced humanitarian crises.[40] These direct impacts can also intensify cascading political and human challenges such as increased tensions and conflict between communities already contending with other economic challenges.[157] As such, improving water supply and food security can be a powerful intervention to build resilience; around Darfur, for example, a combined approach with adaptation of hard infrastructure and nature-based solutions is helping to preserve peace in one of Africa's most fragile states, where three times more people are affected by natural disasters than in other countries.[158]

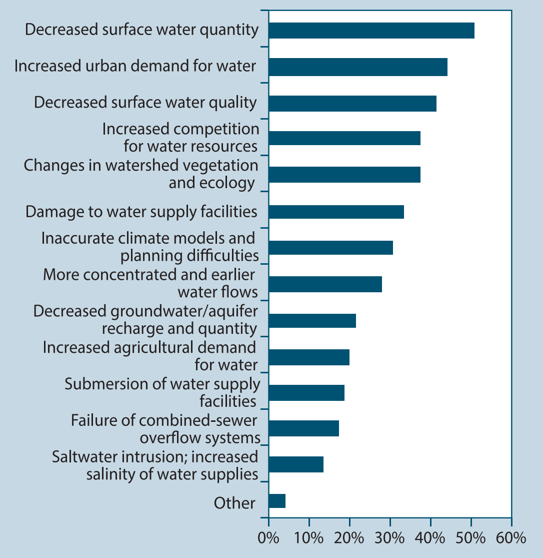


Figure 3.3.3 Exposure of water infrastructure and services to potential climate change impacts. Image source: World Bank (2010)[159]

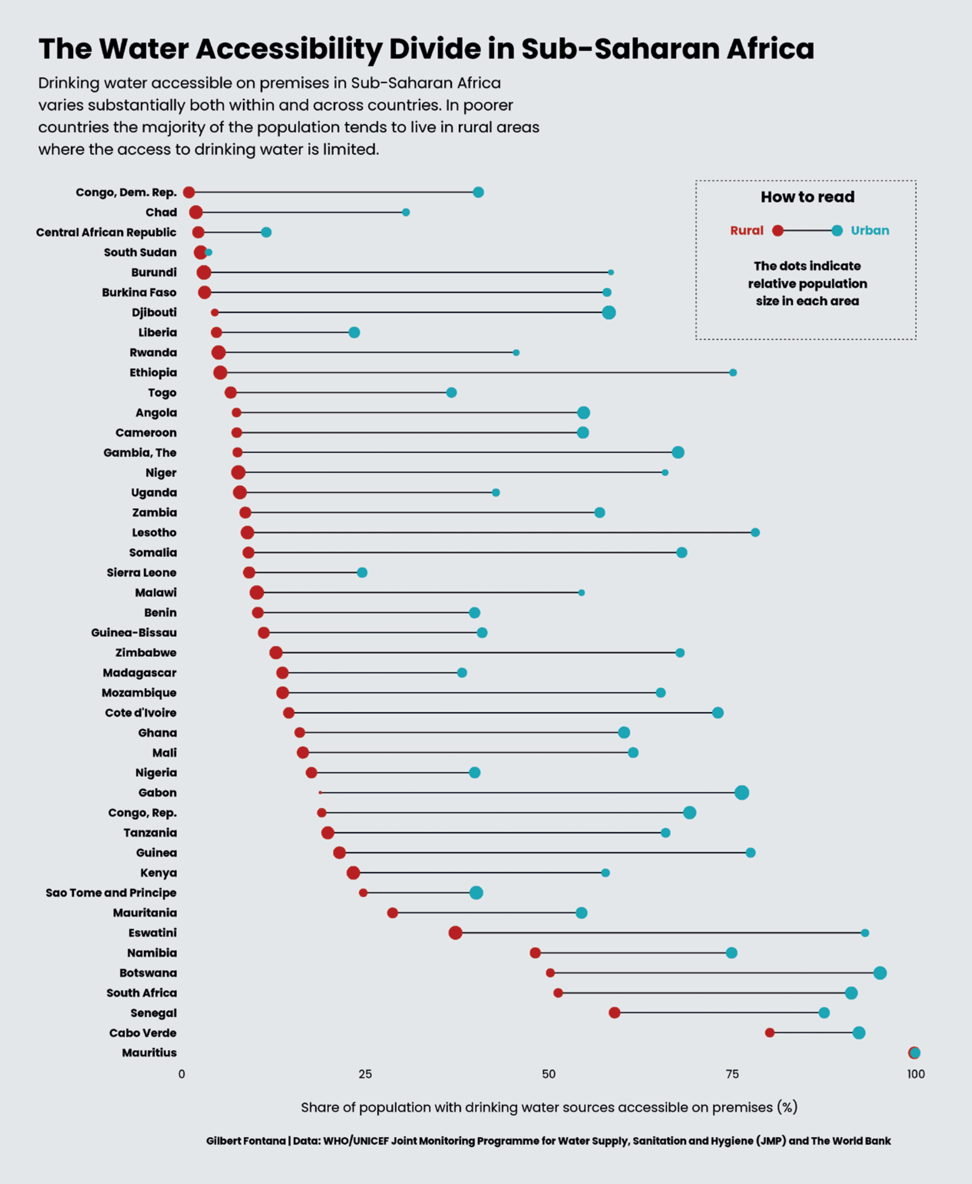


Figure 3.3.4 The rural-urban divide in access to water in Sub-Saharan Africa. Image source: Visual Capitalist (2022)[160]

As is the case in the energy and transport sectors, water infrastructure alone does not inherently create climate resilience. While irrigation for drought-vulnerable farmers will be a crucial part of building rural climate resilience, the expansion and intensification of agriculture through irrigation can also cause surface water and groundwater pollution through use of agricultural chemicals, increased nutrient levels in irrigation and drainage water, resulting in algal blooms, and lead to eutrophication in irrigation canals and downstream – ultimately undermining the health and climate resilience of those downstream. Large irrigation projects which reduce river base flow have led to the concentration of municipal and industrial wastes added downstream, posing significant pollution and health hazards. Although nature-based solutions are promising, they require a nuanced approach to avoid maladaptation. They can be effectively deployed at the basin level to improve water quality, but there is deep concern that their use (particularly tree planting for carbon sequestration and/or resilience to landslides) can reduce water availability in some environments, contributing to water scarcity.[161] In an urban context they are increasingly acknowledged as a critical part of the solution for water-sensitive cities, yet can be associated with the displacement of low-income residents due to increasing rents.[40]

The opportunity

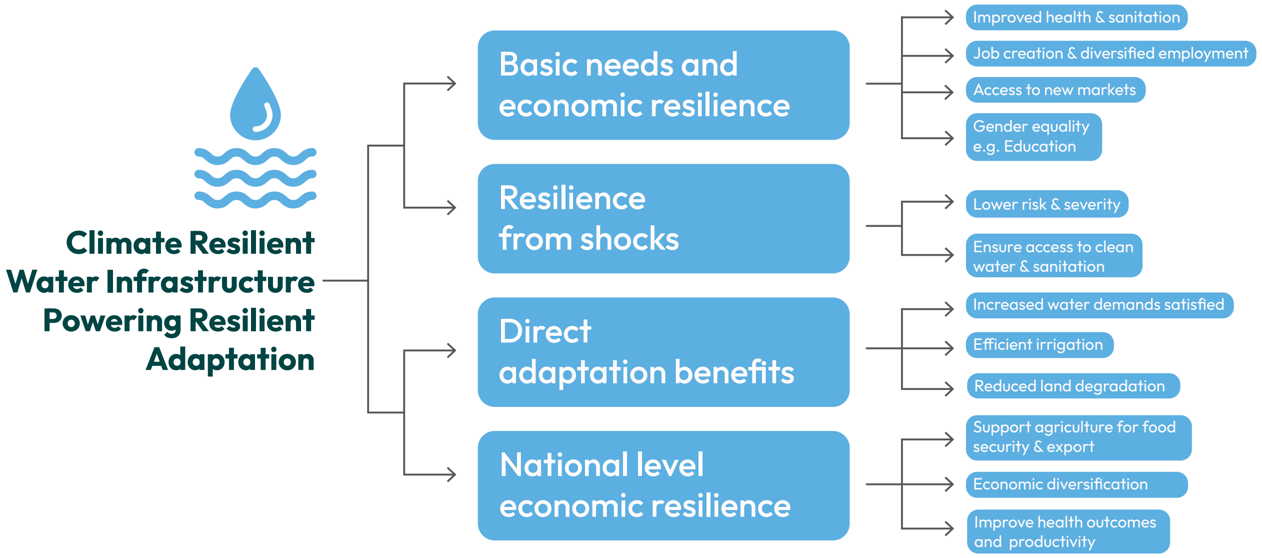


Figure 3.3.5 Pathways for resilience and adaptation through climate resilient water infrastructure development.

The Sharm El Sheikh Agenda calls for water systems to be **smart, efficient and robust** with a **reduction in water loss through leakage;** for **wastewater systems to maximise recycling and reuse** alongside natural wetland filtration; and for **sustainable irrigation systems to be implemented across 20% of global croplands.**[76] Financial returns from water investments in emerging markets make the sector financially attractive, arguing that **scaling and optimising water-related investments can deliver at least US$500bn per year in economic value.**[162] For investors, this means significant opportunities in developing integrated green and grey infrastructure that focus on capturing, recycling and reusing water as efficiently as possible in water-stressed areas; as well as taking full advantage of digital and financial innovation to enable access to safe and robust water supplies. CityTaps is one company enabling improved productivity through water access through the creation of new businesses and business models, as well as the social benefits of affordable and reliable water supply.

A particularly exciting opportunity exists for African cities, with relatively little infrastructure already constructed, to 'leapfrog' towards sustainable and resilient systems faster and more cost-effectively than those which require vast retrofitting and redesign.[40] A 'water sensitive design' approach, which incorporates green infrastructure with engineered water systems through innovative design of built environment and urban landscape, is gaining attention as a solution to urban water problems – with both Johannesburg and Cape Town engaging with it at the policy level. Its implications for infrastructure include a shift towards total **water cycle management** and the use of **sustainable drainage systems** and **green infrastructure** to store, convey, treat and infiltrate rain and stormwater. Leapfrogging to such systems in the Global South is critical for attaining the Sustainable Development Goals.[163]

The Cape Town Water Crisis, an infamous example in which the city nearly ran out of water in its main reservoir, reaching 'day-zero', – resulted in a new strategy which commits to developing new, diverse water supply sources and management options including groundwater, grey water reuse and desalination.[164] Some utilities have taken an active adaptation approach for much longer. In Windhoek, Namibia, the utility has been producing drinking water from recycled wastewater since the 1960s and recharging its aquifers with surplus reclaimed water since the mid-2000s to ensure reliable delivery. Climate hazards facing both Cape Town and Windhoek are described further in Chapter 4.7.

Nature-based solutions are increasingly attractive options for African water system resilience given their multiple potential social, economic and environmental benefits. In Egypt, constructed wetlands for secondary-level treatment of wastewater effluent provide water to irrigate Eucalyptus trees for the manufacture of packaging boxes; this system is helping to preserve groundwater resources and drive local economic prosperity through product sales and costs saved, as the system is more cost-effective over time than conventional wastewater treatment plants. And one study has found that restoring upland forests in watersheds could save water utilities in the world's 534 largest cities an estimated US$890m each year.[165]

Emerging research can support investors to prevent maladaptation – but far more is needed. For example, pumped irrigation solutions risk increasing water consumption (particularly if farmers shift to more water-intensive crops) and causing overexploitation of groundwater resources.166 However, an International Water Management Institute (IWMI) report in 2021 concluded that current markets are likely too small to pose a serious or widespread threat to groundwater availability over the short and medium term. It concluded that (a) given the low aggregated risk to groundwater depletion over most of Sub-Saharan Africa over the next decade, there is vast potential to support sustainable expansion of small water projects, but that (b) in some regions such as Southern Africa, the potential impacts on local groundwater availability pose a higher risk. It emphasised that sustainable groundwater management can not be broadly generalised and the need for locally tailored approaches accounting for specific hydrogeological, climatic and socioeconomic conditions.[166] In this case, tools are available: an online solar irrigation sustainability-mapping framework has been developed, intended to help users identify suitable areas for solar-based irrigation depending on water sources and pump characteristics.[167,168]

Climate resilience of water infrastructure

Solutions to improve the resilience of water and sanitation systems are emerging. Water sources can be diversified, storage capacity enhanced, water reused, and infrastructure at risk of flooding relocated. **Water supply** risks can be addressed through solutions including rainwater harvesting for infiltration, managed aquifer recharge, progressive pricing and water savings requirements in building codes as well as soil moisture conservation techniques, natural wetlands and rainwater harvesting for storage. **Alternative water source** options include sea water desalination, solar water distillation, fog harvesting, inter-basin transfers, groundwater prospecting and extraction, and water recycling and reuse. To protect against **higher precipitation and storm water,** solutions include structural barriers to flooding like dams and dikes, the optimisation of reservoir operations, re-connecting rivers with floodplains, flow-through dams, ecological river restoration, multipurpose dams, and zoning and land development limitations, as well as infrastructural solutions like permeable pavements and parking lots, bioswales, and optimisation of urban drainage systems.[170] With regard to **sanitation and contamination,** wells and sanitary latrines can be built or retrofitted to be flood-proof, water treatment levels can be revised to different dilution at discharge, and can be improved through solutions including constructed wetlands, and improved point-of-use water treatments.[170]

While large-scale water infrastructure must be a core part of the solution, it can be more vulnerable to extreme weather events and, given deeper links across sectors, may increase the risk of cascading failures (e.g. to the power and manufacturing sectors). This supports the case for adaptation to incorporate more decentralised methods, such as point-of-use chemical and solar disinfection, rainwater harvesting and safe water storage, dry toilets and container-based sanitation, as they can be less vulnerable to climate shocks, and more easily recovered and adapted over time.

Case study 8.

Expanding first-time affordable and reliable piped water access to urban Africans with CityTaps[169]

Context and risk: More than a billion people live in urban areas without access to running water in their homes. For residents, disconnection from water supplies due to non-payment is a common challenge. For water utility companies, it can be difficult to expand service to poor communities while also reducing the physical and commercial losses they need to remain financially sustainable. Post-payment systems for water services act as a barrier to access due to opaque payment structures and poor customer service that lead to disconnections. As a result, poor communities often pay more for water from non-utility sources than their wealthier neighbours.[91]

Intervention: CityTaps developed an integrated smart metering and cloud-based account management platform to enable pay-as-you-go water access through mobile payments. This pre-payment model improved reliability and transparency of services to water customers, along with payment convenience following their irregular incomes, while allowing utilities to reduce operating costs and improve collection ratios to 100% through arrears recollection. In Niger and Kenya, Namibia, and Tanzania, CityTaps enabled utilities to expand their service to new, and to previously disconnected customers.[91]

Climate resilience outcomes: CityTaps reduced the ‘poverty penalty’ for water access by driving an average per-litre cost reduction of 20%-80% for new and reconnected customers, helping consumers afford other basic necessities and/or save for the future. With improved access to water, new businesses were set up, with women making/growing and selling lemonade, ice or vegetables.[169] People gained huge time back through not having to collect water, and improved hygiene and reduced water-related sickness were also reported by consumers.[169]

Systems thinking prompts

Transformation through improving the enabling environment: The second-order impact of CityTaps is to free capital access to non-creditworthy water utilities, which is essential for adaptation measures. By routing digital customer payments to a third party before they are transferred to the utility, investors are paid first to repay any loans extended to the utility, therefore gaining utilities access to CAPEX funds. By ensuring that the revenue generated by utility customers can be used to repay investors, even in cases where the utility is not creditworthy, even those utilities not able to finance themselves on pure financial criteria can access capital as the technology is used to reduce counterparty risk.[91]

Climate resilience through water infrastructure

1. Socio-economic development foundations

With reliable, affordable access to clean water and sanitation, people's health risks decrease, in turn reducing missed economic and educational opportunities, and creating new opportunities for income. CityTaps shows how the provision of affordable clean water helped customers afford other basic necessities, save for the future and set up micro-enterprises such as selling lemonade. People gained time by not having to collect water, and improved their hygiene, reducing illness and its associated costs. These benefits in turn reduce pressure on healthcare systems, including during climate hazard events when pressure will be greater.[169,171] The Kigali Bulk Water Project also illustrates how access to piped water is helping women and girls particularly save time and money, and maintain better health.

