# Water Security for Climate Resilience Report

## A synthesis of research from the Oxford University REACH programme

August 2021

Foreign, Commonwealth & Development Office

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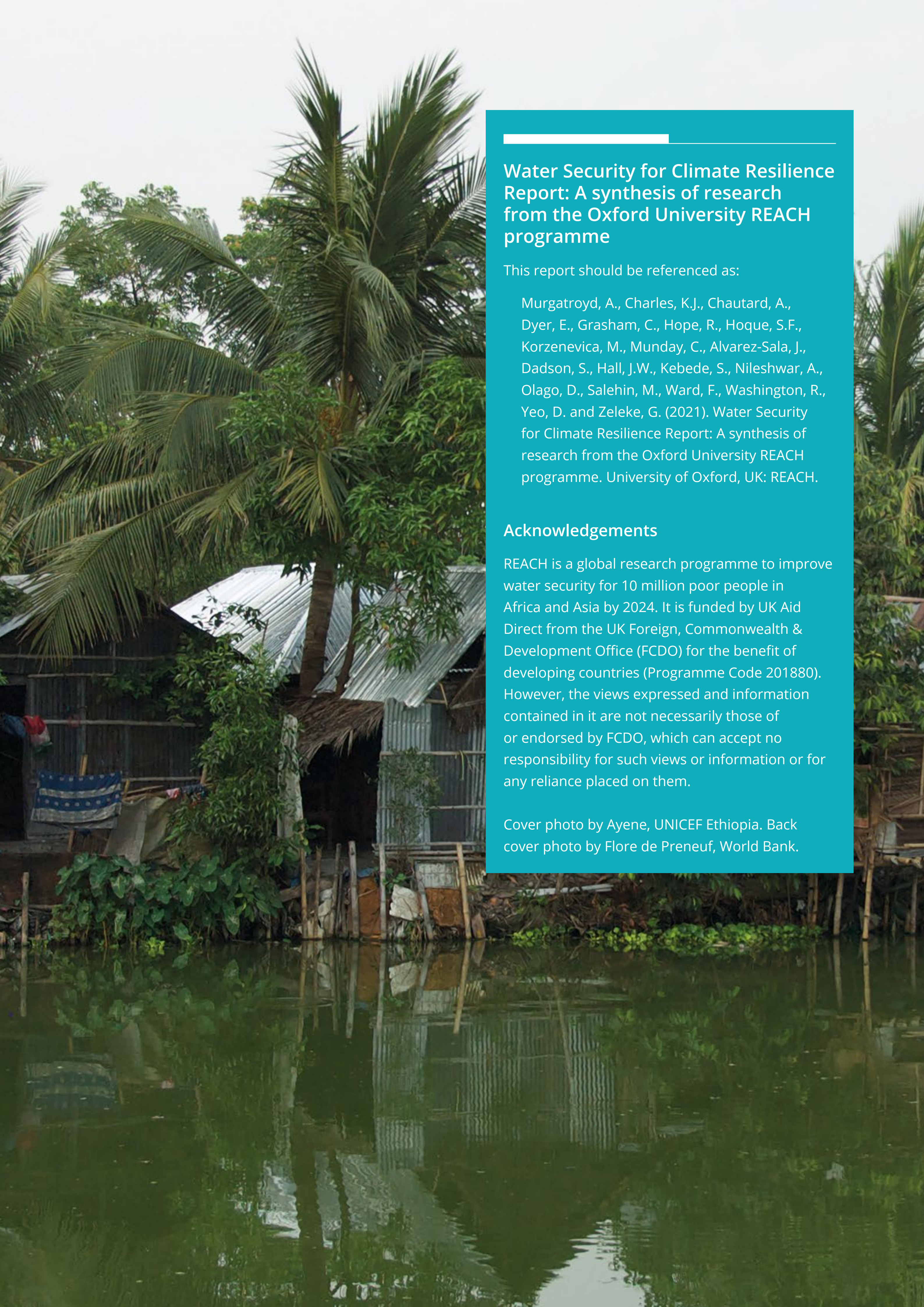

# Water Security for Climate Resilience Report: A synthesis of research from the Oxford University REACH programme

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## Acknowledgements

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# 1. Introduction

The links between water security and climate are broadly well understood but poorly evidenced, particularly at the scales appropriate for policy and practice to advance water security in low- and middle-income countries. Water-related climate hazards such as floods and drought have well established impacts: damaged water supply infrastructure, compromised resource sustainability, deterioration of drinking water quality, and cause of irreparable harm to rural and urban livelihoods. In many cases, climate hazards can set the course for unequitable development of a region. Seasonal changes in climate and extreme weather events also exacerbate issues of water scarcity such as famine (Conway and Schipper, 2011), impact conflicts and migration, trigger ecosystem changes, and differentially affect the lives of women, men and children (Adelekan, 2011; Frick-Trzebitzky et al. 2017; Sevilimedu et al. 2016). Anthropogenic climate change is already impacting the water cycle and represents a significant threat to drinking water supply and sanitation services worldwide (Howard et al. 2010, 2016; Muller, 2018).

Globally, water institutions are working towards climate resilient systems to manage risks from climate shocks, variability and anthropogenic climate change. However, the dominant policy discourse on climate resilience fails to address context-specific climate issues and the distributional impacts of climate events on water security at a human scale. To ensure effective implementation of adaptation actions and reduce the risk of unintended consequences on water security, water policies require more granular analysis and monitoring of ongoing and future climate impacts.

This report presents a synthesis of published and ongoing research by REACH which explores the relationship between water security, climate and climate adaptation decisions, drawing on findings from REACH research conducted in Sub-Saharan Africa and South Asia. This research has been funded by UK Aid Direct from the UK Foreign, Commonwealth & Development Office (FCDO) and will improve water security for 10 million people affected by poverty. We demonstrate the unequal impact of climate on water security, and on people's lives and livelihoods, which can be counter-intuitive to broad narratives around resilience and adaptation. We exemplify the impact of seasonal fluctuations in weather on surface and groundwater quality and quantity, and show that water security risks evolve with shifting climate conditions, water use behaviours, and policy decisions. We also present a deepened understanding of location- and context-specific climate issues and dynamics, revealing a pressing need to consider and plan for different distributional impacts of climate and climate change.

We argue that to build climate resilience we need to improve water security of existing water systems. We identify three actions to build climate resilience:

- Advancement of accurate and granular analyses of climate risks to ensure climate information is relevant to specific users;
- Improvement of metrics for monitoring climate resilience which will help track progress and inform investment decisions;
- Development of new institutional models that improve water security and enable existing institutions to make climate-resilient decisions.

## Water security

Improving water security is essential to achieve environmental protection, economic growth, poverty reduction, and improvements in public health. Water security is often presented as a technical challenge, but the decisions that define it are deeply political. REACH recognises that the risks to the poor are often neither identified nor addressed.

Improving water security requires managing complex and competing water-related risks in order to deliver sustainable and equitable outcomes for all. For our work, it is essential to consider the water system beyond hydrology and infrastructure, to include the social and political drivers that influence institutions and governance.

## Hazards

A hazard is a phenomenon with the potential to cause damage or harm. A water-related hazard may arise from a “natural” event such as a tsunami or climate extreme, a “human-made” threat such as weak governance or financial instability, or a “hybrid” phenomenon arising from natural and human interactions (Opitz-Stapleton et al. 2019).

## Vulnerability

Vulnerability is the propensity to experience harm as a dynamic function of the capacity to anticipate, cope with and recover from harmful events. Our approach to vulnerability draws from different disciplines, following these propositions:

- Vulnerability is dynamic and situated within wider political economy, historical legacy, social norms and power relations;
- It should be seen within the complex system together with physical exposure to hazard, as well as the ability to cope by individuals, social groups and ecosystems at different scales;
- It entails particular forms of activity and agency (Butler, 2016; Devereux et al. 2006; Page, 2018);
- Vulnerability is analysed in relation to outcomes of interest (‘vulnerable to-…’) (Devereux et al. 2006).

### Resilience

Resilience thinking is a useful concept to define persistent and emerging threats to the water system. Climate resilience is the process of bringing climate hazards and vulnerability into decisions. Climate resilience strengthens the inherent ability of society to mitigate risks from, prepare and adapt to, changing patterns in climate hazards and variability for all. To build climate resilience in water systems, it is imperative to understand regional climate processes and climate change risks, existing socio-ecological resilience, community adaptation strategies, and political processes to strengthen capacity to integrate climate information in water policy and practice.

## REACH risk-based framework

The concept of risk provides a common language and focus for academics and practitioners to address the multiple dimensions of water security. There is no unifying theory or model for determining or managing risk, but rather a range of theories, models, and technologies that can help us to improve our understanding of the trade-offs that exist in responding to risk. These range across disciplines, including politics, climate science, hydrology, economics, public health, law and policy, anthropology, and engineering. Work by REACH has been designed based on a risk-based framework, drawing from these diverse approaches.

Our risk-based framework is developed on three pillars. Firstly, it focuses on water security outcomes, considering the trade-offs between different and interrelated outcomes in water resource systems and water services, including climate impacts on outcomes. Secondly, it uses a distributional analysis to evaluate and address inequalities embedded in social practices or generated by ill-conceived interventions. Thirdly, it recognises the intersection of water security and inequalities through the different processes and practices by which water security is managed and realised.

Climate factors are a major driver of water security across different scales. Geographic variability in water availability, reliability of rainfall and vulnerability to droughts, floods and cyclones are inherent hazards that affect development opportunities and that play out at international to intra-basin scales. At local scales, the risks to water security associated with weather and climate are strongly mediated by social vulnerability.

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WHAT

**Water security outcomes**

Water security is an acceptable level of water services for all users and acceptable water-related risks. Improving water security requires consideration of the politics of water security trade-offs.

WHO

**Risk exposure**

Water security risks are experienced differently, varying based on the individual, group and place. Explicitly recognising inequalities based on gender, ethnicity, and wealth identifies how benefits and risks are distributed.

HOW

**Processes and scales**

Water security risks are managed at different scales through multiple processes that determine which risks are addressed and for whom. Understanding these processes is critical to ensuring water security inequalities can be addressed.

Figure 1: REACH risk-based framework.

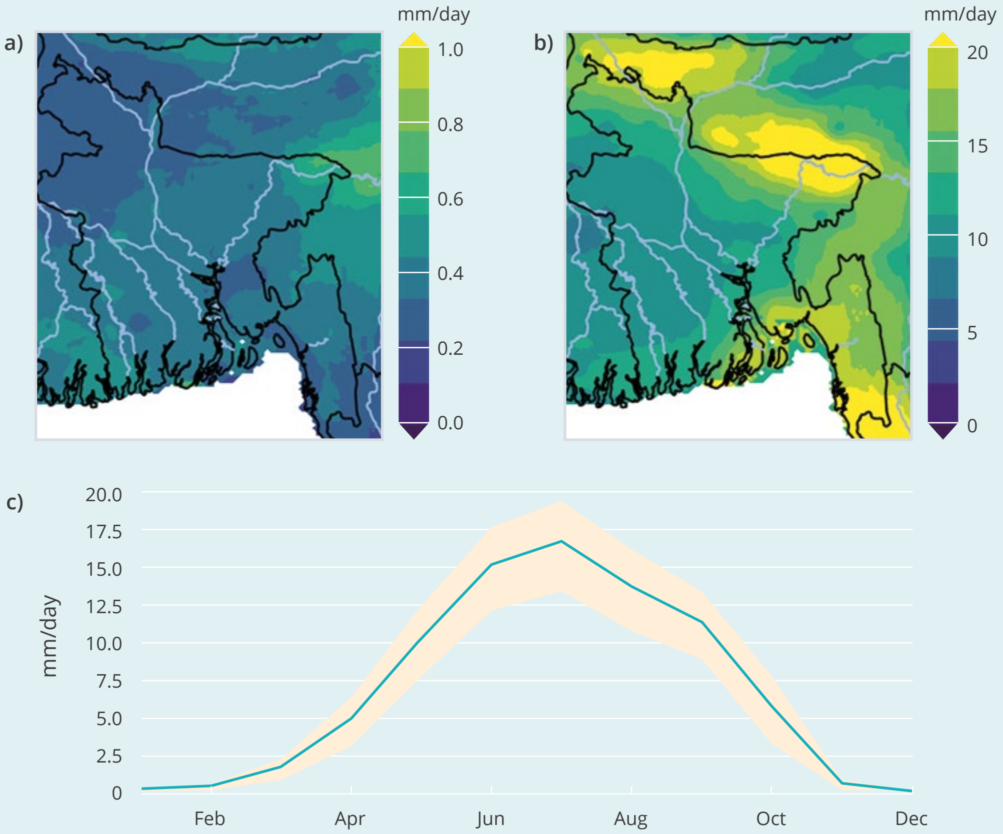
# Where we work

## Bangladesh

Bangladesh is vulnerable to a variety of climate hazards, including riverine flooding, droughts, cyclonic storm surges and salinity intrusion. Improving water security in Bangladesh requires careful consideration of the existing hazards created by monsoon rainfall, urbanisation and the emerging threats from 21st Century climate change.

In Bangladesh's capital, Dhaka – a densely populated megacity – water security is heavily influenced by monsoonal pulses. Discharge of untreated municipal and industrial wastewater have severely degraded the water quality of Dhaka's river systems, exposing low income riverbank communities to harmful heavy metal and pathogen pollution through their daily domestic and productive activities. In the coastal region, cyclonic storms, fluvio-tidal flooding, pluvial flooding or waterlogging, saline water intrusion and erosion frequently damage drinking water infrastructure and surface water sources and destroy crops and fisheries. While polders (embanked islands) were designed to protect communities from flooding events, many embankments are poorly managed and rapidly deteriorating, exposing millions of coastal inhabitants to water-related climate hazards. Climate change and sea-level rise are expected to substantially reinforce these existing stresses.

**Figure 2: a) Average DJF (December to February) rainfall in mm/day. b) Average JJAS (June to September) rainfall in mm/day. c) Mean rainfall climatology of Bangladesh (21-27N,88-93E) bounded by the 25th and 75th percentiles. All rainfall from CHIRPSv2.0 1981–2020.**

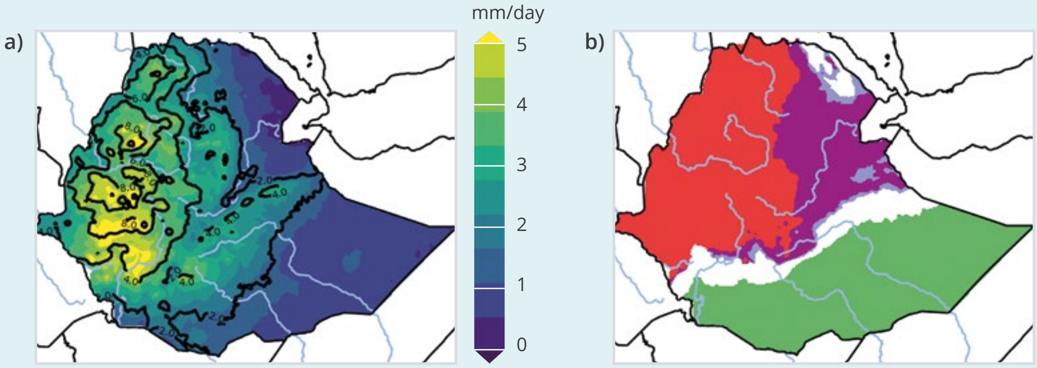


## Ethiopia

Ethiopia faces an array of water-security risks, many of which are exacerbated by climate variability and rainfall shocks. The country is located between the Sahel and East Africa, and is affected by two main climate zones: hot lowlands in the east and wet highlands to the west. In addition to this, Ethiopia's climate is influenced by El Niño–Southern Oscillation events and the Indian Ocean Dipole, but this effect varies temporally and by region. The country has a bimodal pattern of rainfall, with two main rainy seasons in the spring (Belg) and summer (Kiremt). In central Ethiopia, the Awash basin sits at the juncture of the East African and Sahelian climate zones and frequently experiences flood and drought events. These variable climatic conditions mean that water insecurity is experienced differently in the upper, middle and lower parts of the basin.