2. Direct climate adaptation benefits

Climate impact	Climate adaptation and resilience opportunities of water infrastructure access
Heat stress	• Ability to store water such as through rainwater harvesting systems and underground reservoirs. Communities can store water for extended periods, ensuring availability during extreme heat and prolonged droughts.
Drought	• Efficient irrigation systems also allow farmers to cultivate crops during reduced rainfall, ensuring food ecurity and stable incomes.
Rainfall and river floods	• Proper water management can reduce soil erosion and land degradation, reducing the impacts of rainfall and river floods.
Sea level rise/flooding/ cyclones	• Adequate water treatment and storage facilities reduces the spread of waterborne diseases, which can increase during climate-induced extreme events like floods.
Crosscutting	• Stable water supply drives economic activities such as fishing, agriculture and livestock rearing, reducing vulnerability to climate-induced economic shocks. Ability to support livestock is particularly crucial for pastoralist communities. • Access to piped water reduces the time needed for (primarily women and girls) to fetch water, enabling greater time for income-generating and educational activities. • With available water, fewer people are inclined to migrate in search of better living conditions, reducing climate-induced displacements.

Table 3.3.2 Direct climate adaptation benefits of water infrastructure.

Water infrastructure can enable and support adaptation to climate change in a variety of ways. In the face of significant water scarcity, increasing population and the pursuit of economic development and growth, the Gabal El-Asfar wastewater treatment plant – the first of its kind and largest in Africa, is designed to biologically treat sewage water, ensure compliant disposal of treated water and improve environmental and public health in the areas. The sludge produced is used as an input for energy and agriculture. Not only is the plant 60% powered by the gas of the sludge it creates (mitigating risks against grid disruptions)[175] but the project's expansion features an experimental plot of land where treated water is used for irrigation and fruit harvesting, with the aim of increasing irrigated land to 70,000 acres, helping to reverse desertification, improve resilience of the surrounding agriculture against drought risk and improve food security, while increasing access to safely managed sanitation services.[175–177] Durban's grey-green solutions approach, outlined on p.73, also highlights how infrastructure can be used to improve the quality of freshwater supply and to reduce the impacts of flooding on communities, thereby building their climate resilience.

Case study 9.

Expanding piped water access - the Kigali Bulk Water Project

Context and risk: Only 40% of Rwanda's population had access to piped water supply in 2015. One of the country's strategic policy goals has been to achieve universal access to safe drinking water, but rapid urbanisation in the capital, Kigali, exacerbated the challenge of limited supply. Without climate-resilient access to clean drinking water, people are more vulnerable to the impacts of climate hazards such as floods, which can contaminate water supply and increase diarrheal illnesses. In May 2023, flooding across Rwanda led to water shortages caused by river flooding which polluted water sources and triggered a RWF4bn (>US$3.3 million) loss after damaging water treatment plants and supply systems across the country. See Chapter 4.6 for projected climate hazards facing Kigali.

Intervention: The Kigali Bulk Water project is a long-term Public-Private Partnership (PPP) to finance a large-scale water treatment facility which draws water from the Nyabarongo River. Kigali Water Ltd built, maintains and operates the treatment plant, and sells drinking-quality water to Rwanda's public water utility WASAC, which distributes it to consumers. Completed in 2021, the project covered the installation of a new water treatment plant, building new wells and rehabilitating existing ones, as well as pipelines, storage reservoirs, pumping stations and water points.[91,172]

Climate resilience outcomes: The project increased Kigali's existing water capacity by one third, improved access for around 500,000 people daily in the capital and surrounding areas, and serves the country's largest industrial zone, the Kigali Prime Economic Zone. Women and children who previously woke up at 3am to fetch water now walk fewer than five minutes to the tap. Not only do children now get to school on time, but it has also increased the quality of sanitation in schools.[91]

The infrastructure itself in May 2023 proved resilient to flooding, with operations continuing as normal (the only water treatment plant in Kigali for which this was the case).[91] Indeed, it was designed for flood resilience: boreholes and the control rooms which manage them were elevated, the cables connecting them were designed for underwater use, pipes were constructed to drain flood-water quickly back into the river, and control rooms were designed to operate remotely.[91]

Kigali was one of the first water projects to be developed using a public-private model in Sub-Saharan Africa, in theory paving the way for the scaling of blended finance to expand piped water in the region. In reality, however, interviewees implied that the sector remains extremely challenging. While Metito, the project sponsor, is looking at others given the success of KBWP, the demonstration effect isn't clear.

Systems thinking prompts:

Physical resilience and resilience to indirect impacts: It was only after a flooding event in May 2020, which permanently damaged a new borehole and other parts of the project under construction, that a hydrological assessment was undertaken to ensure the infrastructure would be climate resilient, as a result of which the above measures were taken. Although upstream water uses were assessed (e.g. agriculture and hydropower) and revealed possible resource competition, resilience assessments and measures focused on flood risks, and did not consider other projected climate impacts (e.g. the implications of extreme heat for materials or water demand).[91]

Case study 10.

Off-grid wastewater management in Naivasha, Kenya – Sanivation

Context and risk: In Kenya, only 20% of the country is served by wastewater treatment, the rest remaining in the environment, in pit latrines, waterways or sludge ponds, posing imminent health risks exacerbated by flooding. Furthermore, the fecal sludge management (FSM) sector faces challenges in developing viable and investable business models: although the safe management of human waste provides multiple health and other benefits, FSM business models often depend on payments from local governments, influenced by policy priorities. Off-grid FSM service providers often operate in fragmented markets, making it hard to capture the full value of their services (collection, transport, treatment and re-use), making them expensive and unreliable.[162]

Intervention: Sanivation is a small-scale social enterprise developing and building FSM plants in African secondary cities in partnership with local governments. Its facilities treat the fecal sludge and turn it into briquettes sold to local industries for fuel, which covers the operational costs of the facility. Up-front capital for construction of the treatment plant is provided by government partners.1[62]

Climate resilience outcomes: First, the company delivers sanitation benefits – and has so far served nearly 150,000 people. By professionalising waste-collection and making it safe, clean and efficient, it reduces the risk of disease spread and improves community health, as waste is taken out of people's imminent environment.[173] In the event of flooding, there is less waste close to where people live to cause health risks associated with dirty and stagnant water. It is itself also more climate-resilient compared to traditional wastewater treatment, which relies on ponds of yet-to-be-treated water, which can flood. While the 'resilient infrastructure' solution would be to elevate the ponds, Sanivation eliminates the need for ponds by converting waste to briquettes. Furthermore, the solution eliminates huge methane emissions caused by pit latrines (which cause 70% of Kampala's emissions, for example).[174] With utilities companies as its clients, the company is expanding FSM in a revenue-sustainable way, and simultaneously shifting the paradigm to a low water and energy approach.

Systems thinking prompts

Partnership, collaboration and flexibility: Sanivation started out managing household-level sanitation but discovered limited willingness to pay and learned that city-wide waste treatment could have wider impacts. It pivoted from utilities as competitors to utilities as clients, and partnered with public health offices and governments on WASH master planning and implementation, of which their solutions form a part. Sanivation also complements the existing landscape by working with small organisations already collecting solid waste. It has worked with utilities, like Malindi, to formalise solid waste management models to scale sustainable services, and has studied different community-based organisations working on solid waste management and recycling, enabling them to build mutually beneficial relationships to co-process human and solid waste and allowing them to scale their businesses.[91]

Physical resilience and co-benefits: Sanivation partners with local governments to design and operate context-appropriate, climate-resilient sanitation. It delivers different solutions in arid Northern Kenya to those in coastal areas. In Wajir, Somalia, where there is a high water table (making pit latrines and sewerage systems difficult), it worked with the World Bank and a water utility to improve the existing system of bucket toilets, making the container-based sanitation system safer and more dignified. In Kakuma Refugee Camp, Kenya, where pit latrines flood every rainy season, Sanivation worked with the local hospital to design and operate container-based toilets for patients.[91]

Macroeconomic resilience benefits: Currently, the business model involves converting waste into solid biomass fuel – which is less emissions-intensive than LPG or renewables. This is a 'stop-gap' solution given that local businesses to which it sells (e.g. tree plantations, edible oil companies) can not afford LPG so currently use firewood. As the Kenyan economy changes, Sanivation aims to pivot its business model to reduce emissions further, through steam-as-a-service. In the meantime, reducing the need for plantations to grow trees as fuel opens up land for tea, supporting expansion and the wider economy.[91]

Transformation: Sanivation is removing waste from urban vicinities, improving sanitation outcomes and reducing health risks in the event of flooding; nurturing a paradigm shift among utilities and governments towards circular, low water and emissions FSM more widely; turning waste into energy, reducing local companies' dependence on firewood, freeing up land and supporting economies; and preparing to pivot towards an even higher-impact business model when enabling conditions allow.[91]

Case study 11.

Combined grey-green solutions for reduced impacts of flooding and wastewater management in Durban, South Africa

Context and risk: The eThekwini municipality (greater city of Durban) faced deteriorating ecological infrastructure, which compromised the volume and quality of freshwater, as well as the ability to reduce flooding. Different river management scenarios were evaluated for their local benefits and the ecological infrastructure was found to be most cost-effective in delivering wide-ranging benefits, including flood risk reduction, improved water quantity and quality and broader societal gains; while the economic costs of inaction would be significant on the local economy.

Intervention: Interventions included the construction of artificial wetlands to act as biofilters, removing and trapping sediments and pollutants before they entered the local river system. Alien plants were removed and replaced with indigenous plants to stabilise the riverbanks. The plans build on engagement with diverse landowners, collaboration with municipal authorities and various NGO and civil society initiatives.[178]

Climate resilience outcomes: Implementing the full river management plan is an ongoing, iterative task, involving considerable negotiation with diverse landowners and authorities and even anticipated payments by the municipality to private owners to recognise and reward the ecosystem services they provide downstream. It also includes non-infrastructural solutions, including public information campaigns aimed at discouraging waste-dumping from informal settlements bordering the river.[178]

Systems thinking prompts

Partnership and collaboration – and avoiding maladaptation: Despite investments in ecological infrastructure, illegal and harmful chemical and solid waste dumping in the watershed is an ongoing issue. A citizen-organised watchdog group tracks infractions in one sub-catchment, but expresses frustration at the enforcement authorities' speed of response. These tensions demonstrate some of the challenges involved in gaining and maintaining the impact of green infrastructure solutions.[178]

An applied example: SunCulture, solar-powered irrigation farming solutions in Kenya and beyond

Below is an example illustrating how the investment criteria proposed can elicit important information about how a company delivers on adaptation and resilience benefits, how to mitigate risks of maladaptation, and maximise opportunities for impact.

Figure 3.3.7 System mapping the core feedback loop: unreliable rainfall worsens the poverty-indebtedness-food security cycle.

Context and challenge: Smallholder farmers in Africa face key challenges including lack of reliable access to water or irrigation, in the context of economies heavily reliant on agriculture for economic growth and food security. Only 6% of Africa's cultivable land is irrigated, so the majority of farmers are reliant on rainfall.[179] Unpredictable weather and climate change make it ever-more challenging for farmers to maintain consistent crop yields, particularly due to increasing droughts.[180]

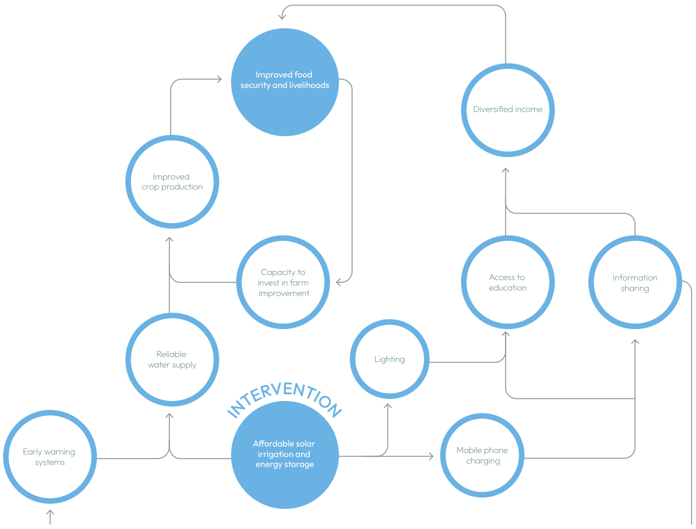


Figure 3.3.7 System mapping the new feedback loop(s): affordable solar irrigation and energy storage improve food security and livelihoods, weakening the impact of unreliable rainfall

Interventions: SunCulture, developed a smart, efficient solar irrigation system (typically utilising groundwater, riverwater or harvested rainwater) with associated products including battery storage and televisions. With highly price-sensitive consumers, the company has developed multiple innovative pricing solutions, and plans to gain revenue from carbon credits to ensure affordable access.

The criteria show that the core adaptation and development objective of SunCulture is to expand and improve highly efficient water irrigation to smallholder farmers, enabling improved crop yields even in the context of drought. Users have increased their crop yields by up to five times and reduced their water usage by 80% and increased income tenfold. In turn, 90% reported increased crop production and 98% reported the ability to cover emergency expenses, which translates to increased resilience against future shocks.23 Secondary benefits and synergies include access to energy for other purposes, including mobile phone charging, lighting and TVs for entertainment and information access. The key risk to the users is the possibility of SunCulture turning off the system and repossession due to non-payment. This is mitigated through tailored pricing and payment schemes. The key environmental risk is exacerbated water scarcity due to over-irrigation, which SunCulture is mitigating through close location-specific research. The product is resilient across multiple climate scenarios and is adaptable given the relatively short lifecycle of the product (25 years compared with 100+ year lifespan of other infrastructure). Further opportunities for impact include supporting an ecosystem of similar companies, and/or nurturing a local manufacturing or component assembly industry within Kenya.

Theme	**Question**	**SunCulture**
Physical resilience of infrastructure assets and systems	Is the project robust and/or adaptable to the physical hazards posed by current and future climate impacts of its location? Can additional actions be taken to ensure high performance under climate extremes, at reasonable cost?	Solar panels are resilient to existing heat ranges. R&D team is working on more heat-resilient battery products for expansion into Western Africa. The lifecycle of the solar panels is 25 years, enabling flexibility and adaptation.
	Does the project improve the resilience of the infrastructure network of which it is a part?	It is creating new, resilient infrastructure networks through decentralised solutions.
	Is the project designed to mitigate or be resilient to behavioural shifts driven by climate impacts (e.g. increased demand for power for cooling, increased water consumption)?	Yes, it is improving livelihood resilience for rural farmers, mitigating the pull of urbanisation and improving food security for rural and urban groups, even in the context of drought.
Economic and social development foundations	Does the project provide accessible, reliable and affordable energy, transport or water access for the first time?	Yes – by providing farmers with solar irrigation and battery storage for surplus energy. It provides a more reliable water supply due to smart technology and is more affordable than diesel-powered equivalents.
	Does the project deliver co-benefits such as health, food or water security, or access to information?	Yes – storage solutions power mobile phones, lighting and TVs, improving access to information
	Does the project enhance the economic resilience of users?	Yes – by improving crop yields, and power creates additional income opportunities.
Direct adaptation benefits	Does the infrastructure provide direct adaptation benefits to extreme heat, drought and flooding?	Yes – solution assumes drought and helps farmers reduce water consumption by 80%.
	Does the project deliver adaptation benefits for all impacted communities (users, upstream/downstream communities, future generations)	Largely. Farmers gain benefits, but a community-ownership approach was not pursued after user-centred design revealed high cultural value in Kenya on individual ownership. Local assembly of components and engineers for implementation and maintenance creates jobs. Communities may be impacted by end-of-life waste disposal, however SunCulture has an Environmental Risk Management Plan and partnerships with recycling companies to address these risks.’

Theme	**Question**	**SunCulture**
Direct resilience benefits	Does the infrastructure improve people's ability to cope with/recover from acute climate hazards?	Mobiles and TVs may improve access to early warning signals, but this would depend on government/other agencies to provide it. The initiative does not yet offer asset insurance to climate hazards, but will consider this if demand emerges.
Macroeconomic resilience benefits	Does the project help decrease dependence on fossil-fuel imports (and ideally other imports too) – while delivering on development goals?	Yes
	Does the project decrease emissions, air pollution and biodiversity loss (ideally enhancing local ecosystems)?	Yes
	Does the solution maximise how it can strengthen local and national economies?	Largely – the company procures components from China and assembly is done in Kenya, creating local jobs and capabilities. Kenya does not have industry for component manufacture at scale to make domestic procurement economical. Possible that more could be done.
Mitigating risks	Have possible negative consequences (e.g. how desired impacts might backfire) of proposed solutions been considered – and is there a process to regularly review this? Are there challenging trade-offs to consider?	A different payment model could create risk of a debt cycle, which exacerbates poverty and climate vulnerability, if farmers become unable to pay for the system (e.g. due to an unexpected hospital expense). SunCulture's payment system prevents this as, with the highest risk of prolonged non-payment being remote shut-off or repossession. SunCulture has identified research concluding that Kenya would benefit from up to 700,000 solar irrigation pumps comparable with their own, before they are likely to exacerbate water scarcity. It has currently sold about 30,000 in Kenya, and is monitoring research closely.
Maximising opportunities	Does the project drive progress towards desirable positive tipping points and cascades, or nurture desirable feedback loops? This might be by improving the enabling environment, delivering an innovative financial solution, or working with partners.	While SunCulture is the largest solar irrigation and agtech company scaling in Kenya, which may show viability, an interviewee argued that it may take a few more companies in this space to scale before there is a convincing demonstration effect. The company is working with local and international researchers to identify and educate farmers on drought-resilient crops and other forms of regenerative agriculture. A critical part of resilience to drought will be the use of drought-resilient crops. There may be potential for SunCulture to support farmers to make this transition. Aligns with Kenya's National Adaptation Plan to (i) promote efficient irrigation systems and (ii) increase the solar, wind and other renewable energy systems networks to provide power to off-grid areas and the broader goal to promote resilient infrastructure.

Table 3.3.3 Applied example of Investor Criteria to the solar-irrigation company, SunCulture.

3. Direct climate resilience benefits

Climate impact	Climate adaptation and resilience opportunities of water infrastructure access
Heat stress	• Water storage solutions can ensure reliable, affordable, accessible access to drinking water, even in the context of increased demand. • Efficient drip irrigation, minimising water use, can prevent crop losses. • Water features using recycled water can lower urban temperatures.
Drought	• Solutions from reservoirs and dams to rainwater harvesting solutions, and water treatment plans, can help ensure reliable, affordable, accessible access even during drought.
Rainfall and river floods	• Flood prevention infrastructure (including wetlands and floodplains) mitigates stagnant water and prevents disease such as dengue or cholera.
Sea level rise/flooding/ cyclones	• Stormwater management systems direct floodwaters away from vulnerable areas to reduce flooding impacts. • Mangrove planting and restoration, as well as coral reef restoration, provide a natural barrier to reduce storm impacts.

Table 3.3.4 Direct climate resilience benefits of water infrastructure

In addition to adaptation, water infrastructure can improve communities' ability to respond to and recover from climate shocks. The example below provides one pertinent example of how water infrastructure provision is supporting the prevention of conflict through infrastructure.

4. National-level economic resilience

There are several macroeconomic resilience benefits of improved water infrastructure. Critically, water infrastructure which is resilient itself and improves the resilience of its communities reduces economic vulnerability caused by droughts, floods and other climate hazards, therefore building economic stability and sustainability. At a national level, highly efficient irrigation can expand agricultural productivity, increase exports and reduce domestic food insecurity even in the face of drought. Improved water infrastructure can attract investment in sectors including agriculture, manufacturing and tourism by reducing the risks associated with water scarcity, and it can facilitate trade and industry dependent on water, therefore supporting economic diversification and growth. Improved health outcomes reduce healthcare costs for governments and increase overall productivity by reducing illness-related work absences.

Case study 12.

Reducing disaster damage to floods and droughts, improving water supply and improving food security for rural and urban populations in Darfur, Sudan – the Wadi El Ku Catchment Management Project

Context and risk: Rainfall had been increasingly erratic in the north Darfur area, linked to climate change and its impacts which magnify natural resource pressures including population, unsustainable farming, deforestation and overgrazing. Climate and demographic change (driven by ongoing conflict associated with the Sudanese civil war) add pressures to the need to retain more water in the local environment for people, livestock and irrigation.[178]

Intervention: In Wadi El Ku, a 50km stretch of one of the largest waterways in north Darfur, community institutions and local government, with international public funding, are delivering ecosystem rehabilitation work to integrate water resources management, food security, disaster risk reduction and local climate resilience. A combination of grey and green infrastructure was implemented, including the adaptation of an existing dam and reservoir to make water available through wet and dry seasons, improve water infiltration into the soil to increase crop productivity and avoid gully erosion downstream, and bring 6,300 hectares of fertile land under cultivation, boosting agricultural production. Alongside this hard infrastructure solution, agricultural land was terraced to enable irrigation of 600 hectares from the reservoir. People were supported to diversify production and seed storage to create resilience during drought periods; a tree nursery and community forests were established for land cover and to generate local employment; and various community governance solutions were kickstarted to calm tensions and create shared management regimes. The project was informed by several policy frameworks and international agreements (e.g. Sudan National Development Strategy/Darfur Development Strategy), which called for integrated water management.[178]

Climate resilience outcomes: For 17,500 inhabitants across five villages, the project improved food security and reduced vulnerability to drought. Agricultural productivity was increased where the water harvesting and water spreading weir techniques were used, with yields of sorghum grain doubling on many of the farms that benefited from improved water harvesting. Most farmers surveyed in a random sample of 200 across the area reported an increase in production from 10% to 70% thanks to the project. Where before, groundwater was overdrawn, generating community tensions over water scarcity, its recharge improved. In several villages, the project's rollout of sustainable irrigation was explicitly connected with improved food security outcomes. Where before they depended on rain-fed agriculture, the irrigation system enabled farmers to produce outside the normal rainy season, resulting in an estimated 4,500 households benefiting and 54% reporting increased crop yields of 50% or more as a result of improved access to water on their farms along the wadi.[178]

The project won the 2017 Land for Life award for improving food security and disaster resilience, and reducing community tensions through sustainable management of dryland areas.

Systems thinking prompts

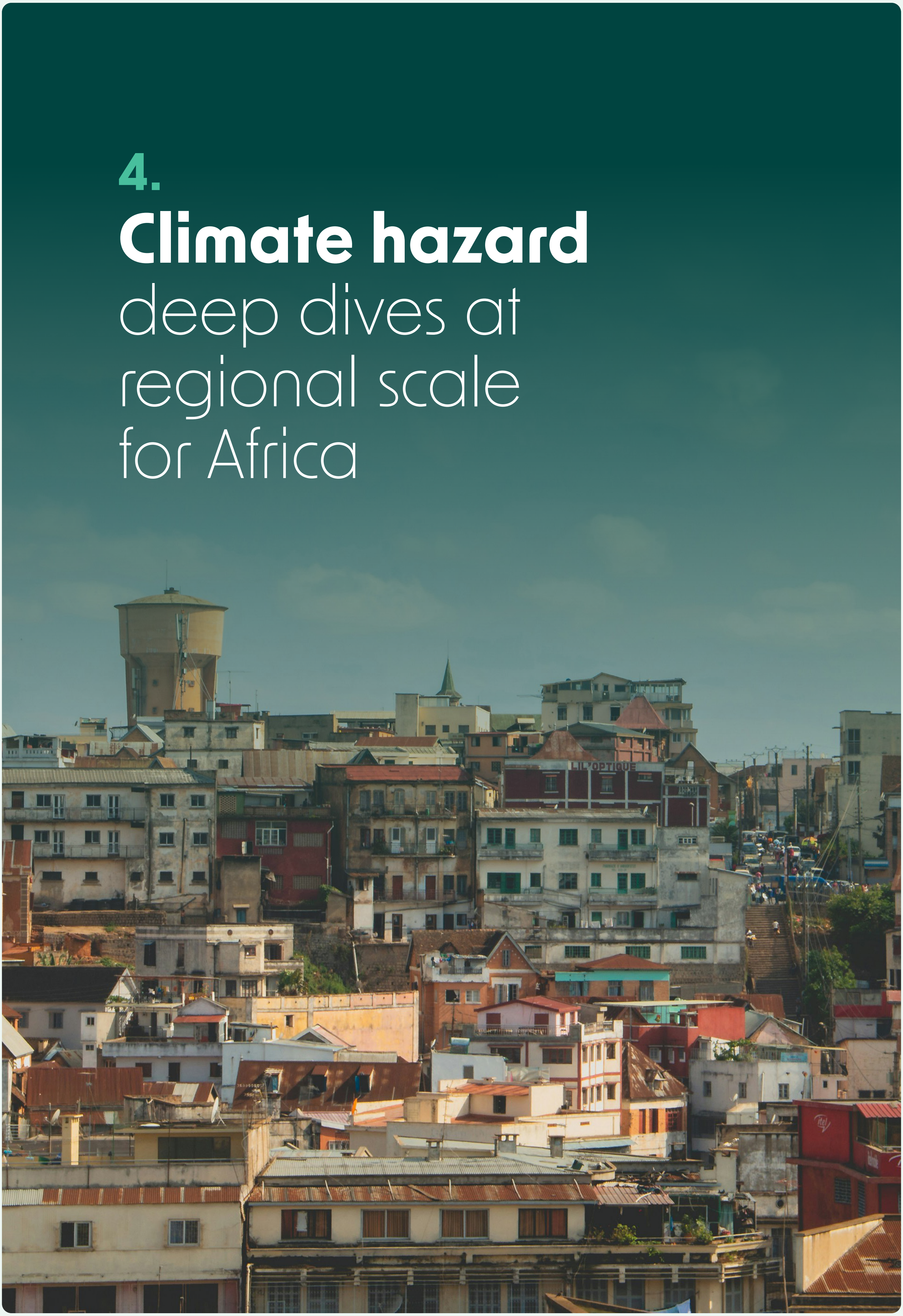
Are positive impacts self-reinforcing or do they create cascading/domino-effect positive impacts?

This project delivers many self-reinforcing water and food security, economic and gender-equality benefits. Improvements in land irrigation mean women and children no longer have to spend hours fetching water, are able to go to school, are not missing school due to illness and are gaining respected roles in the community.[168] Such success is largely attributed to deep engagement with local communities, particularly women. The project was particularly careful to involve women in decision-making processes, and they are now members of water management committees, along with other village representatives. That said, the ongoing improvement of participatory decision-making methods is factored into the second phase.[178]

The infrastructure investment gap

Before accounting for climate resilience, estimates of Africa's water and sanitation infrastructure annual financing needs range from US$55bn to US$66bn, and with average commitments around US$13bn, the annual financing gap is vast.[182] At the same time, projects are not always conceptualised to maximise benefits to the economic activities where they are located and the business case for investing in water-related infrastructure could be stronger if projects were designed to serve multiple purposes (such as water storage, power, irrigation, water supply and tourism). The current financing approach is siloed and mismatched for water resilience, with utilities, water resource authorities and environmental regulators both underfunded and often competing for the same donor funding. The dependence on external funding can present conflicting agendas, inefficiencies and trade-offs that prevent equitable water-resilient investment in cities. Interviewees expressed the importance for investors to take a flexible approach to this challenging sector, and to increase their focus on technology solutions in reducing financial risks.

The examples described in these chapters for energy, transport and water infrastructure projects demonstrate how investment can build systemic resilience and support climate adaptation by being carefully designed to address the specific needs, constraints and vulnerabilities of its users; and how these investments can catalyse new opportunities to drive sustainable development. Using systems-thinking approaches can be a powerful tool for designing or selecting projects that are likely to have successful outcomes, by understanding infrastructure interventions as embedded within wider social, economic, ecological and environmental systems. For such approaches to be effective, investors and project designers need to have access to high-quality, reliable information about the systems in which they are operating. Especially pertinent, if infrastructure access is to specifically address climate vulnerabilities of its users, is for practitioners to be able to access and interpret up-to-date understanding of the distribution of climate impacts at relevant scales.



4.

Climate hazard deep dives at regional scale for Africa

For infrastructure investment, design and delivery to support climate resilient development, it is critical for decision-makers to have access to up-to-date, actionable information on the distribution of climate hazards at relevant scales. Here we assess current understanding of the projected changes in nine regions across Africa which represent a range of different climates, and for each region we also focus in on one representative city in order to give more specific detail, including how the long-term climate change and year-to-year variability evolve with time. We also present assessments of the levels of confidence in projected future changes in different kinds of weather extremes in the different regions.

Our analysis uses the nine climatic regions of Africa defined by the Intergovernmental Panel on Climate Change (IPCC) in its 6th Assessment Report (AR6), shown in Figure 4.1. The regions are defined such that the characteristics of local climates are broadly similar within an individual region, considering both temperatures and rainfall among other aspects of climate. Mediterranean North Africa and the Sahara are hot and very dry. Most of the rest of Africa sees high levels of heavy rainfall, but varies more in temperature. Western Africa and northern areas of Central Africa are hot and humid, while Eastern Africa and southern Central Africa see less extreme high temperatures. Western and Eastern Africa generally see higher extreme temperatures in their southern areas and less high extremes in the north. Madagascar sees less extreme high temperatures but more extreme levels of heavy rainfall.

Within each region, a major city is selected for presentation of trends in climate quantities over time. Where possible, these are chosen to be broadly representative of the region as a whole; while also giving priority to major cities due to their relevance to large populations.

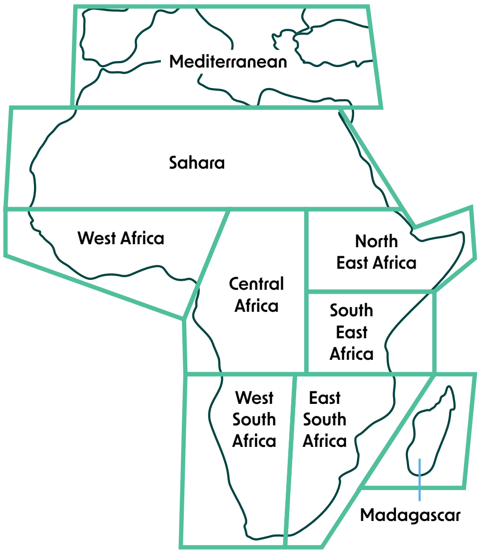


Figure 4.1 Map of the IPCC climate regions over Africa used in this report.[18]

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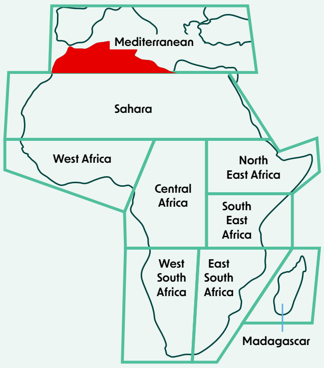
4. The Mediterranean region includes southern Europe as well as northern Africa, but in this report, the focus is on the northern Africa part of this region.



4.1 Mediterranean North Africa

Key messages

- Heatwaves are projected to increase. Extreme heat stress risk emerges after 2050 with a high emissions scenario.
- Extreme agricultural drought is projected to become increasingly likely, and the fire weather season is projected to lengthen.
- Future changes in river flooding risk are unclear and difficult to generalise across the region. Some areas may see increases in river flooding risk, especially some coastal areas, but others may see decreases. The number of people at risk of flooding could still increase if population growth is high.
- Sea level rise and shoreline retreat are projected, but slower than around other African coasts.

4.1.1 Extreme temperatures and heat stress risk

Heatwaves are projected to increase, and conditions of high heat stress risk projected to occur more often. In Algiers, the average annual maximum daily temperature, currently around 34°C, is projected to increase to around 35°C by mid-century, and to around 38°C by the end of the century with high emissions. Risks of heat stress are also projected to increase, with the average annual maximum WBGT increasing from around 29°C (high risk of heat stress) to around 32°C (extreme risk of heat stress) by the end of the century. Days with extreme heat stress risk are projected to begin to occur in the middle of the century, and by the end of the century approximately 10 days per year on average are projected to see extreme heat stress risks, and possibly up to 25 days per year.

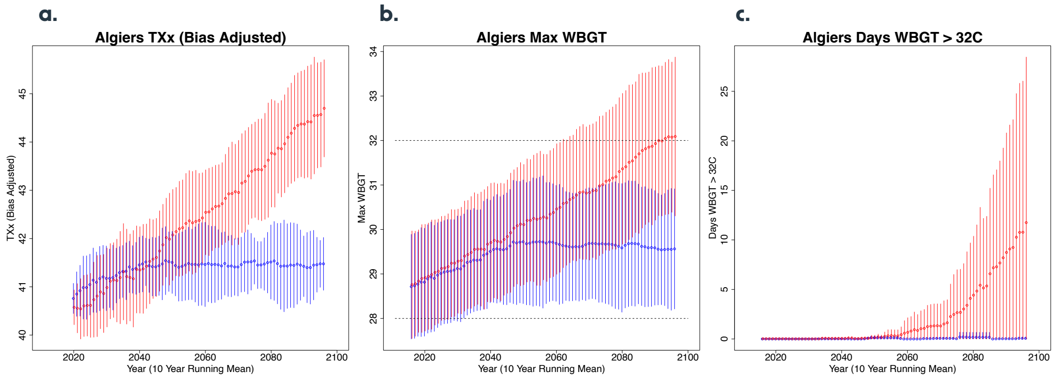


Figure 4.1.1 Projected changes in extreme temperatures and heat stress risk in Algiers in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature (Txx). (b) Annual maximum Wet Bulb Globe Temperature (WBGT). (c) Number of days with WBGT above 32°C, defined as the threshold for extreme heat stress risk. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, with the light red and blue plumes indicating model uncertainty as one standard deviation. Data from Kim et al. (2020)[2] and Schwingshackl et al. (2021)[7].