Delays in the onset of the Kiremt and Belg seasons or reductions in rainfall volumes are hazardous to Ethiopia's rural agricultural-based society, which is largely reliant on rainfed irrigation and surface water abstractions. Historically, erratic rainfall variability and drought events have been detrimental for agricultural activity in the country, affecting the productivity of small-scale subsistence farming, harming the income of households affected by poverty, and contributing to food insecurity.

**Figure 3: Rainfall in Ethiopia. a) Annual average rainfall in mm/day with the interquartile range (25th–75th) of monthly rainfall in mm/day (indicated by black contours). b) Rainfall zones in Ethiopia. Red and purple zones have a Kiremt season (JJAS>MAM), the green zone has a significant short rains season like the bimodal East African climate, and the blue and purple region has a distinct Belg and Kiremt season with J<MAM and MAM<JAS rainfall. All rainfall from CHIRPSv2.0 1981–2020.**



## Kenya

Kenya is a physically diverse country, with mountainous highlands and flat coastal regions. Four fifths of the country are categorised as arid or semi-arid, with many regions experiencing high intra-annual rainfall variability and climate shocks. The country is a physical hub for climate and weather interactions, from the moist belt along the coast to the flood-prone western shores of Lake Victoria. In the dry corridor of northern Kenya low-level atmospheric jets carry water from the Indian Ocean, exerting considerable influence on regional rainfall and contributing to local water scarcity.

The Kenyan census reports that one in five households rely on surface water supplies such as ponds, lakes and rivers as their main sources of drinking water (Kenya National Bureau of Statistics, 2019). Historically, climate shocks such as flash floods and droughts have been hazardous for drinking water supplies in rural and urban Kenya, limiting the treatment of water borne diseases, exacerbating the cost of accessing safe water, and damaging water supply infrastructure. In the semi-arid Kitui County, high poverty, scattered populations and rainfall extremes present key challenges to building climate resilient water secure institutions for rural communities. In Turkana County, the rapidly expanding Lodwar town experiences extreme low and variable rainfall which influence surface water availability, resulting in exploitation of the groundwater aquifer system to buffer growing water demands. Better protection of water resources in Kenya’s arid and semi-arid lands is necessary to sustainably manage the impacts of climate-related events on vulnerable populations.

**Figure 4: a) Average JJAS rainfall in mm/day with the interquartile range (25th-75th) of monthly rainfall in mm/day (indicated by black contours). b) Average OND rainfall in mm/day with the interquartile range (25th–75th) of monthly rainfall in mm/day. All rainfall from CHIRPSv2.0 1981–2020.**

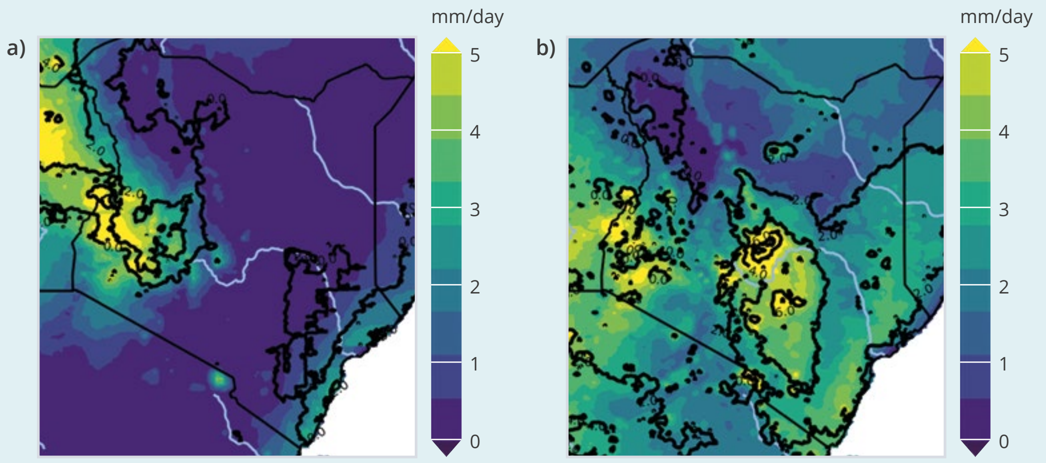


Figure 5: a) High flow along the Turkwel river at Lodwar bridge, caused by four consecutive days of rainfall. Prior to the rainfall the river was nearly dry. b) Nearly-dry river bed one day after the same rainfall event. Photos: Feyera Hirpa.

a) March 28, 17:57

b) March 29, 17:03

# 2. Inequalities exacerbate the impacts of climate shocks

**Seasonal changes and extreme weather events have negative consequences for lives and livelihoods where water security is poor. Where populations are affected by extreme poverty and climate resilience is lacking, these impacts can be devastating**. REACH research has investigated the diverse and poorly documented impacts of extreme water-related events on those most vulnerable, offering a deepened understanding of location specific issues and dynamics – many of which are counter-intuitive. Across countries, people affected by poverty have unequal opportunities to cope with climate shocks. The drivers of inequities are socio-cultural, institutional and biophysical: for example, gendered norms, inequitable water pricing structures and proximity to water resources. In examining the impact of weather extremes on populations affected by poverty, REACH research demonstrates that weak institutional structures and poor regulation offer little help for those in need.

## Weather and climate

This report focuses on the relationships between features of the climate and water security. **Climate** refers to a measure of the observed weather over a region averaged over extended periods of time (e.g. months to years). Measuring the impact of climate change requires long term datasets that span over at least three decades; in many areas of water insecurity in Sub-Saharan Africa and South Asia such local datasets do not exist and research relies on satellite observations and reanalysis models. In contrast, **weather** represents the atmospheric changes observed over a short period of time (e.g. minutes to months). Weather is characterised by short-term changes in temperature, precipitation, cloud cover, humidity and wind strength, and is responsible for phenomena such as thunderstorms, frost and storm surges. Different regions may experience similar weather phenomena like convective storms, but their baseline climate may be very different.

In this report we explore the impacts of seasonal changes and extreme weather events on water security. **Seasonal changes** refer to the month-to-month changes in weather that a region expects to observe every year. For example, rainfall in Bangladesh follows a strong monsoonal pattern; every year we expect to see heavy rainfall between June to September and very little rainfall between December and February. By contrast, a period during which the observed weather deviates strongly from the expected seasonal norm is classified as an **extreme weather** event or **climate shock**. These events include floods, heatwaves and droughts.

Finally, **anthropogenic climate change** may impact the long-term climate of a region and/or the frequency, severity and duration of extreme weather events. For example, some regions may experience gradual deviations in climate as a result of anthropogenic climate change, with marginal changes observed in the average seasonal pattern of weather such as gradual changes in surface temperatures or earlier arrivals of spring events. Other regions may experience an intensification of extreme weather events. Understanding the likelihood and consequences of climate change to seasonal patterns and extreme weather are vital to achieving water security for all.

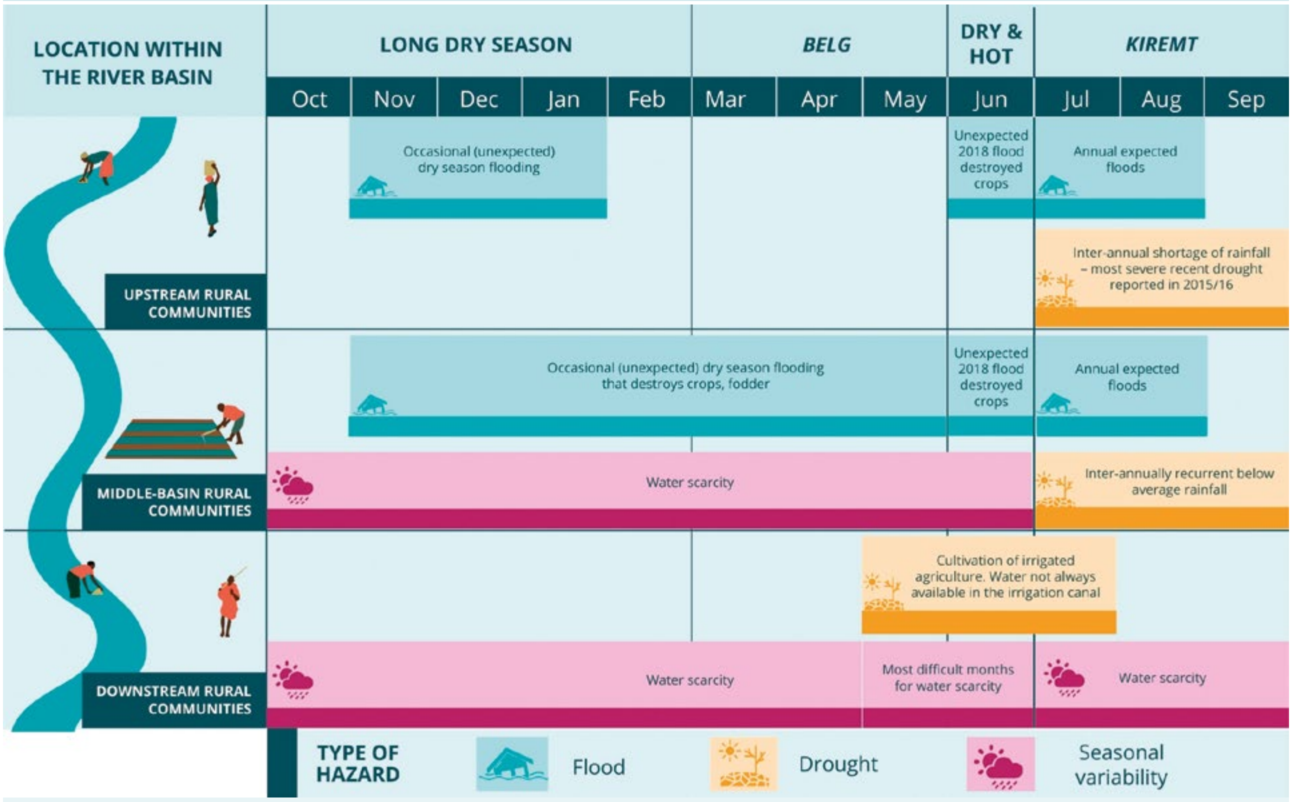
## a. Inequalities in climate impacts on water security are context specific, requiring analysis across scales

**Climate-related impacts on water security are not equal but vary by user and location based on local climate, behaviour of other users, and access to resources to adapt**. In the Awash basin in Ethiopia, interviews with individuals living in rural kebeles, government organisations, industrial water users, and international NGOs, demonstrated stark inequities in climate vulnerabilities between water user groups (agriculture, industry, urban, rural), upstream-downstream inequities, and within communities (Grasham and Charles 2021b, in review). In general, water-intensive private sector operations, such as flower farms, are more resilient to climate extremes due to the availability of financing to invest in more climate resilient water sources, providing for example resources to access groundwater resources during the 2015/16 drought, while water-intensive rural livelihoods, such as subsistence farming have limited resources to mitigate the impacts and are therefore highly vulnerable. The nature and intensity of water-related risks faced by rural communities are strongly determined by their location in the basin, due to the variations in climate across the basin, and by upstream users and polluters. In the Awash, rural communities in the arid lowlands face higher risks from water scarcity while communities in upstream regions suffer from deteriorating water quality and crop destruction from flooding.

**Within urban areas, structural challenges and systemic inequalities increase the vulnerability of the poorest to extreme weather events**. Across Sub-Saharan Africa, the urban poor are more vulnerable to climate shocks because they live in poorly constructed houses, dense settlements and are located in flood prone areas, with the poorest more likely to experience the invisible impacts of flood and drought shocks, such as diminished mental health or increased domestic violence, which can persist long after the weather event has ended (Grasham et al. 2019). In Dhaka, Bangladesh, surveys from over 1,800 households along the Turag-Tongi-Balu river system highlighted unequal water security risks with households affected by poverty reporting more concerns related to flooding compared to wealthier households (REACH, 2018). These groups are also more exposed to the seasonally changing water pollution risks as residents in low-income riverbank settlements, lacking adequate water and sanitation facilities, frequently use the river for washing, bathing, swimming, fishing and faecal water disposal. Domestic activities by women and girls continue year-round, exposed to both weakly diluted industrial wastewater in the dry season and high pathogen loads in the monsoon, while the perceived improvement in water quality in monsoon leads to increased recreational activities by men and children (Hoque et al. 2021, in review).

**Climate shocks force people to abandon their traditional livelihoods, often resulting in coping mechanisms that stretch over decades, generations and spaces**. Research in Turkana, Kenya, reveals that many people tactically flee consequences of droughts by choosing and changing livelihoods, as well as moving spatially and socially. For example, following a climate shock it is common for pastoralist families to temporarily settle around Lake Turkana and engage in low-income livelihoods such as fishing, and later (often in the next generation) move to urban places to become involved in infrequent and poorly paid casual work (Korzenevica et al. 2021a).

Figure 6: Reported temporal changes in recent extremes and recurrent water and climate-related hazards in the Awash basin, Ethiopia, caused by expected and unexpected climate and water resources variability that resulted in exposure and vulnerability to water risk. Water users in the downstream woreda reported rain commonly only falling in July and August and the middle basin user reported rain during kiremt only.

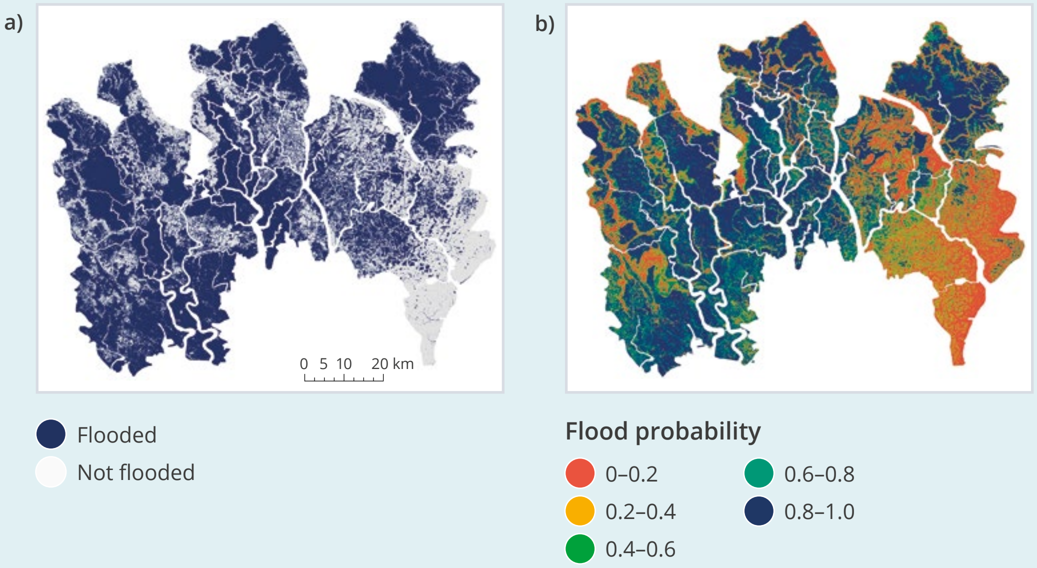


The results are given by month, with the two main annual rainy seasons: belg and kiremt. Rural water users have been divided into three communities: upstream, middle and downstream. Source: Grasham and Charles (2021b, in review).

**Changes in land use is one way in which structural inequalities in resilience are created**. In Bangladesh, Adnan et al. (2020b) estimate changes in poverty with relation to changes in land use and flood risk. Using a multi-model approach, the study shows that pluvial floods cause frequent (near annual) and substantial damage to rural houses with temporary or semi-permanent structures, and pose a significant threat to aquaculture lands where shrimp and fish may escape as water levels increase.

Linear regression analysis reveals that flood risk is positively correlated with land use and expected annual damage, and suggests that ongoing patterns of land use change may be exacerbating the impact of flooding on poverty.

**Figure 7: Historic flooding in coastal Bangladesh.**



a) Displays the extent of inundation during historical flood events in South Western Bangladesh between 1988 and 2012. b) Presents the flood probability index map derived from linear regression analysis. The figure reveals that a major portion of the study area is susceptible to flooding, with 48% of the area estimated to have an annual probability of flooding greater than 0.8.