4.1.2 Drought and fire weather

Drought is projected to increase across the Mediterranean region according to all definitions – meteorological, agricultural/ecological and hydrological drought. An extreme single-year agricultural drought (defined as the driest 10% of years between 1995 and 2014) is projected to be between 50% and 150% more likely at 1.5°C global warming in the areas near the coast. This rises to 50% – 200% across wider areas at 2°C global warming, and over 200% over most of the region at 4°C global warming.

Global warming level	**1.5°C**	**2°C**	**4°C**
Change in likelihood of extreme single-year agricultural drought	50% – 150% in coastal areas	50% – 200% in wider coastal areas	Over 200% in most of region

Table 4.1.1 Projected changes in the frequency of an extreme single-year agricultural drought in Mediterranean North Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The fire weather season in the coastal area of Mediterranean North Africa is currently around 70 days per year, and projected to increase to about 90 days at 1.5°C global warming, 100 days at 2°C and 120 days at 4°C (Figure 1.2.6).

4.1.3 Heavy rainfall and river flooding

Heavy rainfall in coastal regions of Mediterranean North Africa is projected to decline as a result of climate change. This is consistent with the general projected drying trend associated with changes in the atmospheric circulation over the tropics and sub-tropics, with increasing upwards motion of air over the tropics and increasing downward motion over the Mediterranean, which would suppress rainfall. In Algiers, the annual maximum five-day rainfall is projected to decline from about 85mm to around 75mm, but with large year-to-year variability and also large uncertainty in the trend.

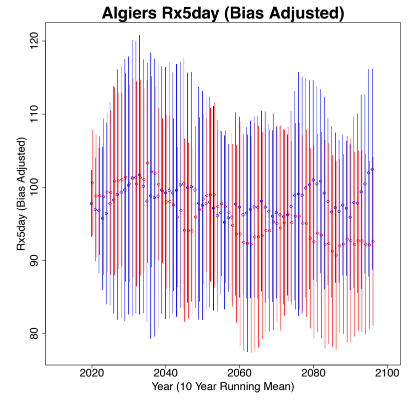


Figure 4.1.2 Projected annual maximum five-day rainfall (Rx5day) in Algiers with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, with the light red and blue plumes indicating model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

Climate change alone is projected to reduce the risk of river flooding in most North African countries bordering the Mediterranean, with the exception of Egypt due to the presence of the Nile as a major river with a basin extending thousands of kilometres to the south into a different climatic zone (Figure 1.2.10, Table 4.1.2). However, a minority of models project an increase in river flooding risk due to climate change in some countries in this region. Population growth is projected to increase the number of people at risk of flooding, and with the high population-growth scenario this would mean an overall increase in the number of people exposed to river flooding even in countries in which climate change decreases the flooding risk. With the low population-growth scenario, the number of people exposed to river flooding is still projected to decrease at 3°C global warming with most climate models, but with this decrease being smaller than that due to climate change alone.

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Morocco	At least 20% reduction	At least 20% reduction	At least 20% reduction
Algeria	At least 20% reduction*	0% – 20% reduction	0% – 50% increase*
Tunisia	At least 20% reduction	At least 20% reduction	At least 20% reduction
Libya	At least 20% reduction	0% – 20% reduction	0% – 50% increase*
Egypt	At least 300% increase	At least 300% increase	No data available

Table 4.1.2 Relative change in number of people exposed to river flooding in countries with part or all of territory in Mediterranean North Africa with 3°C global warming and different population scenarios. Data from Dottori et al (2018)[10].
**Less than 90% agreement between models.*

4.1.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase along the Mediterranean coast of North Africa, with extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20cm and 40cm by mid-century. Increases by the end of the century are projected to be 40cm to 60cm with low emissions and 60cm to 80cm with high emissions. While potentially damaging, these rates are approximately 25% slower than projected rises around most of the coast of Africa. By 2100, with a high warming scenario, the shoreline is projected to retreat by generally a few tens of metres along most of the coast of Morocco and Algeria, but a retreat of 150m to 200m is projected along much of the coast of Libya, which is similar to many other coastal areas around Africa.

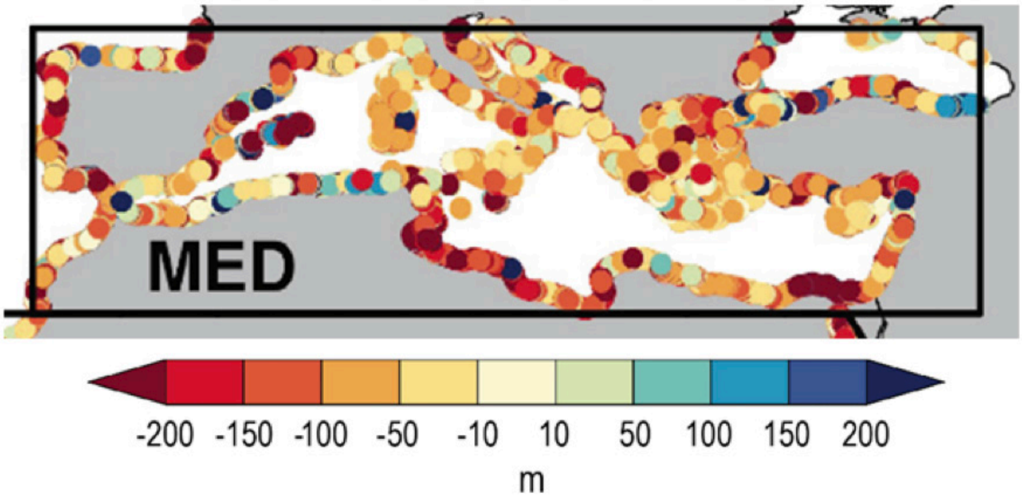


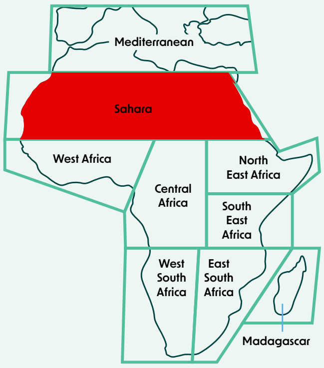
Figure 4.1.3 Projected shoreline position change along coasts of Mediterranean North Africa by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11]

4.1.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves, extreme rainfall and drought are all projected to increase in Mediterranean North Africa, with the IPCC assessment of certainty increasing for higher levels of global warming but at varying levels for the different extremes. Increased intensity and/or frequency of heatwaves has the highest level of certainty compared to other extremes, followed by increased drought. Increased extreme rainfall is projected with confidence levels increasing from low at 1.5C warming to high at 4°C global warming, but without percentage likelihoods being assigned.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	Low confidence	Medium confidence	High confidence
Change in drought	Medium confidence in increase	High confidence in increase	90% - 100% chance of increase

Table 4.1.3 IPCC assessment of confidence in projected changes in weather extremes in Mediterranean North Africa. Source: Seneviratne et al. (2021)[184]



4.2 Sahara

Key messages

- Heatwaves are projected to increase. Extreme heat stress risk emerges in the 2030s with a high emissions scenario.
- Extreme agricultural drought is projected to become more likely in the northern Sahara but less likely in the Sahel.
- Countries in the Sahel are projected to see increases in the number of people exposed to river flooding due to climate change alone, with further increases due to population growth.
- Sea level rise and shoreline retreat are projected, with greater retreat on the Atlantic coast than the Red Sea.

4.2.1 High temperatures and heatwaves

Heatwaves are projected to increase, and conditions of high heat stress risk projected to occur more often. In Timbuktu, the average annual maximum daily temperature, currently around 45°C, is projected to increase to around 46°C by mid-century, and to around 49°C by the end of the century with high emissions. Risks of heat stress are also projected to increase, with the average annual maximum WBGT increasing from just below 32°C (extreme risk of heat stress) to around 35°C (extreme risk of heat stress) by the end of the century. Days with extreme heat stress risk are projected to begin to occur in the 2030s, and by the end of the century approximately 100 days per year on average are projected to see extreme heat stress risks, and possibly up to 140 days per year.

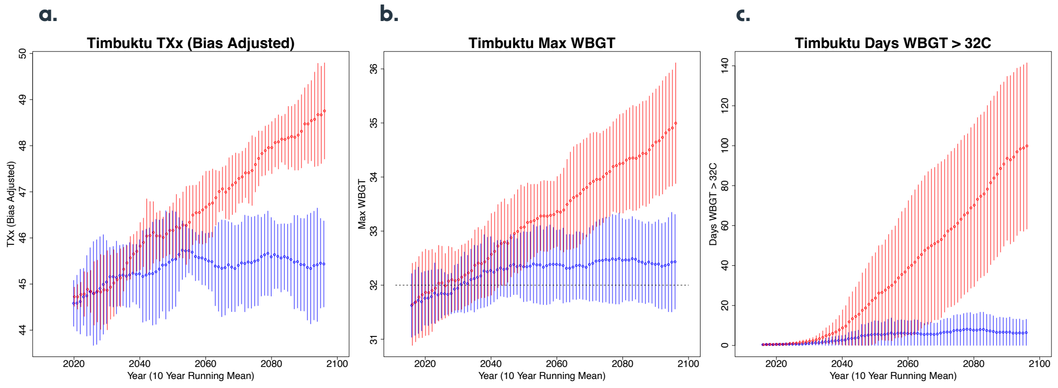


Figure 4.2.1 Projected changes in extreme temperatures and heat stress risk in Timbuktu in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature. (b) Annual maximum WBGT. (c) Number of days with WBGT above 32°C, defined as the threshold for extreme heat stress risk. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, with the light red and blue plumes indicating model uncertainty as one standard deviation. Data from Sillmann et al. (2013)[185], Kim et al. (2020)[2] and Schwingshackl et al. (2021)[7] via Sandstad et al. (2022).[186]

4.2.2 Drought and fire weather

Drought is projected to increase in northern areas of the Sahara region but decrease in the southern areas, particularly in the Sahel in the far south. An extreme single-year agricultural drought (defined as the driest 10% of years between 1995 and 2014) is projected to be between 50% and 100% less likely along the Sahel / Sahara desert boundary at 1.5°C global warming, and over wider areas at higher levels of global warming.

Global warming level	1.5°C	2°C	4°C
Change in likelihood of extreme single-year agricultural drought	Up to 50% increase in northern areas, 50% – 100% decrease in Sahel	Up to 100% increase in northern areas, 50% – 100% decrease in wider areas of Sahel	50% – 200% increase in northern areas, 50% – 100% decrease in wider areas of Sahel

Table 4.2.1 Projected changes in the frequency of an extreme single-year agricultural drought in Western Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The fire weather season is not defined in the majority of the Sahara region because lack of vegetation means that wildfire is not an issue.

4.2.3 Heavy rainfall and river flooding

Instances of relatively heavy rainfall are projected to increase in the Sahara region, although rainfall defined as ‘heavy’ in this region is less intense than in other regions of Africa. For example, the average annual maximum five-day rainfall in Timbuktu is around 50mm – about half that in Kinshasa in Central Africa. In Timbuktu, the average annual maximum five-day rainfall is projected to remain roughly constant until mid-century and then remain constant with low emissions but increase with high emissions, reaching nearly 60mm by the end of the century. In the Senegal, Niger and Nile rivers, the current one-in-100-year flood is projected to become a one-in-25-year to one-in-50-year flood at approximately 2°C global warming, with frequency increasing further with warming, becoming a five-year flood in the Nile at around 4.5°C global warming.

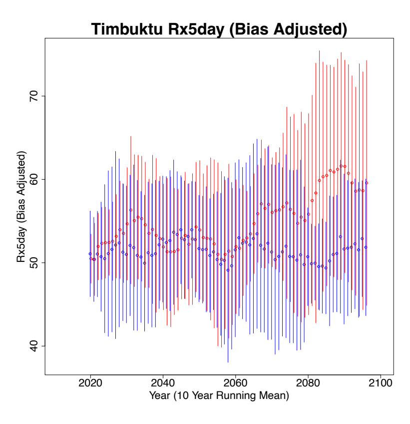


Figure 4.2.2 Projected annual maximum five-day rainfall (Rx5day) in Timbuktu with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

Climate change alone is generally projected to reduce the risk of river flooding in Algeria, Libya and Morocco, although a minority of models project an increase in river flooding risk due to climate change in Algeria and Libya (Figure 1.2.10, Table 4.2.2). In other countries in the Sahara region, climate change increases the risk of flooding, and population growth is projected to further increase the number of people exposed to flooding.

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Morocco	At least 20% decrease	At least 20% decrease	At least 20% decrease
Algeria	At least 20% decrease*	0% to 20% decrease	0% to 50% increase*
Libya	At least 20% decrease*	0% to 20% decrease	0% to 50% increase*
Egypt	More than 300% increase	More than 300% increase	No data available
Western Sahara	0% to 50% increase	At least 20% decrease	0% to 50% increase
Mauritania	50% – 100% increase	100% – 200% increase	200% – 300% increase
Senegal	100% – 200% increase	100% – 200% increase	More than 300% increase
Mali	0% to 50% increase	100 – 200% increase	200 – 300% increase
Niger	200% – 300% increase	More than 300% increase	More than 300% increase
Chad	50% – 100% increase	100% – 200% increase	100% – 200% increase
Sudan#	50% – 100% increase	100% – 200% increase	100% – 200% increase
Eritrea	50% – 100% increase	200% – 300% increase	More than 300% increase

Table 4.2.2 Relative change in number of people exposed to river flooding in countries with part or all of territory in the Sahara region with 3°C global warming and different population scenarios. Data from Dottori et al (2018)[10].
**Less than 90% agreement between models.*

** Data in source study only available for Sudan and South Sudan combined.*

4.2.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase along both the Atlantic and Red Sea coasts of the Sahara region. Extreme total water levels (including relative sea level, storm surges, tides and high waves) increase by between 20cm and 40cm by mid-century. Increases by the end of the century are projected to be 40cm to 60cm with low-emissions and 80cm to 100cm with high emissions. Shoreline retreat by 2100 is projected to be generally larger along the Atlantic coast than the Red Sea coast, with much of the Atlantic coasts projected to see 150m – 200m retreat while retreat on the Red Sea coast is generally tens of metres, but still with some locations with retreat above 100m.

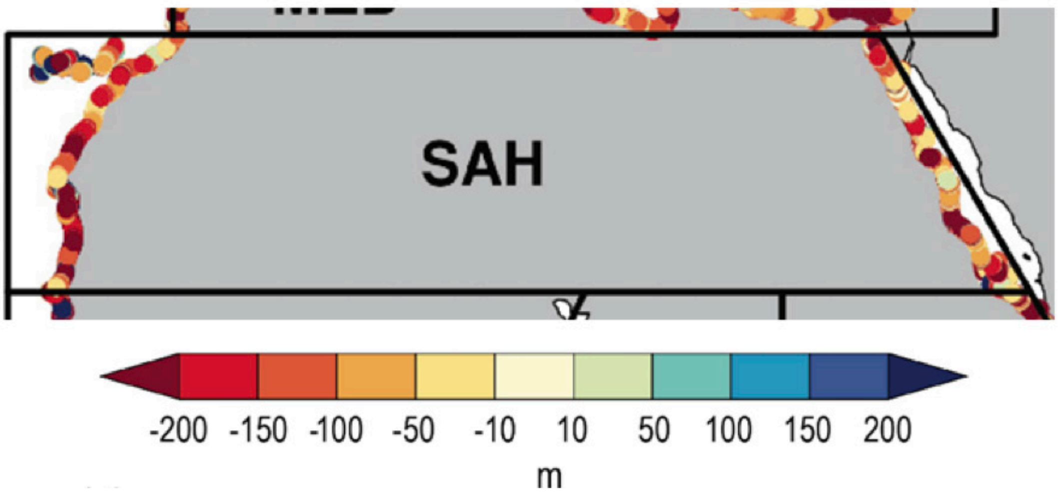


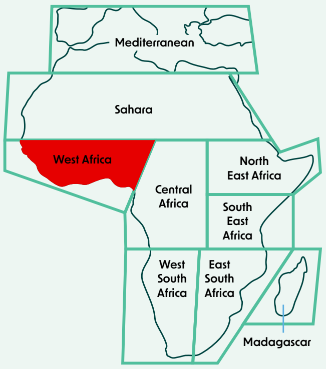
Figure 4.2.3 Projected shoreline position change along coasts of Sahara region by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11].

4.2.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves and extreme rainfall are both projected to increase in the Sahara region, with the IPCC assessment of certainty increasing for higher levels of global warming. Increased intensity and/or frequency of heatwaves has the highest level of certainty, followed by increased extreme rainfall. There is low confidence in projected changes in agricultural drought, even at 4°C global warming.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	High confidence	66% – 100% chance	95% – 100% chance
Change in drought	Low confidence	Low confidence	Low confidence

Table 4.2.3 IPCC assessment of confidence in projected changes in weather extremes in Sahara. Source: Seneviratne et al. (2021)[184].



4.3 Western Africa

Key messages

- Increasingly long periods of extreme heat stress are projected.
- Increased heavy rainfall and river flooding are projected. Increase in landslides reported, but future changes in landslide risk in Africa have not yet been studied.
- Increased coastal flooding and shoreline retreat are projected.
- Increased exposure of large numbers of people to flooding is expected due to urbanisation.
- In the longer term, at higher levels of global warming, Western Africa may also need to prepare for increased drought.

4.3.1 Heatwaves

Heatwaves in Western Africa are already becoming longer and more intense, and this is projected to continue, along with increasing risk of heat stress. A combination of high temperatures and high humidity is a particular danger for heat stress.

Considering temperatures alone, in Lagos, the hottest day of the year has typically been between 37°C and 38°C since 2000, having increased from between 36°C and 37°C in the 1960s. This is projected to increase to around 39°C in the middle of the 21st Century, and if emissions continue to rise, could reach between 40°C and 42°C by the end of the century.

Considering heat stress conditions from a combination of high temperatures and humidity, Lagos is projected to experience particularly large changes. Heat stress conditions defined as ‘extreme’ currently occur between 1 and 10 days per year, but in 2050 without action to cut global emissions, they are projected to occur around 50 days per year (possibly up to 70). This could exceed 200 days per year by the end of the century. Even in a scenario assuming rapid emissions reductions that limit global warming to around 2°C, Lagos would experience between 20 and 40 days per year with extreme heat stress conditions from around 2050 onwards. If emissions are not reduced, Lagos is projected to experience extreme heat stress condition for at least a quarter of the year and potentially up to two-thirds of the year.

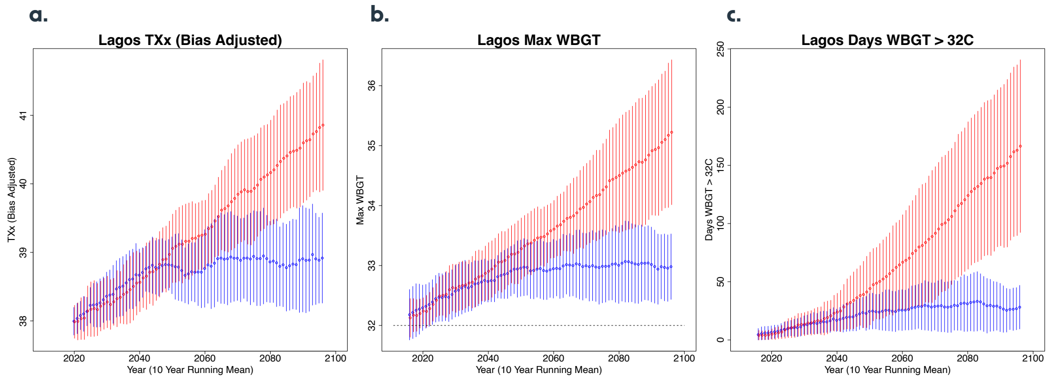


Figure 4.3.1 Projected changes in extreme temperatures and heat stress risk in Lagos in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature (Txx). (b) Annual maximum Wet Bulb Globe Temperature (WBGT). (c) Number of days with WBGT above 32°C, defined as the threshold for extreme heat stress risk. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, with the light red and blue plumes indicating model uncertainty as one standard deviation. Data from Kim et al. (2020)[2] and Schwingshackl et al. (2021)[7].

4.3.2 Drought and fire weather

There is generally low confidence in projected changes in all metrics of drought on average across Western Africa, although confidence increases at higher levels of global warming. At 1.5°C and 2°C global warming, current models project increased likelihood of an extreme single-year agricultural drought in the western part of the region, and a decrease the eastern part (Figure 1.2.5). At 4°C global warming, models project large increases in drought frequency in the far west of the region. The IPCC assigned 'medium confidence' to increases in meteorological drought at 4°C global warming.

Global warming level	1.5°C	2°C	4°C
Change in likelihood of extreme single-year agricultural drought	Increase in west, decrease in east, but low confidence	Increase in west, decrease in east, but low confidence	50% – 250% in increase in far west

Table 4.3.1 Projected changes in the frequency of an extreme single-year agricultural drought in Western Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The fire weather season is currently between 100 and 200 days in most of Western Africa, but shorter nearer southern coasts (Figure 1.2.6). This is projected to increase across most of the region, by up to about 10 days at 1.5°C global warming, 20 days at 2°C and 30 days at 4°C.

4.3.3 Extreme rainfall, river flooding and landslides

Western Africa already sees high levels of heavy rainfall, and this is projected to become even heavier if global warming continues for several decades or beyond. According to the IPCC assessment, increased heavy rainfall is likely at 2° global warming (which could be reached mid-century) and extremely likely at 4°C global warming. However, the projected long-term increases should be seen in the context of already high levels of heavy rainfall and large year-to-year variability. In Lagos, the annual maximum five-day rainfall is projected to vary between approximately 170mm and 270mm throughout the 21st Century in scenarios with both high and low emissions, with a slight upward trend of approximately 10mm over the century in the scenario reaching global warming of 4°C by 2100.

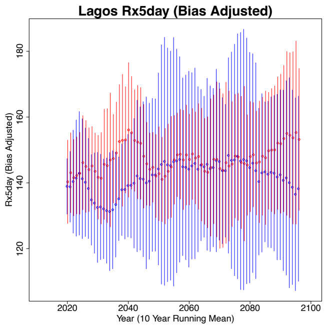


Figure 4.3.2 Projected annual maximum five-day rainfall in Lagos with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Benin	50% – 100%	100% – 200%	200% – 300%
Burkina Faso	100% – 200%	Over 300%	Over 300%
Cabo Verde	No data available	No data available	No data available
Cote D'Ivoire	0% – 50%	0% – 50%	100% – 200%
Gambia	No data available	No data available	No data available
Ghana	50% – 100%	100% – 200%	Over 300%
Guinea	0% – 50%	0% – 50%	100% – 200%
Guinea-Bissau	0% – 50%	50% – 100%	200% – 300%
Liberia	50% – 100%	200% – 300%	Over 300%
Nigeria	100% – 200%	200% – 300%	Over 300%
Senegal	100% – 200%	100% – 200%	Over 300%
Sierra Leone	50% – 100%	100% – 200%	200% – 300%
Togo	0% – 50%*	0% – 50%	50% – 100%

Table 4.3.2 Relative increase in number of people exposed to river flooding in countries in West Africa with 3°C global warming at three different population scenarios: current population, low population growth, and high population growth. Data from Dottori et al (2018)[10]. **Less than 90% agreement between models.*

River flooding is projected to increase in all countries in Western Africa due to increasing heavy rainfall due to climate change. Across southern regions of Western Africa, the 100-year flood is projected to become a five to 25-year flood by the end of the 21st Century with approximately 3°C global warming (Figure 1.2.9). The number of people exposed to flooding is projected to increase both due to heavy rainfall and increases in population (Table 4.3.2). For example, in Nigeria, climate change alone is projected to at least double the number of people exposed to river flooding[10]. With the scenario of high economic growth and relatively small increases in population (known as SSP5), the number of people in Nigeria exposed to river flooding is projected to increase by between 200% and 300%. This increases to over 300% the scenario of lower economic growth and large increases in population (known as SSP3).

Landslides can be a major consequence of heavy rainfall, and there has been a reported increase in landslides in Western Africa.[11] However, the impact of past and future climate change on landslide risks in Africa has so far received very little attention in the scientific literature and is currently a major knowledge gap.

4.3.4 Coastal flooding and shoreline retreat

SSea level rise and coastal flooding are projected to increase along both the western and southern coasts of Western Africa (Figure 4.3.3), with extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20cm and 40cm by mid-century. Increases by the end of the century are projected to generally be 40cm to 60cm with low emissions and 80cm to 100cm with high emissions. Shoreline retreat by 2100 is projected to be between 100m and 200m or more along most coastal areas, with particularly high levels of retreat along the coasts of the Gambia, Guinea-Bissau, Guinea and Nigeria. A few locations see projected retreat below 50m. These projections are based on current models which may not account for the full range of potential global sea level rise if uncertainties in ice sheet loss are taken into account – impacts could be larger if large losses of ice into the oceans occur.

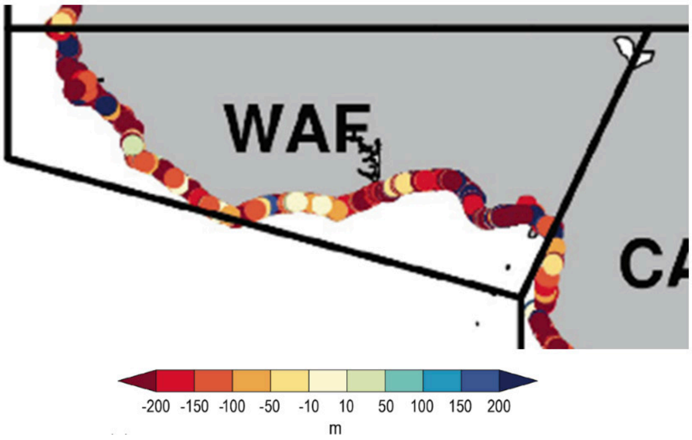


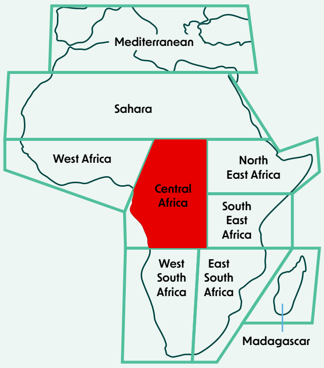
Figure 4.3.3 Projected shoreline position change along coasts of Western Africa by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11].

4.3.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves, extreme rainfall and drought are all projected to increase in Western Africa, with the IPCC assessment of certainty increasing for higher levels of global warming but at varying levels for the different extremes (Table 4.3.3). Increased intensity and/or frequency of heatwaves has the highest level of certainty compared to other extremes, followed by increased extreme rainfall. At 4°C global warming, increased meteorological drought is projected with medium confidence, and agricultural/ecological drought is assessed as 'low confidence' due to differing signs of change in different parts of the region. At lower levels of global warming there is low confidence in projected drought changes in all drought metrics due to inconsistent signals – different signs of change in different areas, and disagreements between models. These confidence and likelihood assignments are based on a comprehensive literature assessment drawing on current and previous generations of climate models. If a large-scale climate system event were to occur that does not emerge in current models, such as a collapse of the Atlantic Meridional Overturning Circulation (AMOC), which is judged to be unlikely this century but still possible, this would alter the assessment here. An increase in heatwaves may become less likely, but an increase in drought may become more likely. Other tipping points such as Amazon forest dieback and permafrost thawing would increase the likelihood of higher levels of global warming being reached.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	High confidence	66% – 100% chance	95% – 100% chance
Change in drought	Low confidence	Low confidence	Medium confidence in increase

Table 4.3.3 IPPCC assessment of confidence in projected changes in weather extremes in Western Africa. Source: Seneviratne et al. (2021)[184].



4.4 Central Africa

Key messages

- Extreme heat stress levels are projected for more of the year with higher levels of global warming.
- Heavy rainfall and river flooding are projected to increase due to climate change, but even larger increases are possible
- due to natural climate variability.
- Shoreline retreat due to sea level rise is projected to be particularly large along the coasts of Central Africa compared to other regions.
- Drought is projected to decrease in northern areas but increase in the south.

4.4.1 Extreme temperatures and heat stress risk

Heatwaves in Central Africa are projected to become longer and more intense, along with increasing risk of heat stress. A combination of high temperatures and high humidity is a particular danger for heat stress. While it is expected from models that heatwaves in Central Africa are already becoming more severe, it is not yet possible to establish this from observations due to lack of data.

Considering temperatures alone, in Douala, the hottest day of the year is estimated to typically be around 36°C. This is projected to increase to around 37°C to 38°C in the middle of the 21st Century, and potentially over 40°C by the end of the century if emissions continue to rise in line with a continuation of current global policies.

Douala is projected to experiencing increasing heat stress conditions from a combination of high temperatures and humidity. It currently sees maximum WBGT of around 30°C to 31°C, which is regarded as high risk for heat stress. The maximum WBGT is projected to increase to between 31°C and 32°C by mid-century, with 32°C WBGT being the threshold for extreme heat stress risk. In a scenario reaching approximately 4°C global warming by the end of the century, Douala is projected to experience extreme heat stress conditions for around 80 days per year by 2100, and up to 140 days per year at the higher end of estimates.

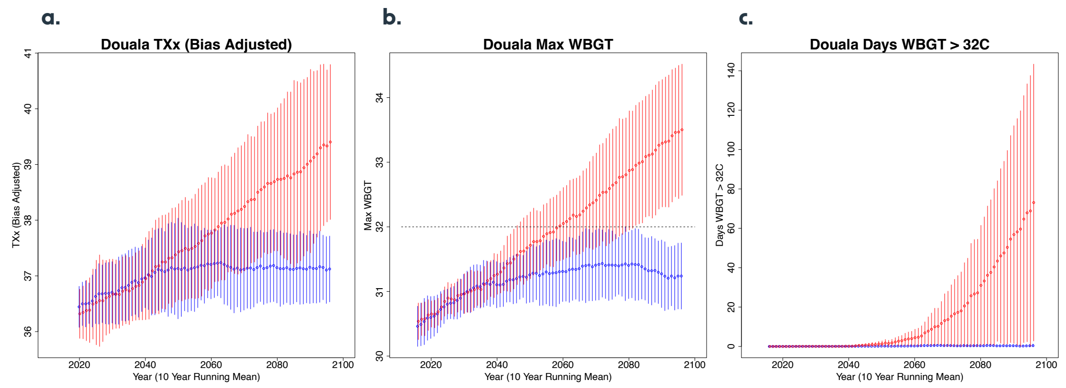


Figure 4.4.1 Projected changes in extreme temperatures and heat stress risk in Douala in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature (Txx). (b) Annual maximum Wet Bulb Globe Temperature (WBGT). (c) Number of days with WBGT above 32°C, defined as the threshold for extreme heat stress risk. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2] and Schwingshackl et al. (2021)[7].

4.4.2 Drought and fire weather

There is generally low confidence in projected changes in all metrics for drought on average across Central Africa. Current models project decreased likelihood of an extreme single-year agricultural drought in the northern part of the region, and an increase the southern part, with changes becoming larger with global warming in both cases.

Global warming level	1.5°C	2°C	4°C
Change in likelihood of extreme single-year agricultural drought	Decrease in the north, over 50% in some areas, and increase in south	Decrease in the north, over 50% in wide areas, and increase of generally 50% – 100% in south	Decrease in the north, over 50% in some areas, and increase of over 50% in the south, 100% – 200% in some areas

Table 4.4.1 Projected changes in the frequency of an extreme single-year agricultural drought in Central Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The fire weather season is over 100 days in northern areas of Central Africa, but only a few days in length in the south (Figure 1.2.6). In both areas, then, it is projected to change little with global warming.

4.4.3 Heavy rainfall, river flooding and landslides

Heavy rainfall is projected to increase in Central Africa if global warming continues in the long term, but large increases and decreases due to natural climate variability are also expected. According to the IPCC assessment, increased heavy rainfall is likely at 2° global warming and extremely likely at 4°C global warming. In Douala, which already receives high levels of heavy rainfall, the annual maximum five-day rainfall (Rx5day) is projected to increase from around 260mm to 280mm in the scenario reaching global warming of 4°C by 2100. In the scenario with warming limited to 2°C, there is little trend over the century. Year-to-year natural variability is large in both scenarios, so even in the 2°C scenario, some years with Rx5day exceeding 300mm are projected.