In their study of historic flooding in the coastal region of Bangladesh, Adnan et al. (2019) identify three types of flooding events: monsoonal precipitation (pluvial), high upstream discharge into the tidal delta (fluvio-tidal), and cyclone induced storm surges (cyclonic). Using a hydrodynamic model, the authors show that historic cyclonic and fluvio-tidal flooding resulted in the largest areas inundated with flood water, with the 2007 cyclone Sidr causing prolonged flooding, economic losses, damage to crops and widespread embankment failure. Of the three flooding types, monsoonal precipitation was the most frequent cause of inundation, affecting on average 11.4% of the study area during each pluvial flooding event.

The subsequent study by Adnan et al. (2020) suggests that implementation of Tidal River Management (TRM) could alleviate flood susceptibility in Bangladesh’s coastal region to monsoonal precipitation, and consequently increase agricultural production in delta regions due to the reduced probability of inundation. However, careful consideration is needed to maximise the performance and sustainability of TRMs within the polders (Uddin and Rahman, 2021, draft). Sedimentation processes in the river, tidal asymmetry, changing river-floodplain flow dynamics, and land use and land topography will each affect TRM success. Source: Adnan et al. (2020).

**Poorly managed climate shocks contribute to people's precarity of jobs and inability to move from the informal economy**. Climate shocks like floods can significantly affect the economy of the household by destroying assets, including cash money that people store in their house. However, research in Lodwar town, Turkana County, Kenya, shows that the effects of climate shocks are deeper. For example, workplaces, such as car operation industries and the construction sector, stall after a shock. Employees are rarely compensated for the time out of work, leaving people in bottom-level jobs without their main income source for several months (Korzenevica et al. 2021a). Likewise, frequent floods have made building new developments hard, firstly, because of changing flood exposure and secondly, because the local aspiring entrepreneurs planning to move into real estate have lost initial capital and have been forced into lower paid and hazardous jobs.

**Development initiatives, adaptation and urbanization planning should acknowledge the multiplicity and variety of climate and other shocks**. Challenging climatic environments can limit people escaping poverty. For instance, in response to multiple drought events in Lodwar, pastoralists started farming in areas adjacent to river banks as closer access to the water ensured easier irrigation. While the businesses were successful for a while, severe floods along the Kawalasee and Turkwel rivers resulted in many farmers' plots being swept away. As a consequence, men (and occasionally women) had to engage in health hazardous income generation activities such as unprotected gravel collection (Korzenevica et al. 2021a).

**Addressing inequalities in vulnerability to climate shocks requires explicit consideration of inequalities in water security programming, as well as consideration of equity in investments**. The funding required to build climate resilience for water systems will vary by user and location, with greater investments needed to ensure climate resilience for those who live in more challenging geographies, or who are more vulnerable to the impacts of climate change.

## Water security investments

Sustainability of water security investments, including those targeted towards marginalised and disadvantaged groups, require complete and contextual understanding of different water related conflicts and their dynamics over time.

An empirical study in Polder 29 of southwest coastal Bangladesh revealed that climate drivers, in addition to socio-economic, environmental, technical, political, and institutional drivers, can trigger water conflicts in rural areas, with wide ranging implications for water security and social inequalities. For example, changing saline environment in rivers and canals, riverbank erosion, siltation, and waterlogging may lead to changing land use practices, hydrological discontinuity, dysfunctional water control structures. This can cause a shift in livelihoods and increase the risk of tension between different water user groups, including the marginal communities (Hasan et al. 2021).

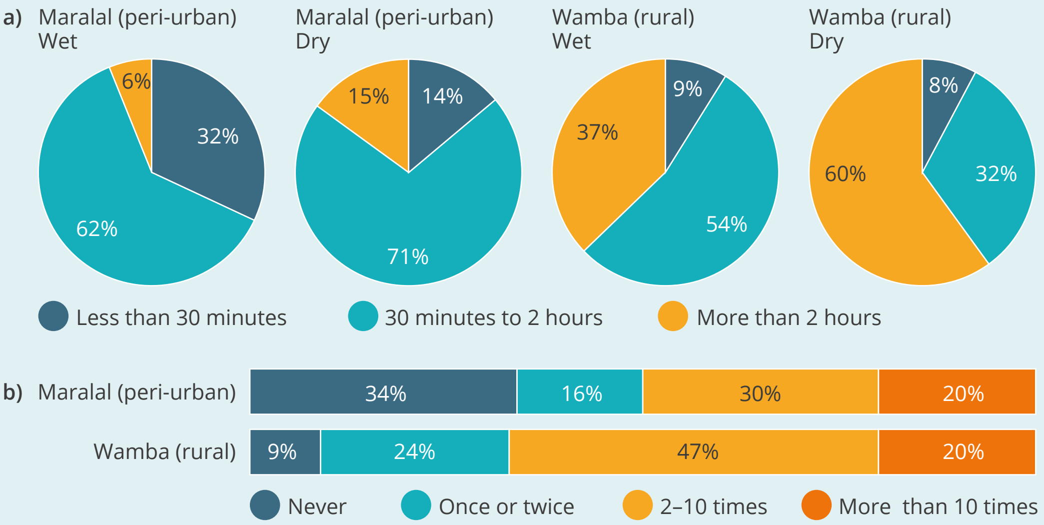
## b. Within the household, the impact of climate events are strongly gendered

**Intersectional vulnerabilities within communities are evident, with women, men and children experiencing vulnerability to climate extremes in different ways**. In the Awash basin, Ethiopia, the impacts of droughts are experienced through gendered household responsibilities with implications for physical and mental health (Grasham et al. 2021b, in review). Men bear the emotional burden when household income is at risk, whilst women have a time-burden in securing household water supplies (see Figure 8). Children's development is diversely impacted by drought and flood-induced events. Grasham et al. (2021b) report that parents must decide how to protect their children during climate shocks, with education often being traded in favour of children's physical health or household income generation. For example, one farmer revealed that he kept his son home during a flood event for fear that it would affect his health, as climate shocks can increase exposure to waterborne diseases such as typhoid and dysentery. Where households experienced a decrease in income from a climate shock (e.g. crop failure), children were taken out of education to work in homesteads and private farms. During dry periods children are also likely to make long journeys with their parents to fetch water, which increases their workload, reduces their time spent in education, compromises their emotional well-being, and impacts their physical health.

During a flood, women, children, sick and old people have the highest risk of death as they are most likely to be at home during the event. In Lodwar, Kenya, women are responsible for repairing the house after the hazard and take care of the family, whereas men often get involved in dangerous rescuing operations, often with severe consequences (Korzenevica et al. 2021b).

**Climate shocks are often interlinked with family dynamics and conflicts, triggering family separation and gendered mobility**. Droughts in Turkana County, Kenya, have resulted in devastating losses of livestock which are the main income source of pastoralists. This has triggered tensions within pastoralist families or larger clans, causing sibling rivalries, jealousy, fights for assets, domestic violence, and in some cases death (often associated with bewitching). Occasionally men, who are typically the main income earners, leave the household (possibly due to the escalating mental health problems). In other instances, women with children or the whole nuclear family decide to move to urban localities. When there is a crisis that involves turmoil in family assets, REACH has found that women in Turkana are least protected due to poor ownership rights and they, together with their children, are the most likely to flee to urban places (Korzenevica et al. 2021a).

**Figure 8: Fetching water in Samburu County, Kenya.**



a) Percentage of time taken by households in rural and semi-urbanised communities in Samburu County, Kenya, to fetch water (go to the source, collect water, and return). b) The percentage of women reporting a reduction in childcare due to water collection in Wamba and Maralal communities in Samburu County, Kenya.

In their study of communities in Samburu, Kenya, Balfour et al. (2020) find that women in rural areas experience a disproportionate level of stress during the dry season because they have to walk further and for longer periods of time (>2 hours) to find water. Overall, 20% of women reported that, over a four-week period in the dry season, they were unable to care for their children more than ten times because they had water collecting duties. Source: Balfour et al. (2020).

## Drought and mental health

In their systematic review of drought and WASH literature, Sule and Charles (2021, draft) identify strong evidence linking drought events to poor mental health, fear, anger and panic, with individuals experiencing emotional distress from coping without adequate water access during drought events. The authors find that mental health issues are often overlooked, with a greater focus placed on identifying interventions that minimise salient physical impacts.

**Empowerment is influenced by climate hazards, and impacts on resilience**. In coastal Bangladesh, the processes surrounding women's empowerment via participation are non-linear and diverse, and influenced by climate (Lima et al. 2021). In areas where water is abundant with acceptable quality and accessibility, and where water security interventions have minimised the impacts of climate hazards such as cyclonic storm surges or fluvio-tidal flooding, REACH research identified that women are more empowered.

In areas beset with water insecurity, women's empowerment is lower. In Burkina Faso, in piloting the Empowerment in WASH Index (Dickin et al. 2021), REACH highlighted empowerment of women and men was associated with access to more climate resilient water sources, but in different ways. For men, those who were empowered were less likely to rely on vulnerable unprotected water sources. For women, those who were empowered were more likely to pay an annual fee for water use, rather than only when there was a break-down or by the container. These interactions between gender, hazard exposure and resilience require further study.

### Research uptake and policy / practice impact

**Incorporating climate into UNICEF's WASH BAT tool**

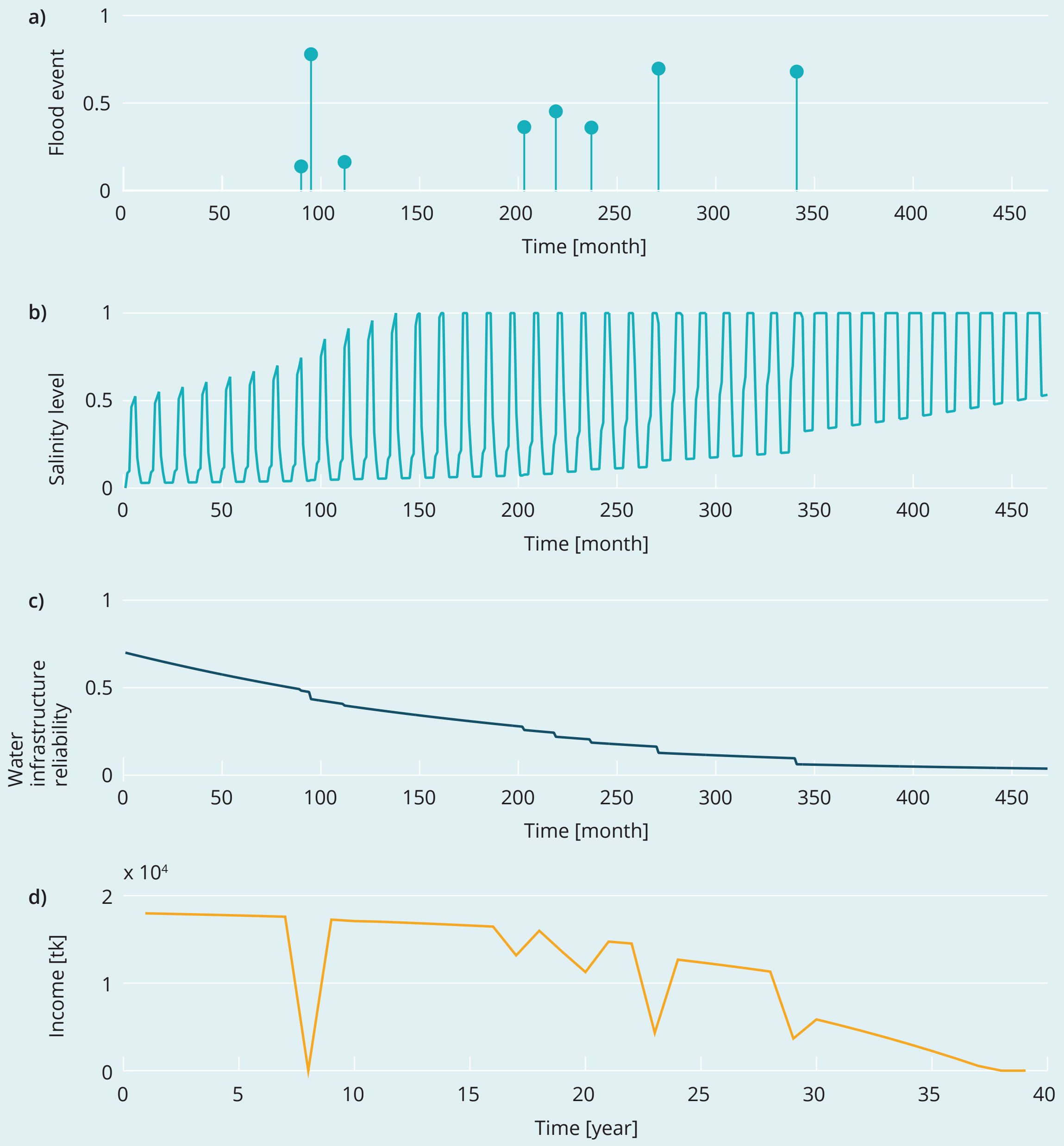
REACH is providing input to UNICEF's work on climate resilience, in particular on climate indicators in the Water, Sanitation and Hygiene Bottleneck Analysis Tool (WASH BAT). WASH BAT helps to systematically and collectively formulate costed and prioritised Action Plans to remove the bottlenecks that constrain the WASH sector and hinder the delivery of sustainable WASH services. The tool is designed for governments to lead the process, guided by trained moderators and facilitators, to reach a broad consensus on the major fundable activities. Although the tool did not originally incorporate a climate perspective as part of the assessment, there has been an increasing push by countries for it to be included. Additional Climate Change Management criteria are now being developed, with support from REACH.

**Communities have multiple mechanisms to target intersectional gendered climate vulnerabilities, but they are not enough**. In Lodwar, research shows that institutional support often does not reach the most vulnerable following a climate shock. Mechanisms such as patronage and bribery, and exclusions based on social group or ethnic belonging, can contribute to the most vulnerable being left without governmental support. Commonly, members of the community (i.e. church groups, individuals, and elders) help those most in need. This coping mechanism is rarely sustainable (with exceptions) and does not reduce climate vulnerability, as individuals become dependent on the chance rather than the security of help (Korzenevica et al. 2021b).

## c. Infrastructure interventions can build climate resilience, but only if carefully planned for equitable outcomes

The impacts of poor climate resilience, through loss of functional water infrastructure, perpetuate water-poverty traps. In their Bangladesh-based study, Borgomeo et al. (2018) find that flooding, in addition to increasing groundwater salinity, deteriorating water sources and poorly maintained water infrastructure, can impact household welfare (see Figure 9). The authors argue that better management and maintenance of water supply infrastructure is necessary for households to escape water-poverty traps.

**Figure 9: Simulation results from the conceptual human-water dynamical modelling experiment by Borgomeo et al. (2018).**



Results are for an embanked area in coastal Bangladesh with deteriorating water infrastructure and lack of maintenance. From top to bottom, the plots show a) the time series of flood peaks, b) monthly salinity, c) embankment reliability, and d) income (tk). The results illustrate the negative impact of rapidly deteriorating water infrastructure on income: a lack of infrastructure maintenance leads to increasing soil salinity and damage from flood events, thus decreasing agricultural production and declining incomes. This dynamic creates a water-poverty trap, in which declining incomes and assets make it more difficult for communities to escape poverty. Source: Borgomeo et al. (2018).

**Measuring access to infrastructure does not capture inequalities in climate resilience of water systems**. In Wukro, a small town in the north of Ethiopia prone to droughts, 97% of households have a piped connection to the formal urban water supply. However, water access is seasonal and is not equal. Despite access to piped water, urban residents reported having to stop water-using activities more frequently in the dry season than the wet season due to poor availability of water (Grasham et al. 2021a, draft). To manage the seasonal water shortages and droughts, shifting intermittent delivery has been used which has created spatial inequalities, with some areas prioritised for more regular flow due to the presence of critical services such as the hospital. These spatial inequalities are significant, even within a small town: in one of the three kebeles 8% of respondents reported stopping activities due to water scarcity, and reported that trouble accessing water would normally extend for less than 3 months, compared to the most water scarce kebele where 66% of respondents reporting stopping activities, with trouble accessing water for 6 months of the year. These impacts were disproportionately borne by those with household enterprises, who were almost twice as likely to experience water shortages that caused them to stop water-using activities. These differences in access can be exacerbated during wider droughts, which can induce rural to urban migration increasing pressure on urban water supplies (Grasham et al. 2019).