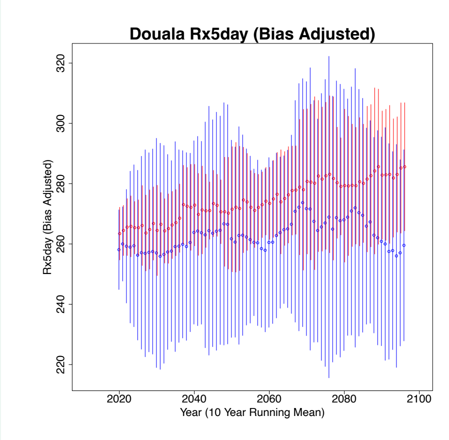


Figure 4.4.2 Projected annual maximum five-day rainfall (Rx5day) in Douala with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

River flooding is projected to increase in all countries in Central Africa due to increasing heavy rainfall due to climate change[10]. Except for in the far north of the region, the one-in-100-year flood is projected to occur between every five and 25 years by the end of the 21st Century with approximately 3°C global warming (Figure 1.2.9). The number of people exposed to flooding is projected to increase to some extent due to climate change and even more due increases in population, both in low and high-population scenarios (Table 4.4.2, Figure 1.2.10). In the Democratic Republic of the Congo, climate change alone is projected to increase the number of people exposed to river flooding by up to 50%.[10] The projected increase becomes 50% – 100% with the scenario of relatively small increases in population in addition to climate change, and 100% – 200% with the large population increase scenario.

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Cameroon	50% – 100% increase	100% – 200% increase	200% – 300% increase
Central African Republic	0% – 50% increase*	0% – 50% increase	50% – 100% increase
Democratic Republic of the Congo	0% – 50% increase	50% – 100% increase	100% – 200% increase
Equatorial Guinea	At least 300% increase	At least 300% increase	At least 300% increase
Gabon	200% – 300% increase	At least 300% increase	At least 300% increase
Republic of the Congo	0% – 50% increase*	50% – 100% increase	100% – 200% increase
Sao Tome and Principe	No data available	No data available	No data available
South Sudan#	50% – 100% increase	50% – 100% increase	50% – 100% increase

Table 4.4.2 Relative increase in number of people exposed to river flooding in countries in West Africa with 3°C global warming and three different population scenarios: current population, low population growth and high population growth. Data from Dottori et al (2018)[10] **Less than 90% agreement between models.*
#Data in source study only available for Sudan and South Sudan combined

Landslides can be a major consequence of heavy rainfall, and there has been a reported increase in landslides in Central Africa.[11] However, the impact of past and future climate change on landslide risks in Africa has so far received very little attention in the scientific literature and is currently a major knowledge gap.

4.4.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase along the coast of Central Africa, with extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20cm and 40cm by mid-century. Increases by the end of the century are projected to generally be 40cm to 80cm with low-emissions and 80cm to 100 cm with high emissions. Shoreline retreat by 2100 is projected to be 100m or more along almost all of the coast, and 200m or more along much of it. These projections are based on current models, which may not account for the full range of potential global sea level rise if uncertainties in ice sheet loss are taken into account – impacts could be larger if large losses of ice into the oceans occur.

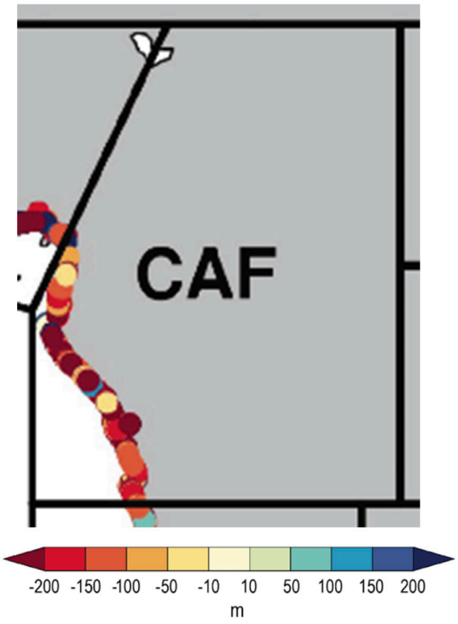


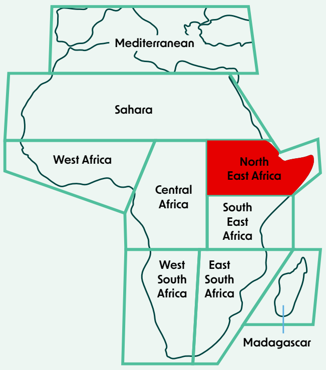
Figure 4.4.3 Projected shoreline position change along coasts of Central Africa by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11].

4.4.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves and extreme rainfall are both projected to increase in Central Africa, with the IPCC assessment of certainty increasing for higher levels of global warming but at varying levels for the different extremes. Increased intensity and/or frequency of heatwaves has a higher level of certainty than increased extreme rainfall. There is low confidence in projected changes in all drought metrics at all levels of warming.

	1.5°C global warming (Next 10-20 years)	2°C global warming (Mid-century unless emissions cut rapidly to net zero)	4°C global warming (End of century with high emissions)
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	High confidence	66% – 100% chance	95% – 100% chance
Change in drought	Low confidence	Low confidence	Low confidence

Table 4.4.3 IPCC assessment of confidence in projected changes in weather extremes in Central Africa. Source: Seneviratne et al. (2021)[184].



4.5 North Eastern Africa

Key messages

- River flooding is projected to occur more frequently at higher levels of global warming.
- Shoreline retreat is projected along the coasts of North Eastern Africa, with greater retreat at the mouth of the Red Sea and less on the eastern coast of the Horn of Africa.
- High levels of heat stress risk are projected to occur for a greater proportion of the year in lowland areas, but cooler conditions limit the risk at higher elevations.
- The fire weather season is projected to become shorter over most of the region.
- Changes in drought are unclear for lower levels of global warming. Decreased drought is projected with higher levels of warming, but only with medium confidence.

4.5.1 Extreme temperatures and heat stress risk

With the exception of South Sudan, much of the North Eastern Africa region currently sees less extreme high temperatures than similar latitudes in Western and Central Africa (Figures 1.2.1 and 1.2.2), largely due to being at high elevations. Heat stress conditions reach high risk levels for around half the year in large parts of South Sudan and coastal regions of Somalia, but rarely reach these levels in Ethiopia (Figure 1.2.3). Heatwaves and heat stress conditions are projected to increase across the region, with high heat stress being seen for more of the year in South Sudan and Somalia. In a scenario reaching 4°C global warming by 2100, high heat stress conditions are also projected to encroach on Ethiopia, despite the higher elevations. In Addis Ababa, risks of heat stress are projected to increase with climate change, but start from a relatively lower baseline, with the average annual maximum WBGT increasing from around 23°C at the present day to approach 26°C (high risk of heat stress) by the end of the century with 4°C global warming.

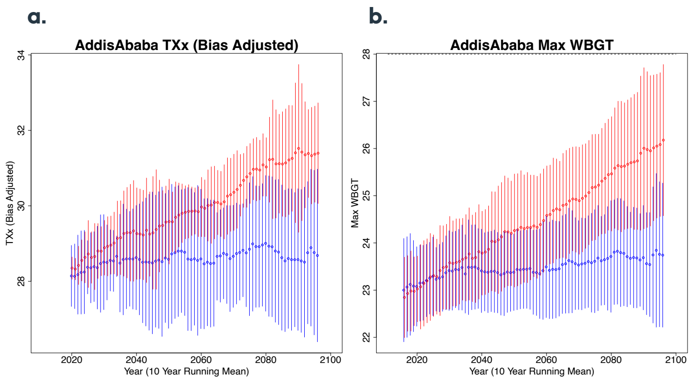


Figure 4.5.1 Projected changes in extreme temperatures and heat stress risk in Addis Ababa in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature (Txx). (b) Annual maximum Wet Bulb Globe Temperature (WBGT). Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2] and Schwingshackl et al. (2021)[7].

4.5.2 Drought and fire weather

In the long term, drought is projected to generally decrease in North Eastern Africa, but projected changes in the nearer term are not clear. In current models, extreme single-year agricultural drought (defined as the driest 10% of years in 1995-2014) is projected to be up to around 50% less likely at 1.5°C global warming in approximately half the region, and around 50% more likely in the other half. At 2°C global warming the balance shifts more towards decreased likelihood of extreme drought, and at 4°C global warming there is a decrease in most of region, especially the Horn of Africa with at least a 50% decrease in likelihood. The main exception is the south of the region in which increased likelihood of extreme drought is projected. The IPCC assign medium confidence to reductions in meteorological, agricultural/ecological and hydrological drought in North Eastern Africa.

Global warming level	1.5°C	2°C	4°C
Change in likelihood of extreme single-year agricultural drought	Small decrease in some areas, small increase in others	Decrease across more areas than at 1.5°C global warming, increase in other more limited areas	Decrease in most of region, especially Horn of Africa with at least 50% decrease. Increase in south.

Table 4.5.1 Projected changes in the frequency of an extreme single-year agricultural drought in North Eastern Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The Fire Weather Season Length (FWSL) is approximately 50 to 100 days in most of North Eastern Africa, and is projected to generally decrease with global warming by up to 10 – 20 days per year at 4°C global warming (Figure 1.2.6).

4.5.3 Heavy rainfall, river flooding and landslide risk

Extreme rainfall is projected to increase in North Eastern Africa: according to the IPCC assessment, increased extreme rainfall is likely at 2° global warming (which could be reached mid-century) and extremely likely at 4°C global warming. However, the projected long-term increases should be seen in the context of large year-to-year variability. In Addis Ababa, the annual maximum five-day rainfall is projected to increase from approximately 80mm at present to approximately 90mm in mid-century, and increasing further to approximately 100mm by 2100 in a scenario reaching 4°C global warming, possibly up about 120 mm.

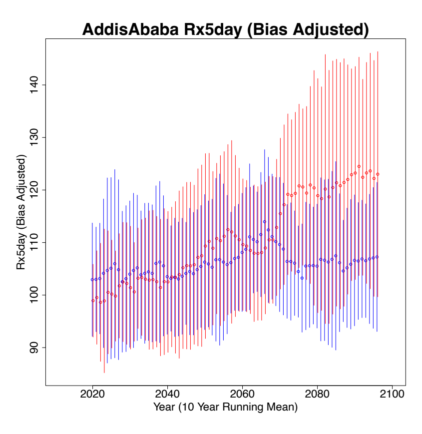


Figure 4.5.2 Projected annual maximum five-day rainfall in Addis Ababa with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

River flooding in South Eastern Africa is projected to become more frequent due to climate change. The current 100-year flood is projected to become a 25-year to 50-year flood at 1.5°C, and a 5-year to 25-year flood at 2°C and 4°C global warming, with high agreement between climate models over some of the region at 1.5°C and 2°C warming and the whole region at 4°C warming (Figure 1.2.9).

Climate change is projected to increase the number of people at risk of flooding by up to 50% in all countries in the region at 3°C global warming, except Somalia where the projected increase is 100%-200%. This increases to 50% – 200% with the low population-growth scenario and 100% – 200% with high population growth (Table 4.5.2, Figure 1.2.10). The numbers increase further with both low and high population-growth scenarios, reaching 100-300% with high population growth in most countries, and over 300% in Somalia.

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Djibouti	No data available	No data available	No data available
Central African Republic	50 – 100% increase	200 – 300% increase	More than 300% increase
Eritrea	0% – 50% increase	50% – 100% increase	100% – 200% increase
Ethopia	Up to 50%	50% – 100%	100 – 200%
Somalia	100 – 200%	100 – 200%	>300%
South Sudan#	50 – 100% increase	100 – 200% increase	100 – 200% increase

Table 4.5.2 Relative increase in number of people exposed to river flooding in countries in North Eastern Africa with 3°C global warming three different population scenarios: current population, low population growth, and high population growth. Data from Dottori et al (2018)[10]. **Data in source study only available for Sudan and South Sudan combined*

Landslides can be a major consequence of heavy rainfall, and there has been a reported increase in landslides in North Eastern Africa.[11] However, the impact of past and future climate change on landslide risks in Africa has so far received very little attention in the scientific literature and is currently a major knowledge gap.

4.5.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase along the coasts of North Eastern Africa, with extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20 and 40 cm by mid-century. Increases by the end of the century are projected to be 40 cm to 80 cm with low-emissions and 80 – 100 cm with high emissions. Shoreline retreat by 2100 is projected to be generally around 50m on the eastern coast of the Horn of Africa, 50m – 100m on the Gulf of Aden coast and 150 – 200m or more at the mouth of the Red Sea.

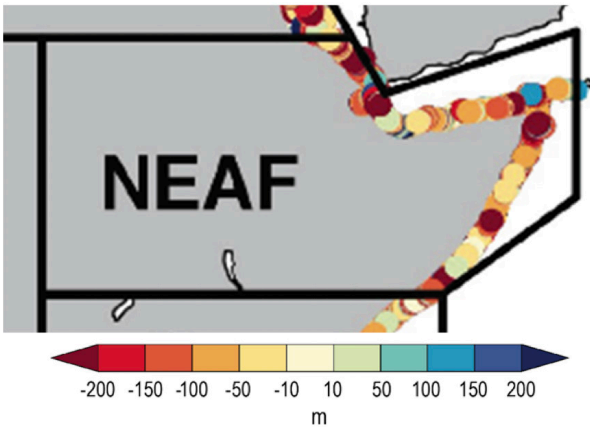


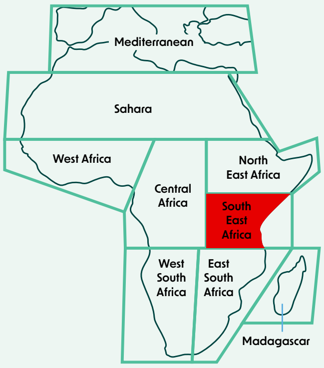
Figure 4.5.3 Projected shoreline position change along coasts of North Eastern Africa by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11].

4.5.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves and extreme rainfall are both projected to increase in North Eastern Africa, with the IPCC assessment of certainty increasing for higher levels of global warming but at varying levels for the different extremes. Increased intensity and/or frequency of heatwaves has a higher level of certainty than increased extreme rainfall. At 4°C global warming, meteorological and agricultural/ecological drought are projected to decrease with medium confidence. There is low confidence in projected changes in all drought metrics at lower levels of warming.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	High confidence	66% – 100% chance	95% – 100% chance
Change in drought	Low confidence	Low confidence	Low Medium confidence of decrease

Table 4.4.3 IPCC assessment of confidence in projected changes in weather extremes in Central Africa.
Source: Seneviratne et al. (2021)[184].



4.6 South Eastern Africa

Key messages

- Increases in high temperatures and risk of heat stress.
- Mixed signals and low confidence for changes in drought across the regions.
- High agreement on projected increases in river flood frequency due to climate change, with increases in the number of people at risk of flooding.
- Population growth substantially further increases the number of people at risk of flooding in both low and high population-growth scenarios.
- Increased risk of coastal flooding and projected shoreline erosion.

4.6.1 Extreme temperatures and heat stress risk

Heatwaves are projected to increase, and conditions of high heat stress risk projected to occur more often, with extreme heat stress risks emerging later in the century in a scenario reaching approximately 4°C by 2100. In Kigali, the average annual maximum daily temperature, currently around 32-33°C, is projected to increase to around 33-34°C by mid-century, and to continue to increase to around 36°C if global warming reaches by 4°C the end of the century (Figure 4.6.1). Risks of heat stress are also projected to increase, with the average annual maximum WBGT increasing from around 24°C- 25°C at present to around 25°C to 26°C mid-century and 28°C (high risk of heat stress) by the end of the century in a scenario of global warming reaching 4°C.