One of the other limitations of using access to infrastructure as a proxy for climate resilience of water systems is the role of household decisions in responding to seasonal and weather-related changes in water access, that can reinforce inequalities due to limitations in access to resources.

### Research uptake and policy / practice impact

**Promoting climate resilience for water security in Wukro**

In Wukro, Ethiopia, UNICEF and FCDO's investments to improve water access brought water from deep boreholes in a more productive aquifer to supplement existing town boreholes, reducing seasonality of urban water supply. REACH has been supporting UNICEF's Water Safety Plan training to strengthen consideration of climate resilience, providing targeted information (Taye and Charles, 2018) on climate impacts on supply, demand and health.

**Climate adaptation interventions should consider distributional outcomes to avoid unintended consequences for the most vulnerable**. Two studies in Bangladesh have highlighted the challenges in building equitable climate adaptations to flood risks. Manandhar et al. (2020) investigate surface water flooding in Bangladesh, using LANDSAT 4-5 TM images to identify breaches in polder embankments during historic flood events, and socio-economic data to quantify the impact flooding has on the welfare of people living both inside and outside the polder infrastructure. Results indicate some but limited benefits to lives and livelihoods from flood protection, with embankments reducing the impact of storm surge breaches but at the cost of higher pluvial flooding. The machine-learning methodology used by the authors, together with the information generated in the study, can be used to guide future policy decisions and investments in climate resilient infrastructure.

Overall, the study shows that flood protection infrastructure does not guarantee higher benefits for those living with higher levels of protection, highlighting that the intended and unintended consequences of interventions must be considered in climate resilience actions and policies.

Lázár et al. (2020) use the integrated assessment model – Delta Dynamic Integrated Emulator Model – to simulate four development trajectories in the southwest coastal zone of Bangladesh under contrasting climate and socio-economic scenarios, with trade-offs a key feature in each trajectory. For example, protective infrastructure and management, such as embankment rehabilitation and controlled sedimentation, ensure the coastal zone remains habitable and agriculturally productive throughout the 21st Century. Yet, rehabilitation comes at a high economic cost and increases the risk of waterlogging, whilst controlled sedimentation raises equity issues as communities are exposed to temporary flooding. Complex human-natural systems require a more integrated-nuanced approach to identify equitable policy interventions.

# 3. As socio-environmental systems, water systems have complex vulnerabilities to climate

Understanding the influence of seasonal variability on water security and vulnerability to extreme events can help us assess the impacts of climate change on users. Conventionally, climate impacts have been thought of in terms of implications for water resources, flooding and agriculture. However, REACH research has shown that climate has diverse and complex impacts on drinking water supplies and water quality.

**Figure 10: Two men navigating by boat over the polluted Turag river in Dhaka, during a low flow period. Many urban poor live on or near the riverbanks, relying on the Turag for their livelihoods through agriculture, fishing, navigation, commerce and more. Photo: Shamima Prodhan.**

### Water system

A water system is dynamic and complex, and is shaped by the individuals, institutions and environmental conditions within it.

Here, we consider a water system to be one which includes:

- a hydrological system that contains the water which may be used by a water user, such as a river or groundwater source;
- the social and political drivers that influence water institutions and governance;
- the water user(s).

The water system may include an infrastructure system which connects a water source to the water user, such as a tubewell or piped water network, and the operational rules which manage the movement of water through the infrastructure system.

## a. The impacts of climate on water systems have complex effects on quality and availability of water

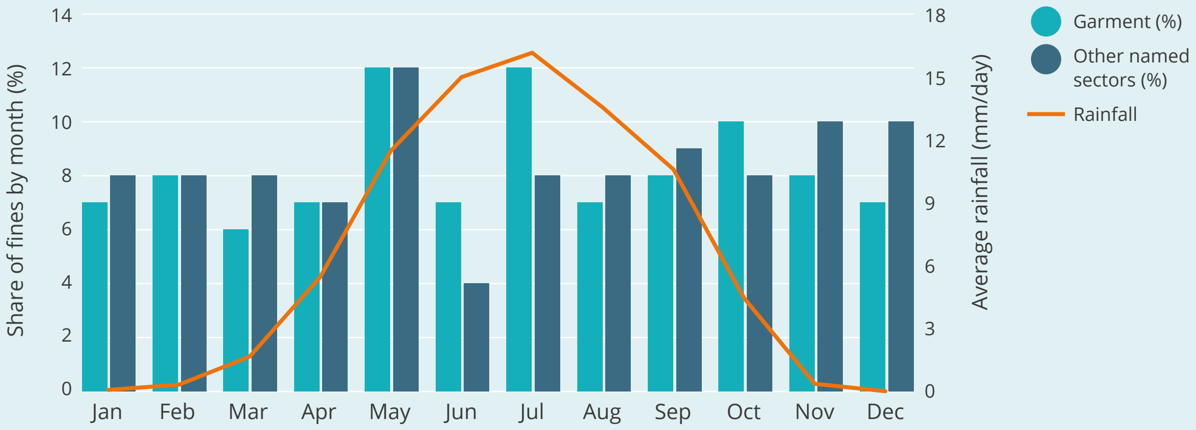
**Complex fluctuations in water quality with weather create changing risks to ecosystems and health across the seasons**. In low flow periods, lower dilution of untreated wastewater from industry and municipal sources is concentrated in rivers, lakes and reservoirs, reducing the performance of treatment processes (Sule and Charles, 2021 draft). In Bangladesh, where the influence of the monsoon in June to September results in large changes to river flow, REACH research highlights the strong seasonal pattern in water quality risks paralleling changes in precipitation and upstream land run-off. During low flow periods in the dry season in Dhaka, heavy metal contamination is high due to less dilution of industrial wastewater discharges (Rampley et al. 2020); during the high flows of the monsoon, effluents from industrial zones and areas of high urbanization are diluted, thus reducing pollution concentrations. In their study of water chemistry in the Turag-Tongi-Balu river system, Whitehead et al. (2018) also identify seasonal differences in water quality, with very low dissolved oxygen levels, high organic loading, and high levels of ammonium nitrate in the river water in the dry season, with significant implications for the river ecosystem. Using the INCA (Integrated Catchments) water quality dynamic modelling software tool, the authors evaluate two management strategies designed to restore water quality in the polluted river system. Simulation in INCA reveals that a combination of effluent clean-up technologies and nature-based solutions based on flow alteration strategies to increase flow in the dry season would significantly reduce concentrations of ammonium nitrate in the water.

**In Dhaka, climate change is expected to impact the remedial measures identified in Bangladesh's River Master Plan and the strategies identified in the Greater Dhaka Watershed Restoration Project**. Firstly, reduced flows in the peripheral rivers around Dhaka City in the dry season will affect flow augmentation strategies aimed at reducing pollutant loading. Secondly, low flows will hamper the government's plan to switch from depleted groundwater to surface water supplies. These impacts will have financial implications for restoring the greater Dhaka watershed.

**Figure 11: Monthly analysis of water quality along the Turag River and Tongi Khal, Bangladesh, showing extreme spatial and temporal variation in physiochemical parameters and heavy metal concentrations. Dashed horizontal line shows the Bangladesh Environmental Quality Standards (MoEF, 1997). Source: Hoque et al. (2021, in review).**

**While the wet season dilutes the concentration of metals, it can increase risks from waterborne diseases**. Waterborne diseases such as cholera, typhoid, and enterotoxigenic *E. coli* demonstrate seasonal changes in prevalence linked to increases in rainfall and the increased flows from faecally contaminated water from urban drainage and agricultural areas. For residents in Dhaka's low-income riverbank settlements, use of the river for domestic activities by women and girls continues year-round, exposing themselves to both dry season and wet season risks (Hoque et al. 2021, in review).

**Figure 12: May is the cruellest month – share of fines by month awarded to garment and other named sectors, 2011–2019. Monthly average precipitation is given in mm/day for the upstream catchment area of Dhaka, Bangladesh (between 23-27N, 88,93E), between 2011–2019. Rainfall data from CHIRPSv2.0. Source: Peters et al. (2021, draft).**



Seasonal fluctuations in water quality are paralleled by fluctuations in water pollution fines and monthly average precipitation. The plot shows the variation in pollution related fines from the Bangladesh Department of Environment (DoE), by month, over the course of 2011–2019. The plot reveals an annual spike in fines between May and July, which the authors hypothesise is due to (i) onset of the monsoonal season, during which dry season 'gunk' is transported through the river systems, and (ii) observance of World Environment Day in June when the DoE steps up enforcement efforts.

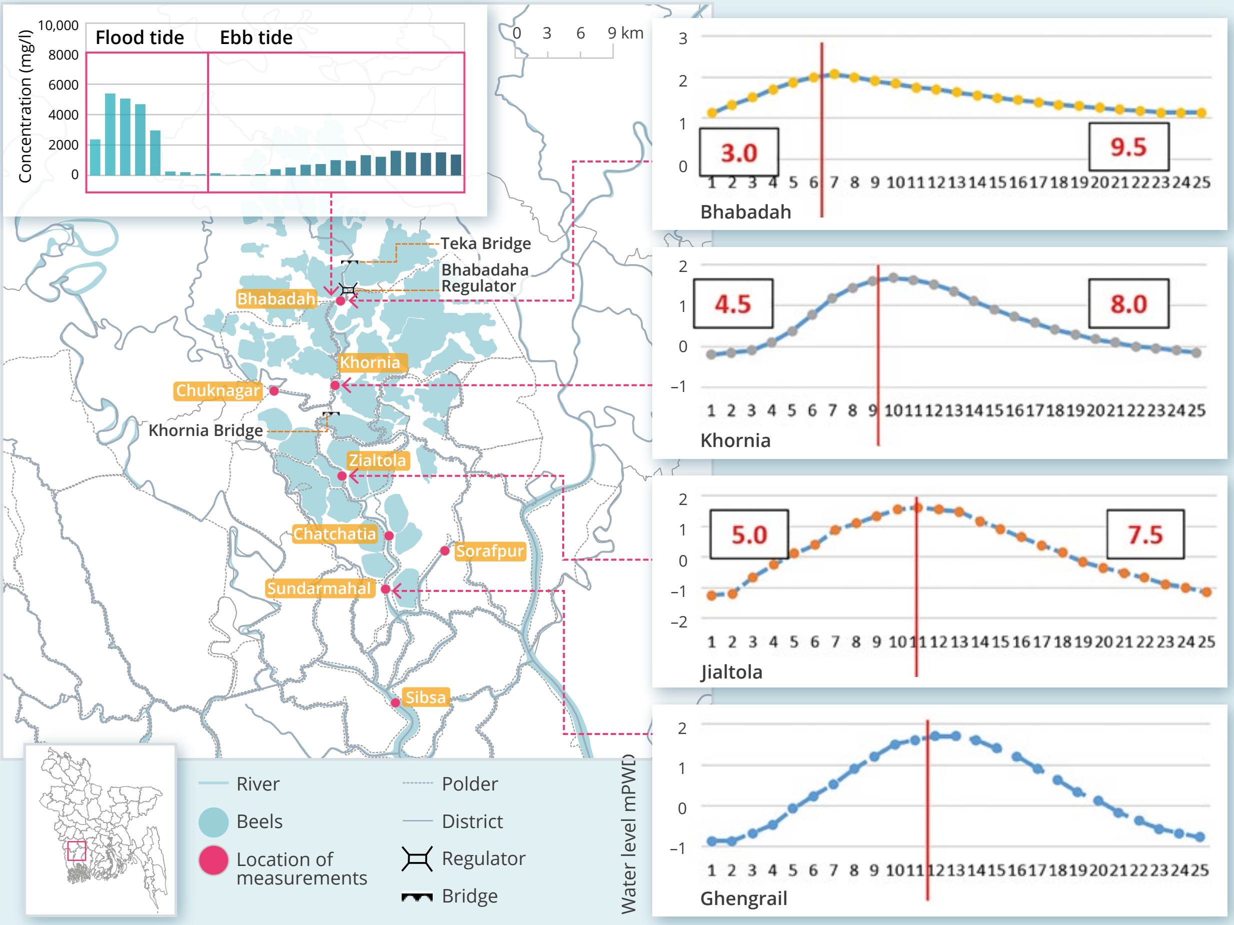
**Wet season impacts on water quality also impact drinking water safety, demonstrating a lack of climate resilience within drinking water systems**. In Bangladesh, warmer and wetter weather is associated with higher faecal contamination in water from tubewells in both flood prone and drought prone areas, with access to safe water (no *E. coli* detected) decreasing by approximately one quarter between the dry season and the monsoon (Charles et al. 2021, draft). A similar drop in access to safe water was measured in Khulna where faecal contamination of deep tubewells rose from 3% to 13% between the dry season and the monsoon, whilst contamination in pond sand filters at the point of collection increased from 30% to 78% (Hoque et al. 2021).

**Figure 13: In Bangladesh, heavy rainfall, flooding events and warmer temperatures increase the risk of faecal contamination of drinking water supplies. Photo: Sustainable Sanitation.**

Figure 14: Expanding Lake Beseka, Ethiopia. Photo: Alice Chautard.

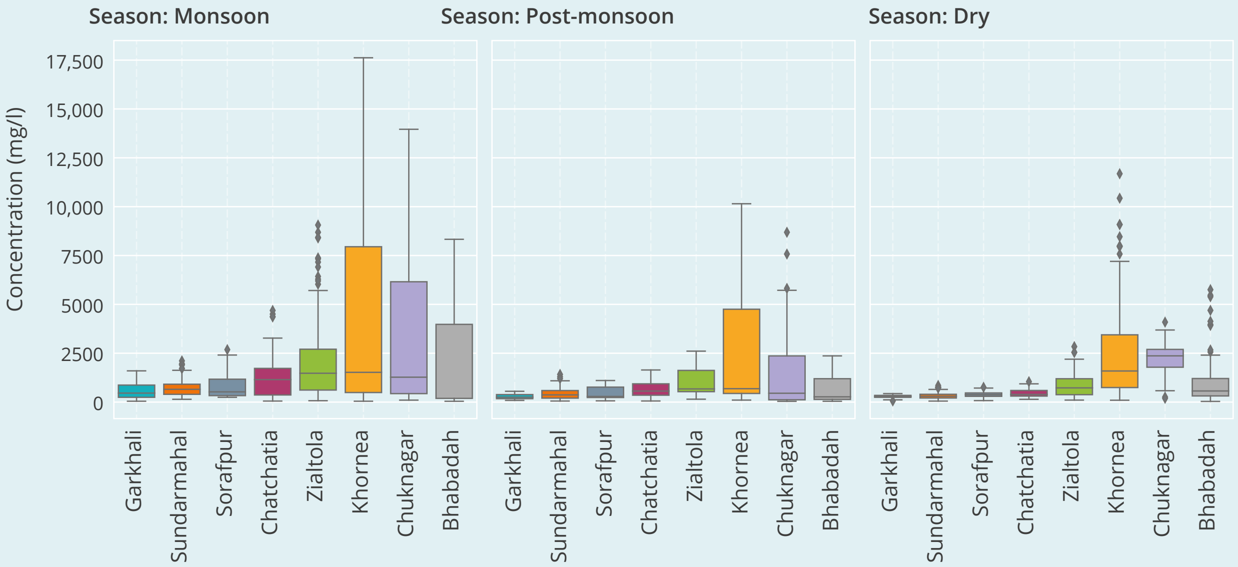
Yimer and Jin (2020) attribute the deterioration of water quality in the middle Awash, Ethiopia, to unregulated discharge of saline water from the expanding Lake Beseka into the Awash river. Analysis of 480 water samples from the river reveals that lake releases during the dry season have a large negative impact on water quality, as there is less water in the river to dilute saline discharge from the lake. To manage the ongoing threat to irrigation and water supply, the authors propose a mixing ratio model to inform the timing and volume of lake water discharges throughout the year. By coinciding releases with high flow periods in the wet season, it is possible to manage water quality for downstream users.

Figure 15: Tidal asymmetry in Bangladesh's coastal river.



Changing flows in freshwater in the Ganges-Brahmaputra river system, driven by seasonal precipitation patterns, are impacting siltation in Bangladesh's coastal zone, with implications for waterlogging rates and flooding. Lack of adequate understanding of seasonal sediment transport and deposition processes in coastal rivers hinders efforts to manage riverbed siltation and waterlogging problems with the changing climate. Through an intensive hydraulic and sediment concentration measurement campaign in coastal rivers, REACH research has shown that Tidal Asymmetry, which increases from downstream to upstream, and increasing sedimentation concentration from the sea towards inland, are major factors behind sedimentation at Bhabadah and adjacent areas. Climate is a significant driver of sedimentation with sediment transported inland with flood tide during the monsoon, while major sedimentation in rivers occurs during dry season (Uddin and Rahman, 2021, draft). The new insights have aided analysis of potential of adaptation interventions such as tidal river management, strategic dredging, pumped drainage of water, or hydraulic structures. The results suggest that a sustainable and equitable solution to waterlogging and sedimentation will require a system-wide solution instead of a siloed thinking. Source: Uddin and Rahman (2021, draft).

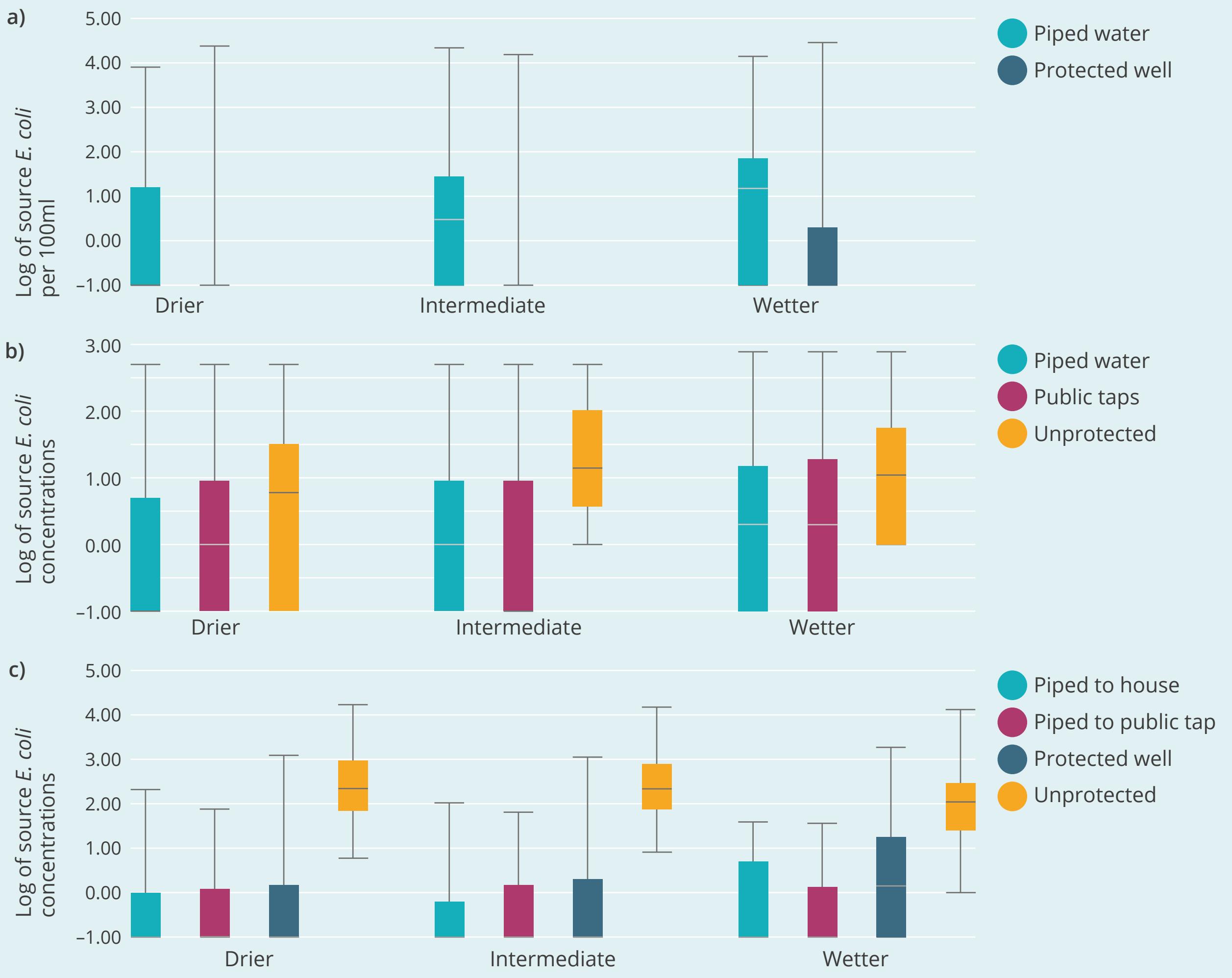
Figure 16: Sediment transport towards inland with flood tide during dry, monsoon and post-monsoon seasons. Sediment transport is maximum during monsoon, but major sedimentation in rivers occurs during dry season. Source: Uddin and Rahman (2021, draft).



**Decision makers must recognise that water quality varies in time and space, and that the quality of water supplies may be vulnerable to extreme weather events**. Charles et al. (2021b, draft) consider the impact of weather extremes on water quality in three different countries: Bangladesh, Nepal and Tanzania. The observational field study tracked households and water sources across seven different geographies, measuring portable pH, temperature and turbidity, and sampling for *E. coli*. Household surveys were also conducted to collect information on socio-demographics, self-reported diarrhoea, WASH access and behaviours. Results reveal that rainfall and temperature extremes significantly impact water quality at the water source and the household (point of use) via different mechanisms.

Heavier rainfall, higher maximum temperatures, and lower minimum temperatures are associated with increases in faecal contamination at the source, although the mechanisms for this vary by location. In Bangladesh, for example, water quality at the source was most strongly influenced by extreme daily rainfall events (>95th percentile), whilst water quality in Nepal was associated with extreme temperatures and the length of rainy periods (Charles et al. 2021b, draft). Other research highlighted that the impact of weather extends beyond faecal contamination, as the impact of cyclone Amphan on the coastal area of Bangladesh increased saline intrusion into groundwater supplies, as well as damaging water supply infrastructure and washing away embankments (Hoque et al. 2021). The vulnerability to extreme events, which are increasing with climate change, will increase risks to health and is further evidence of the lack of climate resilience in water systems. Overall, the results demonstrate that consideration of weather variables in future analyses of water quality are imperative to understand the climate resilience of WASH interventions. More work must be done to ensure that high-risk events do not compromise existing efforts to sustain safe water treatment and storage.

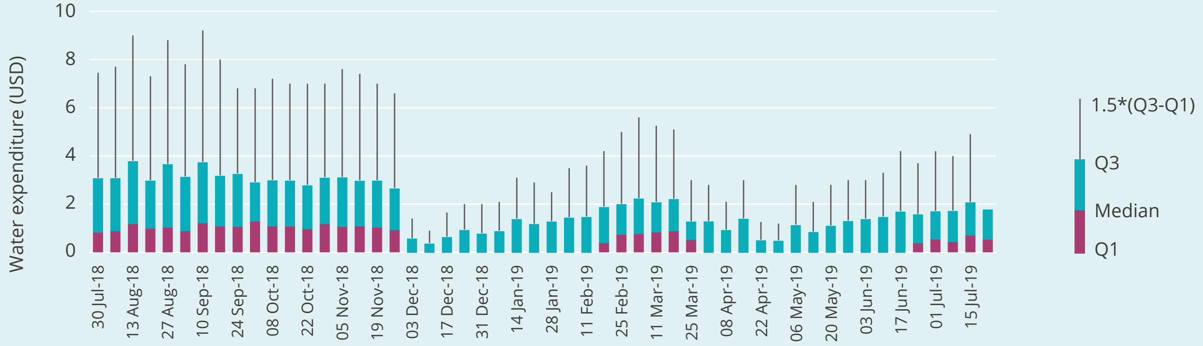
**Figure 17: Water quality for different water sources in Bangladesh a), Nepal b) and Tanzania c), in dry, normal and wet conditions. *E. coli* concentrations are used as a proxy for water quality. The figures show that water quality varies by method of access, country and weather conditions. Source: Charles et al. (2021, draft).**



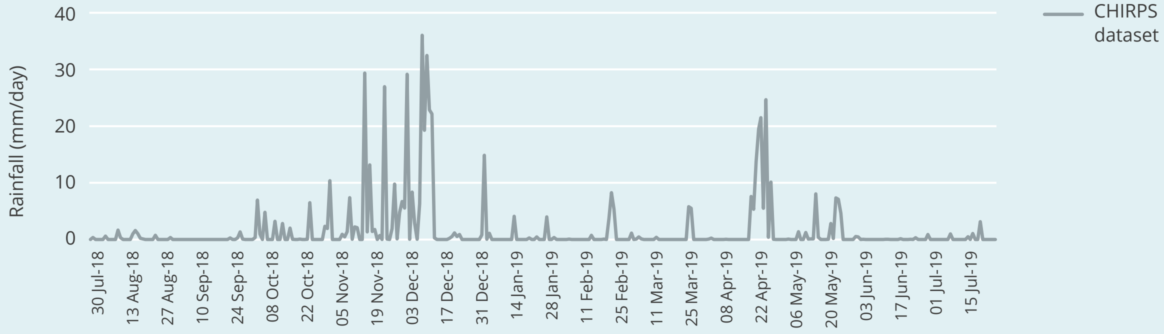
**Seasonal fluctuations in water quantity also affect water supply choices**. Using the water diary method to investigate water insecurity in Mwingi-North sub-county, Kenya, Hoque and Hope (2018) show that unavailability of water during dry periods results in women travelling to find alternative water sources. During the four-week study, the authors found that water sources used by the female respondents closely mirrored rainfall patterns, with respondents using rock catchment sources in the early part of the study, then rainwater harvesting when the first of the long rains arrived in mid-April. Towards the end of the study, respondents ran out of stored rainwater and had to use water from hand-dug wells and earth pans. Eventually, the women had to seek alternative handpumps and kiosks outside of the village. As a consequence of the varying access to consistent water sources, water used for hygiene activities (laundry, dish washing, cleaning and bathing) was reduced during dry periods. Roughly half of the households surveyed did not have sufficient water for personal hygiene for several days in the four-week study.

**Figure 18: Water sources, amount, and expenditures between August 2018 to July 2019, Mwingi-North sub-county, Kenya.**

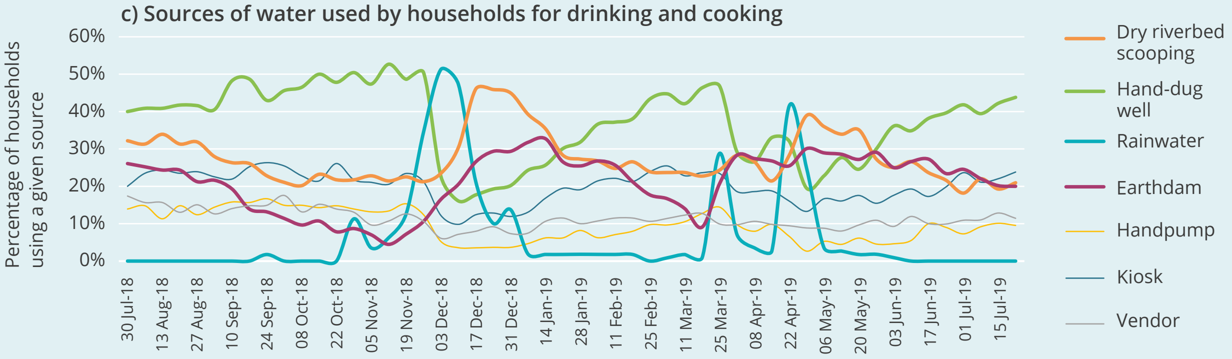
a) Weekly variation in water expenditure



b) Rainfall in Mwingi North sub-county

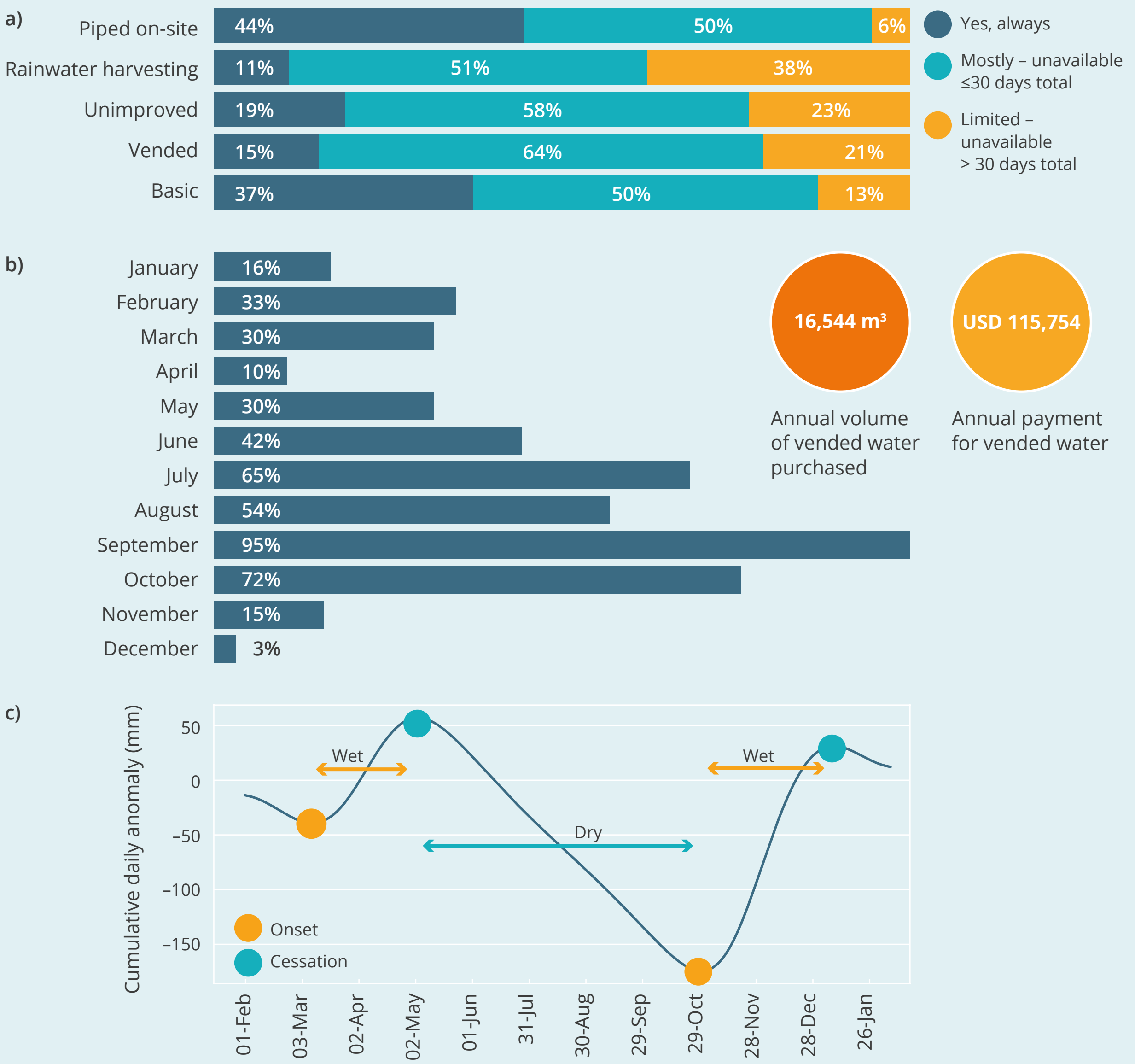


c) Sources of water used by households for drinking and cooking



In Mwingi-North sub-county (Kitui county), 115 households, randomly selected from a cross-sectional survey of about 1400 households, were trained to record their water sources, amount, and expenditures in pictorial charts (see Hoque and Hope, 2018) every day for a 52-week period between August 2018 to July 2019. Findings reveal that household choice of water sources and expenditures closely mirrored rainfall patterns, with sharp shifts from groundwater to surface sources following onset of the 'short rains' in late November. When earthpans dry up, people shift to dry riverbed scooping followed by hand-dug shallow wells, though there is considerable spatial heterogeneity based on availability of water supply infrastructure. Water crisis and expenditures peak during June to September, with many reporting payment difficulties and increasing salinity in groundwater sources like handpumps and shallow wells. Source: Hoque and Hope (2021).