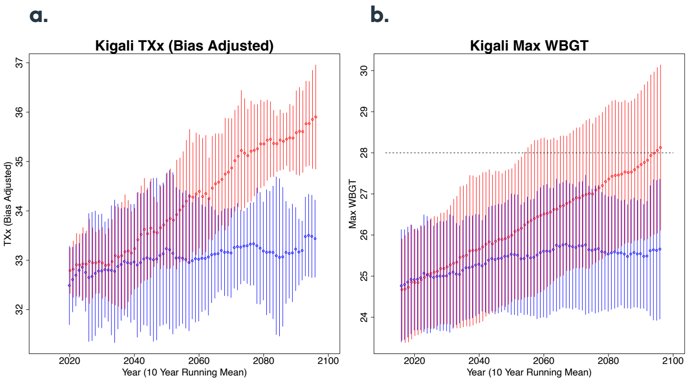


Figure 4.6.1 Projected changes in extreme temperatures and heat stress risk in Kigali in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Change in annual maximum temperature (Txx) relative to the present day. (b) Annual maximum WBGT. (c) Number of days with WBGT above 32°C, defined as the threshold for extreme heat stress risk. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, with the light red and blue plumes indicating model uncertainty as one standard deviation. Data from Kim et al. (2020)2 and Schwingshackl et al. (2021)[7].

4.6.2 Drought and fire weather

Projected changes in drought in South Eastern Africa are mixed. Small increases and decreases are projected across the region at 1.5°C and 2°C global warming. At 4°C global warming, the likelihood of agricultural/ecological drought is projected to generally decrease by 50% or more in the north-eastern part of the region and increase by 50% or more in the south-west. The IPCC assign low confidence to changes in meteorological, agricultural/ecological and hydrological drought in South Eastern Africa.

Global warming level	1.5°C	2°C	4°C
Change in likelihood of extreme single-year agricultural drought	Small decrease in some areas, small increase in others	Small decrease in some areas, small increase in others	Decrease of 50% – 100% in north-east of region, increase of over 50% in south.

Table 4.6.1 Projected changes in the frequency of an extreme single-year agricultural drought in South Eastern Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The fire weather season is approximately 100 days in most of South Eastern Africa, and is projected to decrease with global warming in the north of the region and increase in the south (Figure 1.2.6). Projected increases and decreases are up to around 20 days at 2°C global warming and 30-40 days at 4°C global warming.

4.6.3 Heavy rainfall, river flooding and landslide risk

Extreme rainfall is projected to increase in South Eastern Africa: according to the IPCC assessment, increased extreme rainfall is likely at 2°C global warming (which could be reached mid-century) and extremely likely at 4°C global warming. However, the projected long-term increases should be seen in the context of large year-to-year variability. In Kigali, the annual maximum five-day rainfall (Rx5day) is projected to increase from approximately 185 m at present to approximately 200 mm in mid-century and potentially up to 210 mm by 2100 in a scenario reaching 4°C global warming, possibly up to 230 mm. With global warming limited to 2°C, there is little projected long-term trend in this indicator of heavy rainfall, although year-to-year natural variability is still large and some years with Rx5day reaching 210 mm are possible at any point in the coming decades.

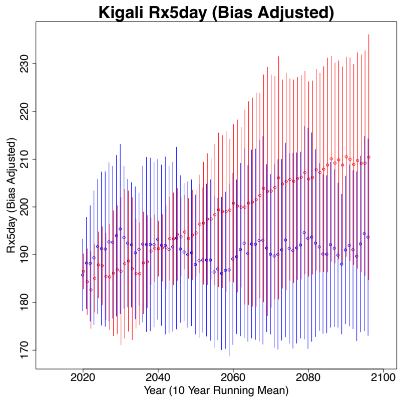


Figure 4.6.2 Projected annual maximum five-day rainfall in Kigali with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

River flooding in South Eastern Africa is projected to become more frequent due to climate change. The current 100-year flood is projected to become a 25-year to 50-year flood at 1.5°C and 2°C global warming, and a five-year to 25-year flood at 4°C global warming, with high agreement between climate models (Figure 1.2.9).

Climate change is projected to increase the number of people at risk of flooding by up to 50% in all countries in the region at 3°C global warming. This increases to 50% – 200% with the low population-growth scenario and 100% – 200% with high population growth (Table 4.6.2, Figure 1.2.10).

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Burundi	0% – 50% increase	50% – 100% increase	100% – 200% increase
Kenya	0% – 50% increase	100% – 200% increase	200% – 300% increase
Rwanda	0% – 50% increase	100% – 200% increase	200% – 300% increase
Tanzania	0% – 50% increase	50% – 100% increase	100% – 200% increase
Uganda	0% – 50% increase	100% – 200% increase	200% – 300% increase

Table 4.6.2 Relative increase in number of people exposed to river flooding in countries in South Eastern Africa with 3°C global warming at three different population scenarios: current population, low population growth, and high population growth. Data from Dottori et al (2018)[10]

Landslides can be a major consequence of heavy rainfall, and there has been a reported increase in landslides in South Eastern Africa.[11] However, the impact of past and future climate change on landslide risks in Africa has so far received very little attention in the scientific literature and is currently a major knowledge gap.

4.6.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase along the coasts of South Eastern Africa, with extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20cm and 40cm by mid-century. Increases by the end of the century are projected to be 40cm to 80cm with low emissions and 80cm to 100cm with high emissions. Shoreline retreat by 2100 is projected to be generally around 200m along most of the coast of Kenya and Tanzania, with generally smaller changes on the southern coast of Somalia.

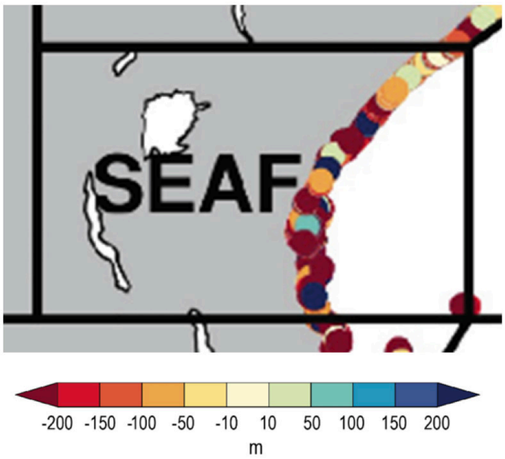


Figure 4.6.3 Projected shoreline position change along coasts of South Eastern Africa by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11]

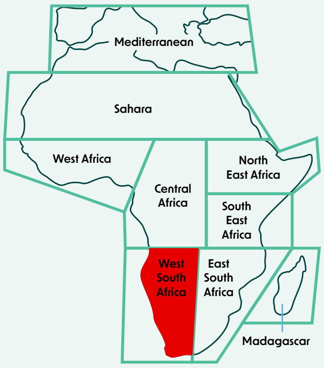
4.6.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves and extreme rainfall are both projected to increase in South Eastern Africa, with the IPCC assessment of certainty increasing for higher levels of global warming but at varying levels for the different extremes. Increased intensity and/or frequency of heatwaves has a higher level of certainty than increased extreme rainfall. There is low confidence in projected changes in all drought metrics at all levels of warming.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	High confidence	66% – 100% chance	95% – 100% chance
Change in drought	Low confidence	Low confidence	Low confidence

Table 4.6.3 IPCC assessment of confidence in projected changes in weather extremes in South Eastern Africa. Source: Seneviratne et al. (2021)[184].

4.7 West Southern Africa



Key messages

- Increased drought risk is a particular issue in West Southern Africa, with confidence in increased drought being particularly high in this region.
- Wildfire risk is also a particular issue, with the fire weather season projected to become substantially longer over most of the region.
- Extreme high temperature are projected to increase. Heat stress risk is also projected to increase, reaching less extreme levels than other regions of Africa but nevertheless still becoming high.
- Climate change could increase the risk of river flooding, but with less certainty than in other regions. Nevertheless, both high and low population-growth scenarios would put more people at risk of river flooding.
- Increased coastal flooding and shoreline retreat are projected around the coasts of the region.

4.7.1 Extreme temperatures and heat stress risk

Heatwaves are projected to increase, and conditions of high heat stress risk projected to occur more often. In Cape Town, the average annual maximum daily temperature, currently around 36°C, is projected to increase to around 37°C by mid-century and around 38°C by the end of the century with high emissions. Risks of heat stress are also projected to increase, with the average annual maximum WBGT increasing from around 27°C at present to around 28°C (high risk of heat stress) by mid-century and around 29°C by the end of the century with high emissions.

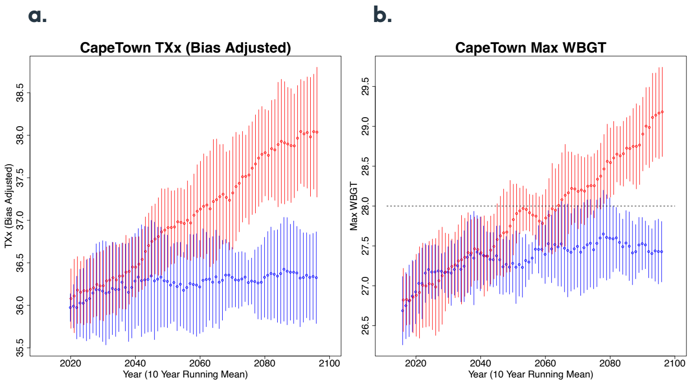


Figure 4.7.1 Projected changes in extreme temperatures and heat stress risk in Cape Town in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature (Txx). (b) Annual maximum Wet Bulb Globe Temperature (WBGT). Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)2 and Schwingshackl et al. (2021)[7].

4.7.2 Drought and fire weather

Drought is projected to increase across the West Southern Africa region according to all definitions – meteorological, agricultural/ecological and hydrological drought. An extreme single-year agricultural drought (defined as the driest 10% of years in 1995-2014) is projected to be between 50 and 150% more likely at 1.5°C global warming in many areas. Area with this increase in likelihood become more widespread at 2°C global warming, and some areas see projected increases in likelihood of 150 – 200% across wider areas at 2°C global warming, and over 200% over most of the region at 4°C global warming.

Global warming level	1.5°C	2°C	4°C
Change in likelihood of extreme single-year agricultural drought	Increase across whole region, 50%-100% increase in many areas	Increase of over 50% across most of region, 150%-200% increase in some areas	Increase of over 200% across most of region

Table 4.7.1 Projected changes in the frequency of an extreme single-year agricultural drought in West Southern Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The Fire Weather Season Length (FWSL) in West Southern Africa is currently around 100 days per year, and projected to increase by around 10-30 days at 1.5°C global warming and 20-40 days at 2°C. The FWLS is projected to increase by over 40 days in most of the region at 4°C global warming.

4.7.3 Heavy rainfall and river flooding

At around 4°C global warming at the end of the century, heavy rainfall is projected to increase in northern and eastern areas of the region but decrease in the south-west (Figure 1.2.8). In the nearer term, and at lower levels of warming, the projected changes are smaller and increases and decreases are mixed across the region (Figure 1.2.7) with natural climate variability dominating (Figure 4.7.2).

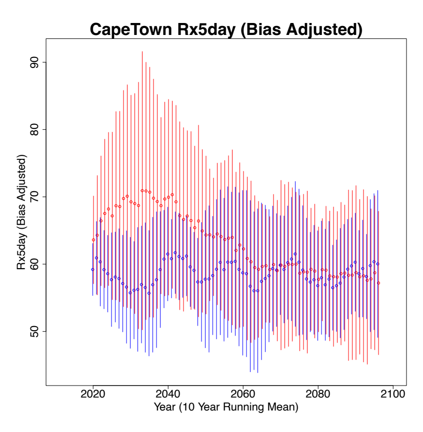


Figure 4.7.2 Projected annual maximum five-day rainfall in Cape Town with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

River flooding in the northern areas of West Southern Africa is projected to become more frequent due to climate change. The current 100-year flood is projected to become a 25-year to 50-year flood at 2°C and 3°C global warming, and a 5-year to 25-year flood at 4°C global warming, with high agreement between climate models (Figure 1.2.9). Most of the rest of the region has few major rivers due to very dry conditions, but in several rivers, flood frequency is projected to decline at 2°C and 3°C global warming, with the exception of the Orange River for which the current 100-year flood is projected to become more frequent at 3°C global warming and also at 4.5°C global warming.

All countries in West Southern Africa are projected to see an increase in the number of people exposed to river flooding at 3°C global warming, but with lower confidence for Namibia and Botswana. The numbers increase further with both low and high population-growth scenarios, with higher confidence.

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Angola	50 – 100% increase	200 – 300% increase	200 – 300% increase
Zambia	50 – 100% increase	100 – 200% increase	200 – 300% increase
Namibia	0 – 50% increase*	50 – 100% increase	50 – 100% increase
Botswana	50 – 100% increase*	100 – 200% increase	50 – 100% increase
South Africa	100 – 200% increase	100 – 200% increase	200 – 300% increase

Table 4.7.2 Relative increase in number of people exposed to river flooding in countries in West Southern Africa with 3°C global warming and three different population scenarios: current population, low population growth, and high population growth. Data from Dottori et al (2018)[10]. **less than 90% model agreement.*

4.7.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase along the coast of West Southern Africa, with extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20 and 40 cm by mid-century. Increases by the end of the century are projected to generally be 40 cm to 80 cm with low-emissions and 80 – 100 cm with high emissions. Projected shoreline retreat by 2100 varies between about 50 and 200 m along the coast of West Southern Africa. These projections are based on current models which may not account for the full range of potential global sea level rise if uncertainties in ice sheet loss are taken into account – impacts could be larger if large losses of ice into the oceans occur.

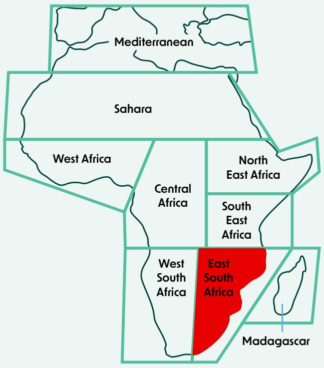
Figure 4.7.3 Projected shoreline position change along coasts of West Southern Africa by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11]

4.7.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves, extreme rainfall and drought are all projected to increase in West Southern Africa, with the IPCC assessment of certainty increasing for higher levels of global warming but at varying levels for the different extremes. Increased intensity and/or frequency of heatwaves has the highest level of certainty compared to other extremes, followed by increased drought. Increased extreme rainfall is projected with confidence level increasing from low at 1.5°C and 2°C warming to high at 4°C global warming, but without percentage likelihoods being assigned.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	Low confidence	Low confidence	High confidence
Change in drought	Medium confidence in increase	High confidence in increase	66 – 100% chance of increase

Table 4.7.3 IPCC assessment of confidence in projected changes in weather extremes in West Southern Africa. Source: Seneviratne et al. (2021)[184].



4.8 East Southern Africa

Key messages

- Increasing wildfire risk is a particular issue in East Southern Africa, with the fire weather season projected to become substantially longer across the entire region, even at lower levels of global warming.
- Extreme drought is projected to become more likely over much of the region, especially away from the eastern coasts.
- Increased river flooding is projected, mainly in eastern parts of the region, although all countries are projected to see increases in the number of people affected.
- Increased coastal flooding risks and projected shoreline retreat are relatively large along much of the East Southern Africa coast in comparison with other regions.
- Heat stress is projected to be an increasing risk, especially in the north of the region.

4.8.1 Extreme temperatures and heat stress risk

Heatwaves are projected to increase, and conditions of high heat stress risk projected to occur more often. In Durban, the average annual maximum daily temperature – currently around 36°C to 37°C – is projected to increase to around 37°C to 38°C by mid-century, and to around 40°C by the end of the century with high emissions. Risks of heat stress are also projected to increase, with the average annual maximum Wet Bulb Globe Temperature increasing from around 29°C (high risk of heat stress) at present to around 30°C by mid-century and around 32°C (extreme risk of heat stress) by the end of the century with a high scenario.

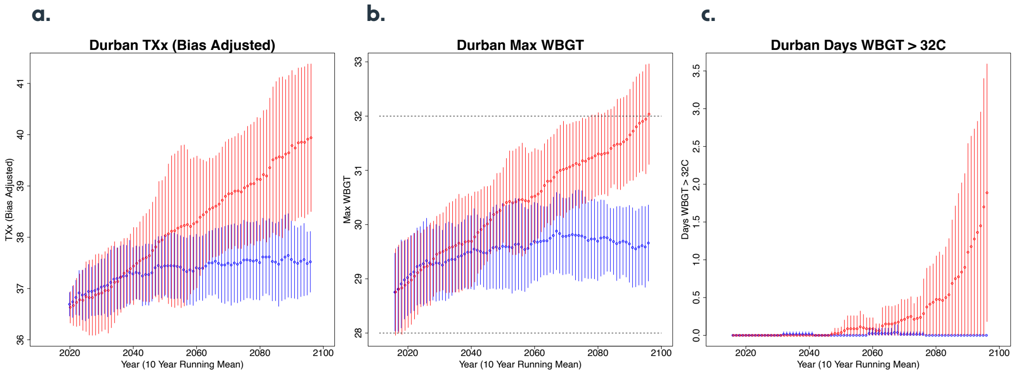


Figure 4.8.1 Projected changes in extreme temperatures and heat stress risk in Durban in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature (Txx). (b) Annual maximum Wet Bulb Globe Temperature (WBGT). (c) Number of days with WBGT above 32°C, defined as the threshold for extreme heat stress risk. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)2 and Schwingshackl et al. (2021)[7].