Figure 19: Water availability in schools, sources and seasonality of rainfall patterns in Kitui County, Kenya.



a) Reported water availability from main water source in Kitui County schools over a one-year period with categories of i) always available, ii) mostly available (<30 days with no service), iii) limited availability (>30 days with no service).

b) The percentage of schools reporting 'high vending' by month. The figure indicates that the largest proportion of schools use vendors in September and October, when rainfall is lowest.

c) The seasonality of vended water reflects the bimodal rainfall pattern in Kitui County. The figure shows the rainy season onset and cessation period, produced using the 1981-2018 CHIRPS climatology data and accumulation method of Liebmann et al. (2012).

Hope et al. (2021) investigate climate-related risks to water security in 1,878 primary and secondary schools in Kitui County, Kenya. The uptake of water from vendors closely follows Kenya's bimodal rainfall pattern, with peak vendor rates occurring in the dry period between June and September. The study finds that no single water source (piped, rainwater, vended, handpump) guarantees availability throughout the year. Schools using rainwater harvesting as their main water source have the highest frequency of periods with limited water availability, with insufficient storage to see out the dry months. While one third of schools spends money on vended water during the dry months, one third of schools spend nothing. This insecurity is not spatially homogenous with schools in southern parts of the country being more vulnerable to short dry periods (<10 days) and less vulnerable to longer dry periods (>30 days). However, water risks are managed by each school leading to inequalities in service delivery with gendered inequalities affecting girls with insufficient water for menstrual hygiene management. Source: Hope et al. (2021).

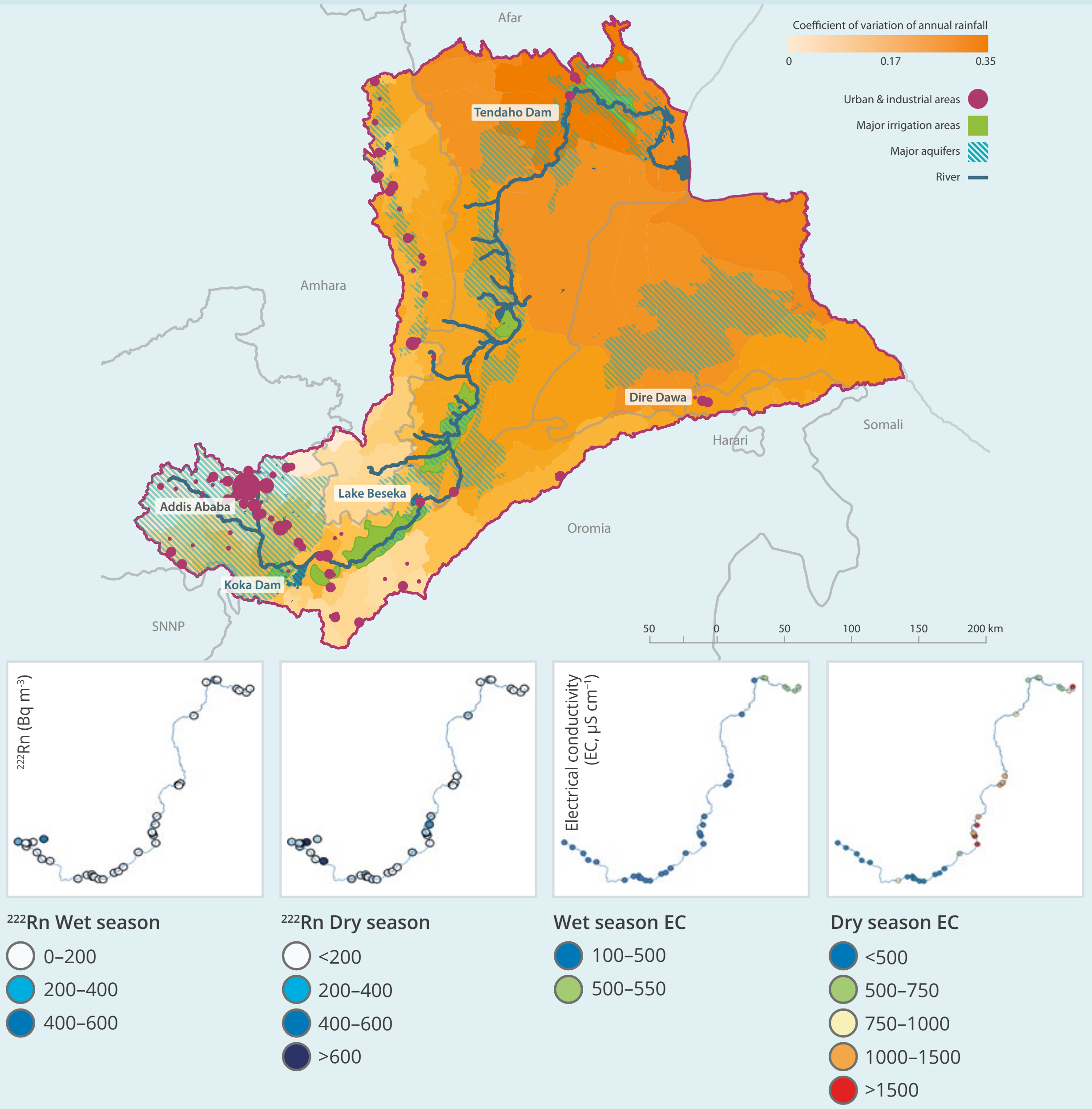
## b. Groundwater offers resilience, but climate impacts on groundwater systems need to be understood

Groundwater is an important resource for settlements in Sub-Saharan Africa (Olago, 2019). Improving groundwater access can increase climate resilience where the mechanisms for recharge, quality, quantity and interactions with surface water are sufficiently understood.

**Groundwater storage offers resilience to seasonal fluctuations in water availability, with sustainability dependent on understanding of the interlinkages between groundwater and surface waters**. In Ethiopia, water quality in the Awash river is closely linked to regional-scale interactions between groundwater and surface water, and to anthropogenic influences such as irrigation. Using geochemical isotopic tracers and regional- and local-scale piezometry, Kebede et al. (2021) show that, in the upper Awash the river recharges the groundwater in the wet season, while groundwater makes up a larger proportion of water flowing into the tributaries of the main river in the dry season. In the middle and lower Awash, there are only a few sites where regional groundwater contributes to flows in the river, making groundwater management in the upper Awash critical for downstream river users, but also for water quality to manage dry season salinity issues.

Birhanu et al. (2021) demonstrate the vulnerability of groundwater resources in the upper Awash basin to over-abstraction with future demand from within the upper basin and climate pressures, arguing for the need for careful management. Risk-based planning and development of surface-groundwater conjunctive use would help to manage the threat to groundwater systems from larger and more frequent abstractions, and maintain important regional-scale interactions between groundwater and surface water resources.

**Figure 20: In the Awash river, Ethiopia, $^{222}$Rn and electrical conductivity have been used to identify seasonal changes to groundwater influence and water quality.**



The images show $^{222}$Rn (Bq/m$^3$) and electrical conductivity (EC, µS/cm) of the main course of the Awash river from its headwaters (bottom left) to terminus at the Abhe lake (top right). In the upper river, higher concentrations of $^{222}$Rn in the dry season indicate the high inflows of groundwater to the river in those areas, while in the middle to lower basin, the river water contains low concentrations of $^{222}$Rn in both seasons, indicating little regional or local groundwater flow into the river. Also in the middle to lower basin, the surface water has high electrical conductivity in the dry season, making the river water unsuitable for non-salt tolerant crop irrigation. Increasing salinity of surface water has led some towns in the middle and lower basin to change their water sources from the Awash river to groundwater during the dry season. Careful management of groundwater in the upper basin, and reservoirs, wetlands and lakes are necessary to reduce salinisation in these regions and protect water supplies during dry periods. Source: Kebede et al. (2021).

**Changes in surface water salinity threaten the quality of groundwater supplies**. In Bangladesh, REACH research using a groundwater flow and variable density model (SEAWAT – set-up for Polder-29 in visual MODFLOW platform) has revealed that groundwater salinity in the shallow aquifer may be impacted by increases in river salinity caused by climate change induced reduction of freshwater flow and anthropogenic interventions, posing a considerable risk to drinking water supplies in areas served by shallow tubewells (Akhter and Salehin, 2021a, b). Short term, a scenario of rapidly increased river salinity due to sudden reduction of freshwater flow has a bigger potential to influence groundwater salinity compared to a scenario of gradually increasing river salinity due to sea level rise, as the lateral advancement of seawater interface due to sea level rise is an extremely slow process. Over 50- and 100-year time scales, vertical exchange between river and aquifer, although a slow process, is expected to increase salinity in the shallow aquifer in the middle and south of the polder, which correspond to places where shallow tubewells are used for drinking water.

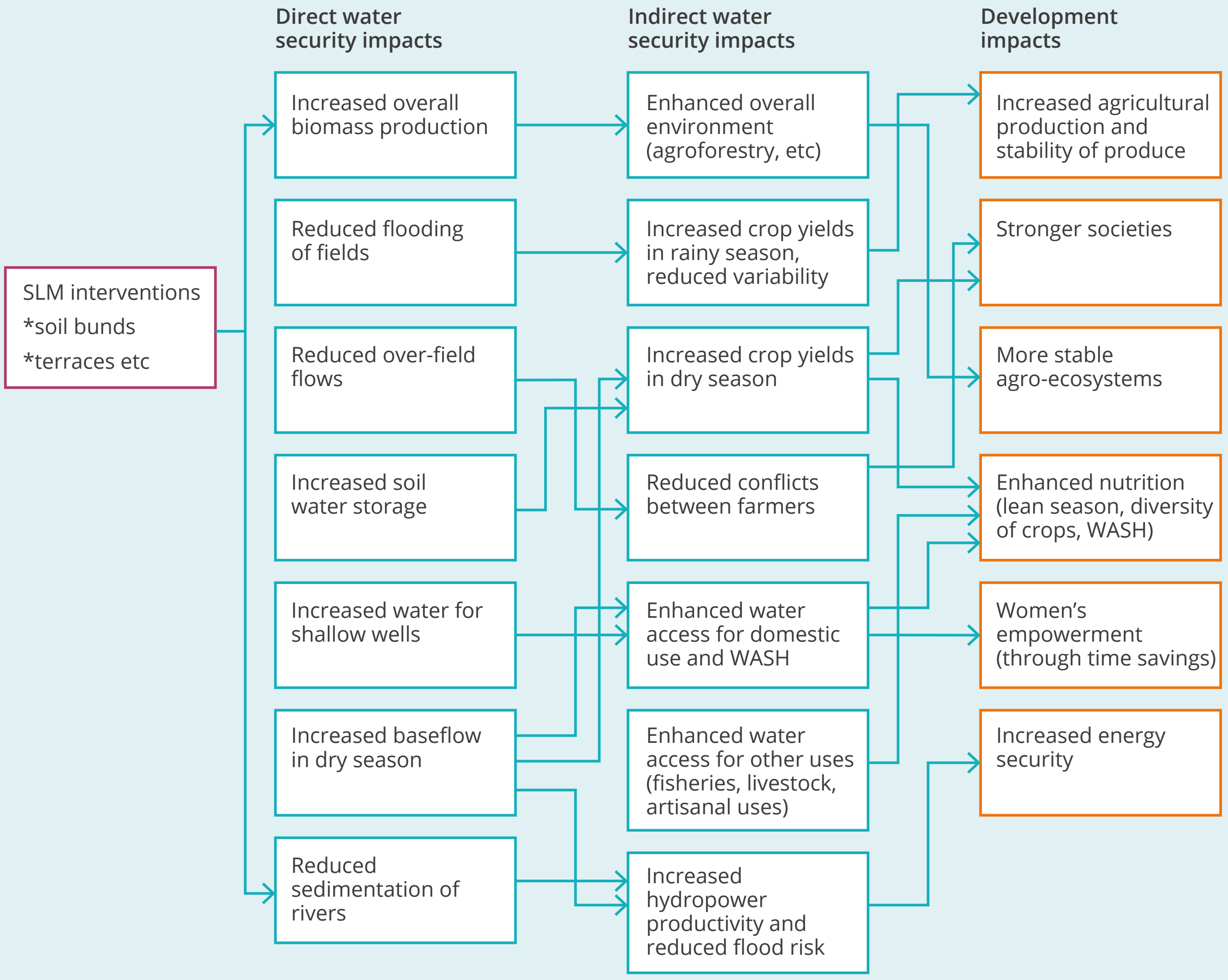
**With sustainable use, groundwater can improve the resilience of rural agricultural communities to seasonal changes in water availability**. In the north western highlands of Ethiopia, Gowing et al. (2020) demonstrated groundwater resources remained available even in the driest year observed. Analysis of aquifer recharge rates suggests that sustainable small-scale groundwater-fed irrigation is feasible for farmers in the region, allowing them to cultivate market oriented horticultural crops throughout the year. The household survey based study by Edward et al. (2019) illustrates the benefit of such groundwater use on the welfare of smallholders in Ethiopia, examining the impacts of sustainable land management (SLM) on water security and poverty in two watersheds in Amhara regional state. Results show that farmers that benefit from SLM programmes, including promotion of groundwater use for crop irrigation, experience higher yields for maize, mango and finger millet due to improved water availability and baseflow during the dry season. In addition, SLM contributes to reduced sedimentation in surface water bodies and enhances water availability for livestock.

### Research uptake and policy / practice impact

#### Improving water security through sustainable land management

Learnings from REACH research on SLM – a collaboration between WLRC, the University of Oxford, IFPRI and IRC – has directly shaped the scope of a new €16M project (2021-2025) funded by the Dutch and Ethiopian governments. The project is led by WLRC and implemented with SNV as a consortium member. The Integrated Landscape Management and WASH (ILMWA) project will support integrated land management and improve WASH in the Kunzila area – directly benefiting 35,000 and indirectly 65,000 people. As discussed above, SLM is expected to build farmers' and households' climate resilience by improving water availability for irrigation and livestock production, especially in the dry season, thus benefiting agricultural productivity and household income.

Figure 21: The direct and indirect linkages between Sustainable Land Management and elements of water security. Source: Edward et al. (2019).



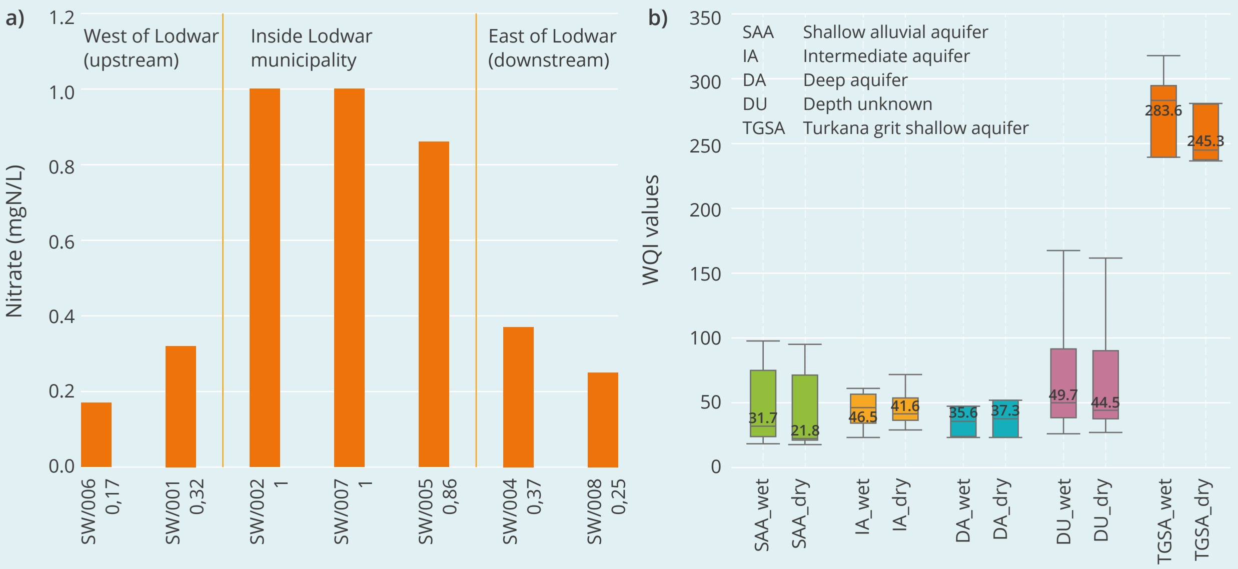
## Research uptake and policy / practice impact

### Influencing national initiatives on participatory water resource management

REACH-funded research designed and led by Newcastle University and IWMI has focused on developing a novel approach to water security and poverty research through participatory monitoring at community scale. Using data from citizen-scientists, the research has confirmed both the utility of citizen science hydrometeorological data and the availability of shallow groundwater to support small-scale irrigation. This work has resulted in the recognition of the value of citizen science and has influenced the design of two major national Ethiopian initiatives implemented by the Ministry of Agriculture and National Resources: The Resilient Landscape and Livelihood Project to restore degraded landscapes and build resilient livelihoods; and The Participatory Small-scale Irrigation Development Programme II to improve farmers' access to small scale irrigation and enhance climate-smart agriculture

**Unsustainable groundwater use can have long-term impacts, with small community drinking water supplies from shallow aquifers among the most vulnerable**. A coastal Kenyan study by Ramos et al. (2020) reveals that successive periods of lower than average rainfall will impact all water users in the region who are dependent on aquifer abstractions. Extended wet periods are necessary for aquifer levels to return to the initial state following a dry period. In addition to this, increased groundwater abstraction following a dry period would delay recovery of the aquifer system and increase the risk of saline intrusion inland. The study shows that it is important to design long-term groundwater management plans which protect vulnerable communities depending on shallow aquifers against the anticipated negative effects of climate change on groundwater systems.

**Figure 22: Nitrate levels and water quality indices in the Lodwar Alluvial Aquifer System, Kenya. The figures suggest that pollutants are flushed into the groundwater system during periods of high rainfall, via recharge water from the river and through piston recharge from the ground surface.**



a) Nitrate levels across the Turkwel river samples indicating elevated levels for the samples within the Lodwar Municipal, Kenya. b) Water quality indices of Lodwar boreholes and handpumps showing higher values during the wet season, implying poorer groundwater quality.

REACH research in the Lodwar Alluvial Aquifer System, Kenya, has provided timely scientific data and information for a strategic urban aquifer in an arid area (Tanui et al. 2020). The lack of reliable surface water supplies in the region due to low and erratic rainfall makes groundwater the primary source of water supplies for domestic, agricultural and industrial uses. However, young groundwater accessed via boreholes and handpumps along the riparian zones of the Turkwel River, are highly vulnerable to climate-induced risks and anthropogenic contamination, as evidenced by observations of increasing nitrate concentrations during the wet season. Source: REACH (2021).

Figure 23: Groundwater hydrocensus that was conducted in Lodwar, Kenya, and its environs in May and June 2018, featuring Florence Tanui, REACH Kenya Team. Photo: Bonface Wanguba.

Research uptake and policy / practice impact

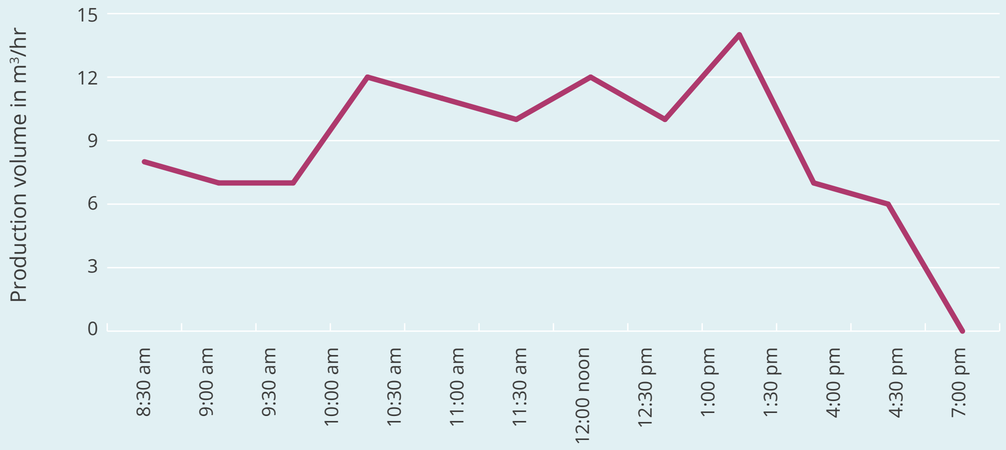
**Protecting groundwater to build climate resilience in Turkana, Kenya**

In North-West Kenya, the Lodwar Alluvial Aquifer System (LAAS) is a strategic aquifer supporting the rapidly growing Lodwar Municipality. REACH has been advancing understanding of the aquifer's key features and of the pressures it faces, demonstrating that sound scientific evidence is required to sustainably manage the groundwater resources in the area and to meet national and international goals for sustainable development.

These findings have supported Turkana County policy and practice, including the Turkana County Climate Change Policy, the Turkana County Integrated Development Plan 2018/2022 and the Annual Development Plan 2020/2021. These policies are promoting aquifer protection to ensure the growing water demand can be resilient to climate risks and reduce vulnerability for close to one million people who rely on groundwater in the county.

**The impacts of weather on groundwater access are also mediated by impacts on access to energy**. In their analysis of the water stressed urban area, Lodwar, Kenya, Maxwell et al. (2020) show that water availability fluctuates intra-annually, with supply from the water utility LOWASCO peaking in May during the wet season. However, water availability also depends on the energy available for groundwater pumping, with 80% of the boreholes in the multi-source groundwater system relying on a hybrid-energy pumping system of solar and grid power. Weather factors such as cloud cover can cause erratic pumping rates and therefore impact water supply, so careful design of the system's pumping operations is crucial. In their study of water supply in Bangladesh's Sahas union of Dumuria upazila, Hoque et al. (2021) also report that cloudy and foggy weather conditions can limit groundwater supply in systems using solar-powered pumps. Overall, design and management of water supply infrastructure needs to consider energy security to guarantee consistent water supply in all seasons.

**Figure 24: Daily variation of borehole production ($m^3$/hr) in a Lodwar Water Supply and Sanitation borehole, Kenya. The figure indicates that water availability depends on the energy source used in pumping, with erratic pumping observed in boreholes using solar energy. Source: Maxwell et al. (2020).**



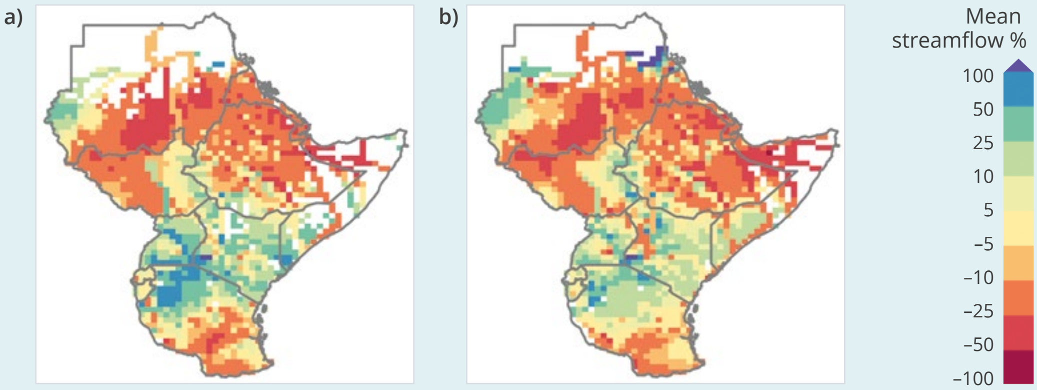
## c. Climate change, alongside other stressors, will have severe implications for future water security if unmanaged

**Climate change projections show changes to the water cycle that require significant adaptation to prevent impacts on water security**. However, data is poor, nationally appropriate climate models are lacking, and policy makers and water managers should be aware of modelling uncertainties when planning for climate change.

**In Ethiopia, the impact on future water availability in the country could affect operation of existing and proposed hydroelectric infrastructure in the Awash, Ghibe and Nile river basins**. Using high resolution climate projections from the EC-EARTH3-HR climate models and the distributed LISFLOOD rainfall-runoff model, Hirpa et al. (2019) produce an ensemble of future streamflow scenarios for seven Greater Horn of Africa river basins.

Comparison between the projected future streamflow in two 21st Century periods (2030-2059; 2070-2099) and a baseline period (1976-2005) reveals varying changes in streamflow magnitude (i.e. the total amount of flow at any given time), variability and trend across the study region, with the magnitude of changes intensifying towards the end of the 21st Century. In Ethiopia, the long-term streamflow ensemble mean is projected to decrease by 10% to 25%, whilst high flows (i.e. when the projected flow exceeds the baseline Q5 flow) see reductions of up to 50%. In the equatorial river basins, an increase of more than 10% is projected for the ensemble mean flow, and high flows are anticipated to increase by up to 50%.

Figure 25: Projected change in streamflow in the 2080s across the Greater Horn of Africa.



a) Percentage change in projected long-term ensemble mean streamflow (averaged over six CMIP5 model simulations) for the 2080s compared to the baseline period (1976–2005). Areas with Q values less than 5 $m^3$/s (white) are filtered out. The figure indicates that mean streamflow in parts of the equatorial region may increase by up to 25%, whilst streamflow in the southern and western parts of the Greater Horn of Africa region may see decreases of up to 25%. In Ethiopia, mean streamflow could experience a –10% to 5% change. b) Projected percentage changes in ensemble mean streamflow in the 2080s for the summer season (JJAS). Overall, simulations show a large flow decrease for Blue Nile, Upper Awash, Ghibe and Baro river basins compared to the baseline period. Source: Hirpa et al. (2019).

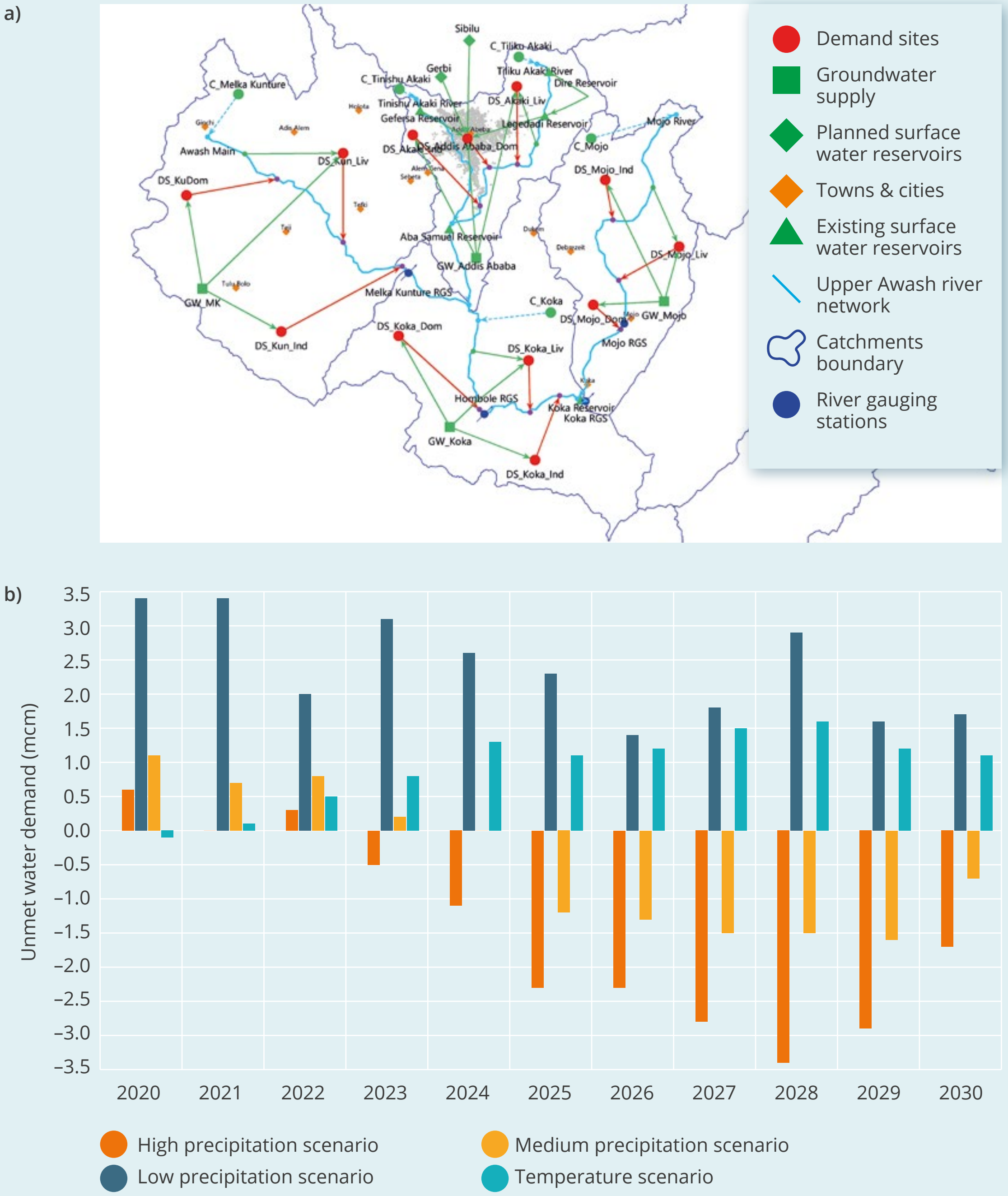
**Increased demand from population and irrigation growth will aggravate the impact of droughts triggered by strong El Niño–Southern Oscillation events in Sub-Saharan Africa**. Hirpa et al. (2018) adopt a decision-scaling approach to model the response of the Turkwel river basin (Kenya) water system to future stressors. Using CMIP5 climate model projections and water demand scenarios, the authors demonstrate the potential for unmet water demand under different development pathways. Even under significant climate model uncertainty, development pathways which increased crop irrigation always resulted in an increased probability of experiencing severe water shortage risks. The results indicate that, whilst climate is an important driver of water insecurity, other stressors such as population growth and irrigation policy will also have severe implications for water users in the basin. The work by Hirpa et al. (2018) demonstrates that inclusion of climate resilience analysis in development planning and economic policy can help to manage competing climate and anthropogenic stressors in the future.

Figure 26: REACH research finds that without adaptation the Awash river basin, Ethiopia, which already frequently experiences climate extremes, will become seriously water stressed by the mid-21st Century. Photo credit: Alice Chautard

**In Ethiopia's Awash basin, water shortages are likely to increase as a consequence of several factors, including climate change induced changes in streamflow**. In their analysis of future water availability in the upper Awash basin, Birhanu et al. (2021) find that domestic unmet demand is likely to increase by 2030 as a consequence of population growth, water supply infrastructure leakage, increased temperature and decreased precipitation.

Simulations using the dynamically linked WEAP-MODFLOW model and climate change projections indicate that increased groundwater abstraction could help to alleviate future water stress, but only if it is supported by careful management of surface water schemes (Birhanu et al. 2021). In other parts of the Awash basin, Taye et al. (2018) show similar increases in water deficiency due to projected increases in temperature and decreases in precipitation. Using output from three climate models from CMIP5, the authors identify decreases in water availability for most months of the year except February and March, with the largest deficits observed between April and June. The findings indicate that without adaptation, the basin will become seriously water stressed by the mid-21st Century. An enhanced water management strategy which builds equitable climate resilience for all water users in the basin is needed to manage the threat of climate change.