4.8.2 Drought and fire weather

Drought is projected to increase across East Southern Africa at higher levels of global warming according to all definitions – meteorological, agricultural/ecological and hydrological drought. At 4°C global warming, an extreme single-year agricultural drought (defined as the driest 10% of years between 1995 and 2014) is projected to be more than twice as likely across about half the region and more than three times as likely in some areas. At 2°C and 1.5°C global warming, projected increases in drought likelihood are smaller, and some small areas are projected to see decreased likelihood of drought.

Global warming level	**1.5°C**	**2°C**	**4°C**
Change in likelihood of extreme single-year agricultural drought	Increases across most of region, over 50% in some small areas, and decreases in some small areas	Increases across most of region, over 50% in some areas, and decreases in some small areas	Increases over whole region, over 100% in about half of region and over 200% in some areas

Table 4.8.1 Projected changes in the frequency of an extreme single-year agricultural drought in East Southern Africa with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The fire weather season is currently approximately 70 days per year, and is projected to increase by 10-40 days at 1.5°C global warming, with larger increases at higher levels of warming (Figure 1.2.6). At 4°C global warming, increases of over 40 days are projected across virtually all of East Southern Africa, more than doubling the fire weather season across the region.

4.8.3 Heavy rainfall and river flooding

For higher scenarios of global warming, heavy rainfall is projected to increase over most of East Southern Africa from mid-century onwards, especially northern and eastern areas (Figures 1.2.8 and 4.8.2). For lower scenarios, the projected changes are more mixed, with some areas seeing increases and some seeing decreases (Figure 1.2.7), and natural climate variability being the dominant factor for lower warming scenarios (Figure 4.8.2).

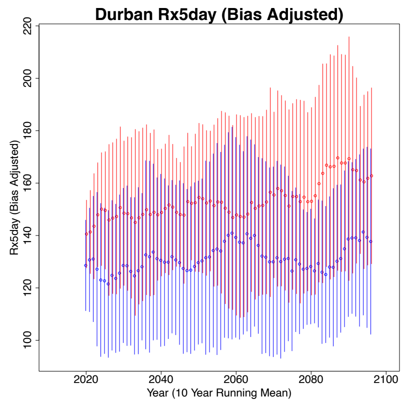


Figure 4.8.2 Projected annual maximum five-day rainfall in Durban with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

River flooding in the northern areas of East Southern Africa is projected to become more frequent due to climate change. The current 100-year flood is projected to become a 25-year to 50-year flood at 2°C and 3°C global warming, and a 5-year to 25-year flood at 4°C global warming, with high agreement between climate models (Figure 1.2.9). Much of the rest of the region has few major rivers due to very dry conditions, but in central parts flood frequency is projected to decline at 2°C and 3°C global warming, while it is projected to increase in the south. In central and southern regions, the current 100-year flood is projected to become more frequent at 4.5°C global warming.

All countries in East Southern Africa are projected to see an increase in the number of people exposed to river flooding at 3°C global warming, but with lower agreement between models for Malawi and Botswana (Table 4.8.2, Figure 1.2.10). The numbers increase further with both low and high population-growth scenarios, with the exception of Zimbabwe, which is projected to see an overall decrease in exposure to flooding with the low population scenario.

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Zambia	50% – 100% increase	100% – 200% increase	200% – 300% increase
Malawi	50% – 100% increase*	100% – 200% increase	200% – 300% increase
Mozambique	50% – 100% increase	100% – 200% increase	200% – 300% increase
Zimbabwe	0% – 50% increase	At least 20% decrease	50% – 100% increase
Botswana	50% – 100% increase*	100% – 200% increase	50% – 100% increase
South Africa	100% – 200% increase	100% – 200% increase	200% – 300% increase
Eswatini	0% – 50% increase	50% – 100% increase	200% – 300% increase
Lesotho	0% – 50% increase	0% – 50% increase	50% – 100% increase

Table 4.8.2 Relative increase in number of people exposed to river flooding in countries in East Southern Africa with 3°C global warming a three different population scenarios: current population, low population growth, and high population growth. Data from Dottori et al (2018)[10]. **less than 90% model agreement.*

4.8.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase along the coast of East Southern Africa, with extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20cm and 40cm by mid-century. Increases by the end of the century are projected to generally be 40cm to 80cm with low emissions and 80cm to 100cm with high emissions. Shoreline retreat by 2100 is projected to be generally between 50m and 200m along most of the coast of Mozambique, but with some areas of extending coast, with generally smaller changes on the coasts of South Africa. These projections are based on current models which may not account of the full range of potential global sea level rise if uncertainties in ice sheet loss are taken into account – impacts could be larger if large losses of ice into the oceans occur.

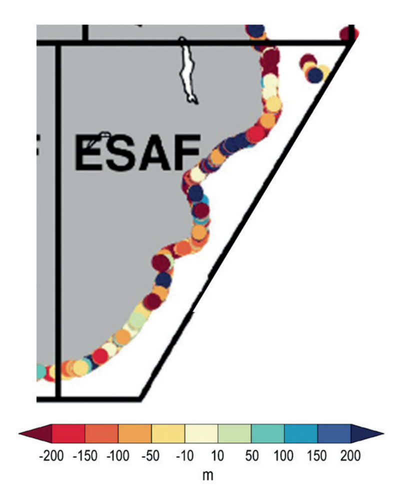


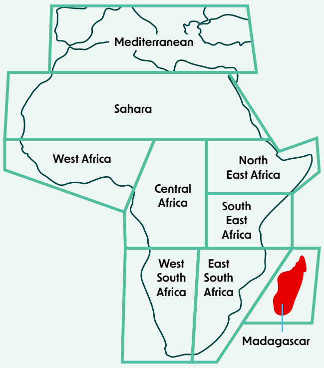
Figure 4.8.3 Projected shoreline position change along coasts of East Southern Africa by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)11

4.8.5 Assessment of confidence and likelihood of extreme weather changes

Heatwaves, extreme rainfall and drought are all projected to increase in East Southern Africa, with the IPCC assessment of certainty increasing for higher levels of global warming, but at varying levels for the different extremes. Increased intensity and/or frequency of heatwaves has the highest level of certainty compared to other extremes, followed by increased extreme rainfall. Increased drought is projected with confidence level increasing from medium at 1.5°C and 2°C warming to high at 4°C global warming, but without percentage likelihoods being assigned.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 - 100% chance	90 - 100% chance	99 - 100% chance
Increased extreme rainfall	Medium confidence	High confidence	90 - 100% chance
Change in drought	Medium confidence in increase	Medium confidence in increase	High confidence in increase

Table 4.8.3 IPCC assessment of confidence in projected changes in weather extremes in East Southern Africa. Source: Seneviratne et al. (2021)[184].



4.9 Madagascar

Key messages

- Drought is projected to become more common, and the fire weather season is projected to increase.
- Madagascar already sees heavy rainfall, and this is projected to increase overall, but with large increases and decreases due to natural climate variability.
- River flooding may occur more frequently, but this is uncertain. Increased coastal flooding and shoreline retreat are projected, especially on the western coast of Madagascar.
- Tropical cyclones are projected to become more intense but less frequent.
- Levels of heat stress risk are projected to increase.

4.9.1 Extreme temperatures and heat stress risk

Heatwaves are projected to increase, and conditions of high heat stress risk projected to occur more often. In Antananarivo, the average annual maximum daily temperature, currently around 35°C, is projected to increase to around 36°C by mid-century, and to continue to increase to around 39°C by the end of the century with high emissions. Risks of heat stress are also projected to increase, with the average annual maximum WBGT increasing from around 26°C (moderate risk of heat stress) at present to around 28°C-29°C (high risk of heat stress) by the end of the century. Days with extreme heat stress risk are projected to begin to occur in the middle of the century, and by the end of the century approximately 10 days per year on average are projected to see extreme heat stress risks, and possibly up to 25 days per year.

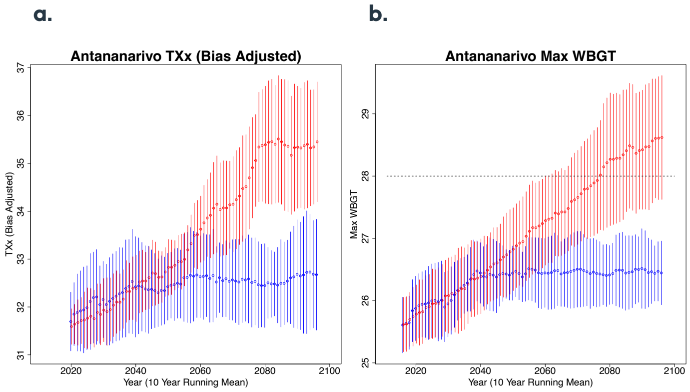


Figure 4.9.1 Projected changes in extreme temperatures and heat stress risk in Antananarivo in scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. (a) Annual maximum temperature (Txx). (b) Annual maximum Wet Bulb Globe Temperature (WBGT). Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)2 and Schwingshackl et al. (2021)[7].

4.9.2 Drought and fire weather

Madagascar is one of the regions of Africa where the IPCC has relatively high confidence in drought increasing in the future. Increased agricultural drought is assessed with medium confidence at 1.5°C global warming, high confidence at 2°C and likely at 4°C. The latest models suggest up to a 50% increase in the likelihood of an extreme one-year agricultural drought in most parts of the region, with a 50%-100% over some areas at 2°C and wider areas at 4°C.

Global warming level	**1.5°C**	**2°C**	**4°C**
Change in likelihood of extreme single-year agricultural drought	Up to 50% increase across most of region	Up to 50% increase across most of region, slightly more in a few places, possibility of small decrease in south	Up to 50% increase across most of region, 50-100% in some areas

Table 4.9.1 Projected changes in the frequency of an extreme single-year agricultural drought in Madagascar with 1.5°C, 2°C and 4°C global warming. Data from Caretta et al. (2022)[8].

The fire weather season is currently approximately 100 days per year, and is projected to increase by between 10 and 30 days at 1.5°C global warming, with larger increases at higher levels of warming (Figure 1.2.6). At 4°C global warming, increases in fire weather season length of around 40 days are projected across Madagascar.

4.9.3 Heavy rainfall and river flooding

Extreme rainfall is projected to increase in Madagascar: according to the IPCC assessment, there is high confidence in increased extreme rainfall at 2° global warming (which could be reached mid-century) and increases are very likely at 4°C global warming. However, the projected long-term increases should be seen in the context of already-high levels of extreme rainfall and large year-to-year variability. In Antananarivo, the annual maximum five-day rainfall is projected to vary between approximately 120mm and 170mm throughout the 21st Century in scenarios with both high and low emissions, with a slight upward trend of approximately 20mm over the century in the scenario reaching global warming of 4°C by 2100. Uncertainty also increases, with annual maximum five-day rainfall of around 220mm as an upper end of the projections for 2100.

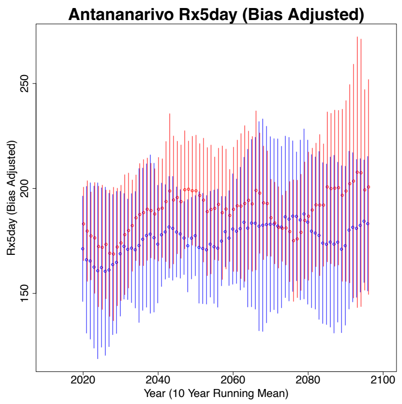


Figure 4.9.2 Projected annual maximum 5-day rainfall in Antananarivo with scenarios reaching approximately 4°C global warming (red) and 2°C global warming (blue) by 2100. Data are smoothed to show a 10-year running mean. Dark red and blue curves show the means from multiple models, while the light red and blue plumes indicate model uncertainty as one standard deviation. Data from Kim et al. (2020)[2].

Projected changes in flood risk due to climate change in Madagascar are uncertain. In a scenario reaching approximately 2°C global warming by 2100, the central estimates of projections using a large number of recent climate models suggest the present-day 100-year flood occuring more frequently in some areas but less frequently in others. At higher warming scenarios the projection moves to more frequent flooding across all of Madagascar, with the 100-year flood projected to become between a 50-year and five-year flood. However there is not high agreement between models. In an assessment of numbers of people exposed to river flooding at 3°C global warming using an older and more limited set of climate models, climate change alone is projected to decrease the number of people in Madagascar exposed to river flooding by up to 20%. When scenarios of low and high population growth are considered, this shifts the projection to increases of up to 50% and between 100% and 200% respectively.

Country	Climate change alone	Climate change and low population-growth scenario	Climate change and high population-growth scenario
Madagascar	Decrease of up to 20%	Increase of up to 50%	Increase of between 100% and 200%

Table 4.9.2 Relative change in number of people exposed to river flooding in Madagascar with 3°C global warming and different population scenarios. Data from Dottori et al (2018)[10]

4.9.4 Coastal flooding and shoreline retreat

Sea level rise and coastal flooding are projected to increase around the coasts of Madagascar. Extreme total water levels (including relative sea level, storm surges, tides and high waves) increasing by between 20cm and 40cm by mid-century. Increases by the end of the century are projected to be 20cm to 60cm with low emissions and 60cm to 100cm with high emissions. Shoreline retreat by 2100 is projected to be substantially larger along the western coast of Madagascar, with much of it projected to see retreat of 150m to 200m or more, while retreat on the eastern coast is generally tens of metres, but still with some locations with retreat above 100m. Some locations around Madagascar are projected to see shorelines extend.

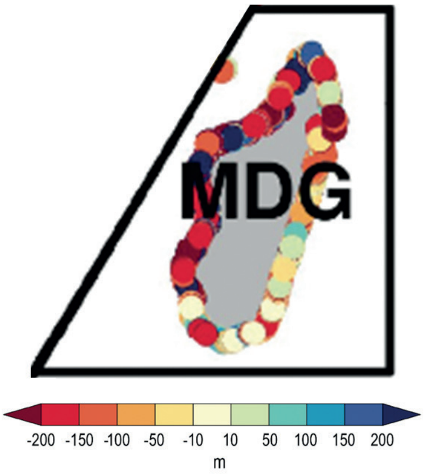


Figure 4.9.3 Projected shoreline position change along coasts of Madagascar by 2100 with a very high emissions scenario. Reproduced from Ranasinghe et al (2021)[11]

4.9.5 Tropical cyclones

Madagascar has been impacted by a number of tropical cyclones or storms in recent years. Cyclone Gafilo (2004), Cyclone Enawo (2017), Tropical Storm Ana (2022) and Cyclone Batsirai (2022) caused tens to hundreds of deaths each, and displaced tens to hundreds of thousands of people. Impacts of cyclones arise from extremely high winds, extremely heavy rainfall and coastal flooding due to storm surges. Climate change is projected to increase the intensity of tropical cyclones over Madagascar, but decrease their frequency, with the IPCC assigning medium confidence to this assessment.[11]

4.9.6 Assessment of confidence and likelihood of extreme weather changes

Heatwaves, extreme rainfall and drought are all projected to increase in Madagascar, with the IPCC assessment of certainty increasing for higher levels of global warming but at varying levels for the different extremes. Increased intensity and/or frequency of heatwaves has the highest level of certainty compared to other extremes, followed by increased extreme rainfall. At 4°C global warming, increased meteorological drought is assessed to be likely, and agricultural/ecological drought is assessed as high confidence but with no quantification of likelihood. Similarly, increased agricultural/ecological drought is assessed with lower confidence than meteorological drought at lower levels of warming.

	1.5°C global warming (Next 10-20 years)	**2°C global warming (Mid-century unless emissions cut rapidly to net zero)**	**4°C global warming (End of century with high emissions)**
Increased heatwaves	66 – 100% chance	90 – 100% chance	99 - 100% chance
Increased extreme rainfall	Medium confidence	High confidence	90 – 100% chance
Change in drought	Medium confidence in increase	High confidence in increase	66% – 100% chance of increase

Table 4.9.3 IPCC assessment of confidence in projected changes in weather extremes in Madagascar. Source: Seneviratne et al. (2021)[184].

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