**Figure 27: Projected water demand in the upper Awash basin, Ethiopia.**



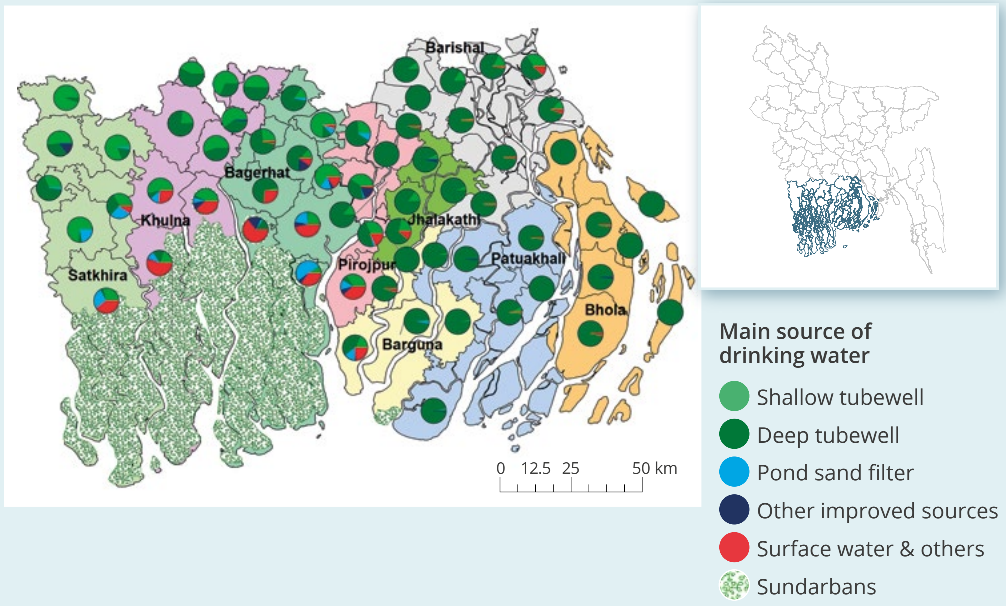
a) WEAP-MODFLOW model schematic for the upper Awash basin, with demands, supply nodes, transmission links and return flows. b) Unmet water demand variation due different precipitation and temperature scenarios. The figure shows the difference between unmet domestic water demand due to climate change scenarios and the reference condition. The results indicate that more extreme climate scenarios increase unmet domestic demand, with decreases of 6% to monthly domestic water demand coverage under the low precipitation scenario, and decreases of 1.5% under the high temperature scenario. Source: Birhanu et al. (2021).

**In Bangladesh, changing rainfall patterns under climate change may impact on flooding in the monsoon, the availability of freshwater flow during the dry season, and the availability of fresh water during the agricultural calendar**. Climate projections show increasing temperatures over Bangladesh during the 21st Century, increasing annual rainfall by the end of the century, a decrease in light to moderate rainfall events (i.e., an increase in number of dry days), an increase in heavy rainfall events, and a large increase in very heavy events (Caesar et al. 2015; GED, 2018; Hasan et al. 2018). Further projections indicate more variable and erratic rainfall pattern and reduction of rainfall in the greater southwest and eastern hilly region (GED, 2018). Floods will likely become more frequent, and their magnitude will become more severe (Mohammed et al. 2017; Mohammed et al. 2018; Whitehead et al. 2015).

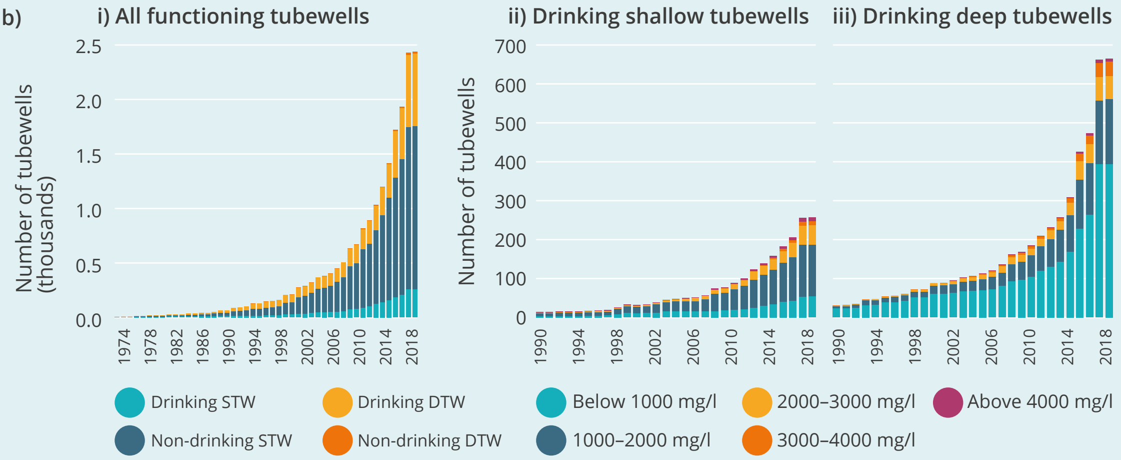
**In the coastal zone of Bangladesh, changing seasonal distribution of flows and/or reduction of dry season freshwater flow may reinforce several other existing stresses**. With sea level rise and possible reduction of freshwater flow, river salinity would further increase in the greater southwest coastal area, with the highest increase to be seen in the south-central region (Akter et al. 2019). Furthermore, increased river salinity has implications for groundwater salinity, soil salinity and irrigated agriculture (Akhter and Salehin, 2021a, b). Soil salinity is strongly controlled by river salinity in most saline prone areas, with depth of groundwater table also playing a role in others (Salehin et al. 2018). Investigations indicate that irrigation water salinity greater than 4 ppt and 5 ppt may lead to 25% and 50% reduction in crop yield, respectively (Clarke et al. 2015; Salehin et al. 2018). To manage future risks to surface and groundwater supplies from increased salinity, future adaptation interventions could target a reduction of river salinity via increase in freshwater flow.

Figure 28: Research shows that salinity in coastal groundwater is a major threat to safe drinking water access in coastal Bangladesh.

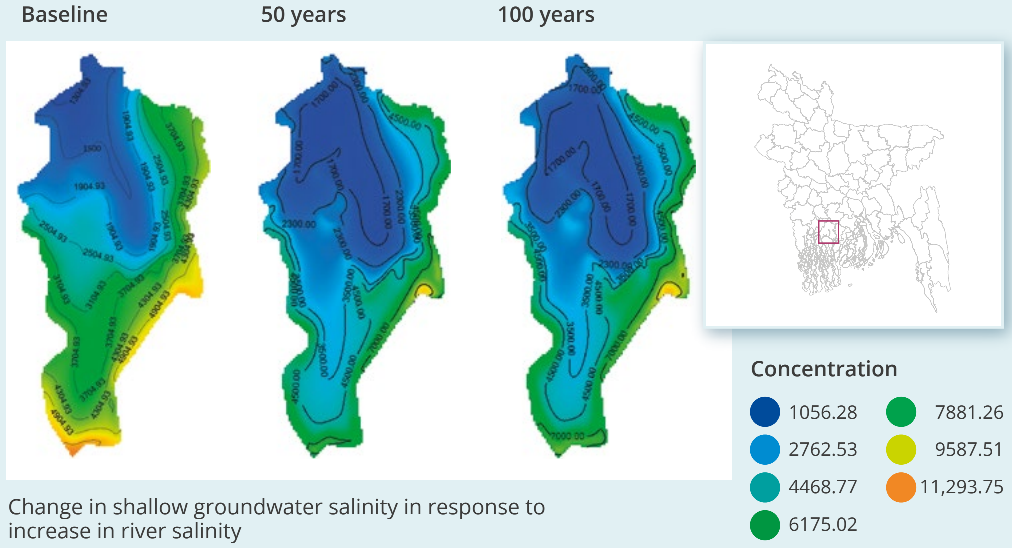
a)



b)



c)



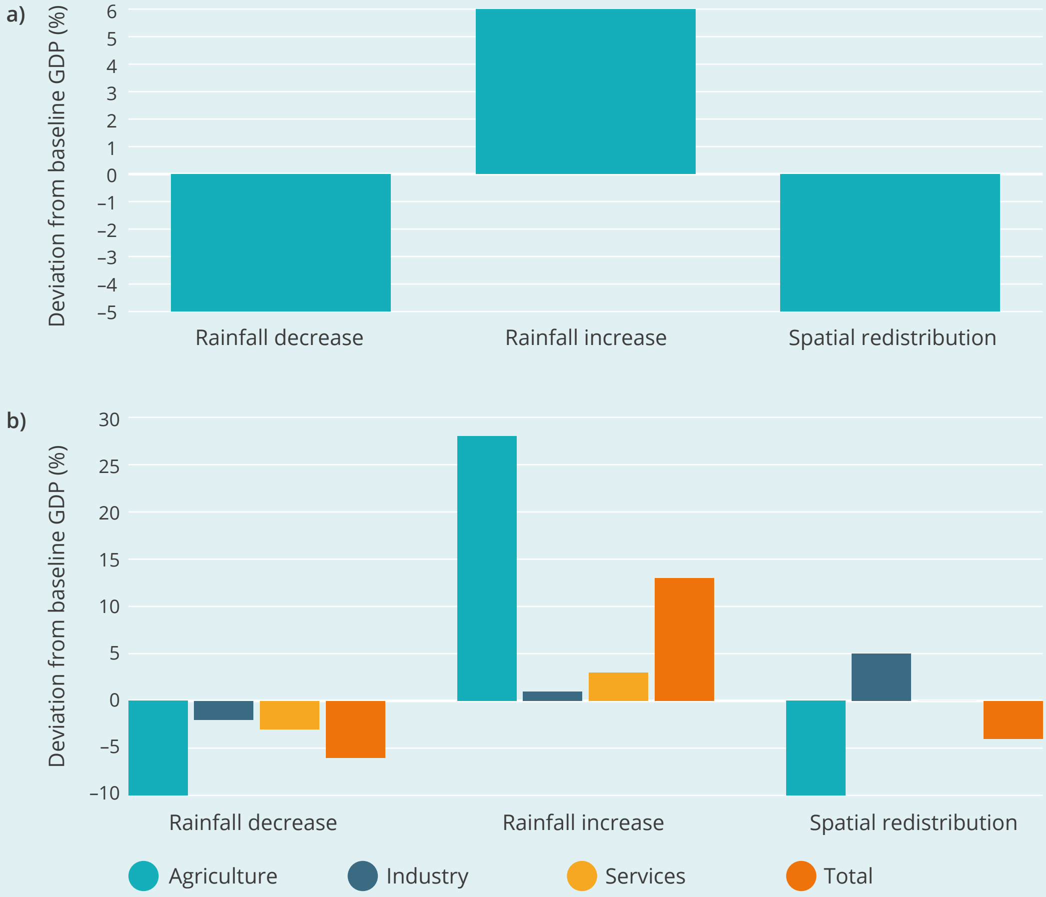
Change in shallow groundwater salinity in response to increase in river salinity

a) Main drinking water sources in the southwest coastal zone of Bangladesh. b) Growth of tubewells since early 1970s: (i) growth of all functioning tubewells; (i) growth of drinking shallow tubewells and associated salinity levels; (iii) growth of drinking deep tubewells and associated salinity levels. c) Potential risk of increased salinisation of shallow aquifer due to increase in river salinity. Source: Akhter et al. (2021a, in review) and Akhter and Salehin (2021b, draft).

Tubewells have been the dominant mechanism for drinking water supply; the choice of which (i.e., between shallow tubewells and deep tubewells) depends on availability of aquifers and water quality, and the accessibility of alternative technologies which have emerged in the freshwater stressed areas (Akhter et al. 2021a). An extensive field investigation by REACH in the coastal observatory, Polder 29, reveals exponential growth of tubewells. Yet, this has not resulted in improved access to safe water as salinity concentrations in roughly half of the drinking tubewells exceed the acceptable limit, with nearly two-fifths (41%) of all drinking deep tubewells and over two-thirds (79%) of shallow tubewells used for drinking exhibiting high levels (Akhter et al. 2021a). People are unknowingly drinking saline water in some places, while in others they are compelled to do so due to lack of alternatives. Nationally and internationally, the threat of increasing salinity in drinking water is not being tracked in water quality monitoring programmes such as MICS.

**Changes in climate and hydrological factors will affect sectors of the economy that are more exposed to water risk**. In Ethiopia’s Awash basin, basin-wide Gross Domestic Product (GDP) could drop by 5% under a rainfall decrease scenario compared to the current GDP, whilst increases in rainfall could lead to GDP increases in the range of 5 to 10%. The REACH research by Borgomeo et al. (2018) presents a novel method to analyse these multi-sectoral and distributional economic impacts of rainfall shocks on GDP, using disaggregated data on crop production to estimate the direct impacts of extreme rainfall events on agricultural productivity in the basin and a Computable General Equilibrium model to simulate economy wide impacts of climate shocks. Three rainfall scenarios from CMIP5 are used to explore the impact of changes in rainfall in the basin, with the authors finding that the basin’s economy and expanding agricultural sector are highly vulnerable to impacts of rainfall shocks. Sector-by-sector analysis reveals that rainfall decreases could lead to losses of up to 10% in the agricultural sector, and decreases of around 3% in the service and industrial sectors. All sectors benefit from rainfall increase scenarios. The granular approach builds on conventional assessments of economic impacts of hydro-climatic variables on economies (e.g. Sadoff et al. 2015), focusing on the direct impact of rainfall shocks on crop production and the indirect distributional impacts on households. The research has widespread implications for policy makers, helping to improve understanding of current vulnerabilities to climatic factors, identify regions that are the most vulnerable to future changes in climate, and inform adaptation strategies that will help to build the climate resilience of water systems in the basin.

Figure 29: Rainfall impacts in the Awash basin, Ethiopia.



a) Economy wide impacts of three rainfall scenarios (decrease, increase, spatial redistribution) on the GDP of the Awash basin, relative to the baseline GDP (2011-2015). The figure suggests that the economy of the basin is vulnerable to changing rainfall patterns, with all scenarios apart from the rainfall increase scenario causing decreases in GDP. b) Sectoral output in the Awash basin relative to the baseline GDP (2011-2015) under three rainfall scenarios. Source: Borgomeo et al (2018).

# 4. Climate information must be accurate, locally adapted and accessible to water managers

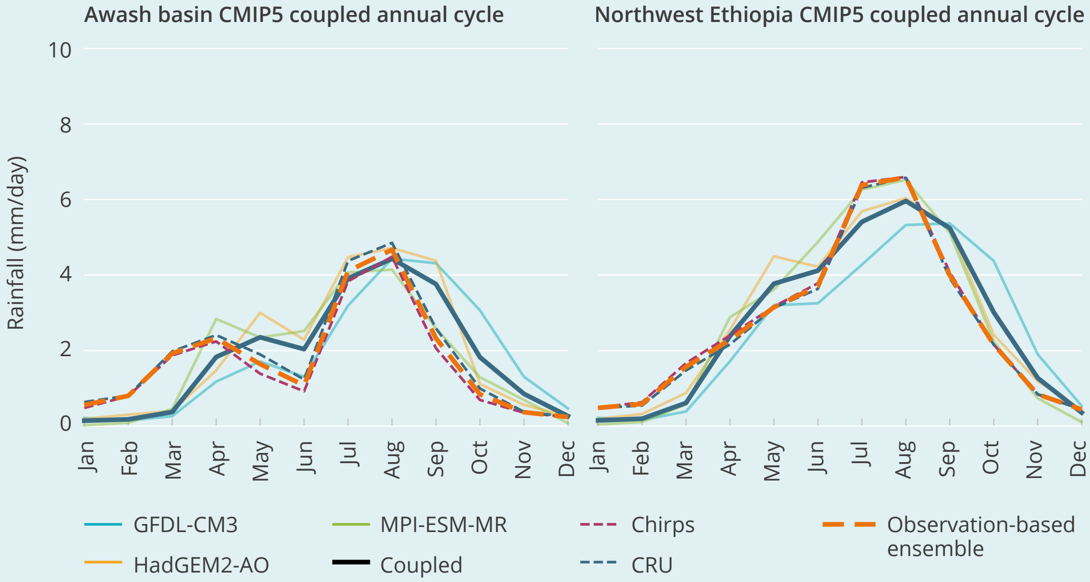
## a. Climate information needs to accurately represent regional climate

**Climate models can reasonably capture large-scale trends in the global climate, but there is lower confidence in their simulation of rainfall and regional climates, particularly in Sub-Saharan Africa.** This is partly because they are not designed or evaluated with the region in mind, and this has been compounded by the uneven quality of the regional observational record. For example, Hirpa et al. (2019) show that the skill of modelled streamflow, that is the model's ability to reproduce important features of the climate, is poor in the equatorial region of Sub-Saharan Africa, with half of the climate model ensemble members missing the equatorial bimodal rainfall season. The results indicate that climate model skill for some countries must improve before being used to inform climate adaptation policies. Where possible, policy makers and water managers should use other sources of climate information to complement modelling results from nationally appropriate, high skilled models.

**Methodological advancements and modelling results from the REACH multi-phase model evaluation study provide guidance for tailoring future climate impact assessments for regional needs**. By investigating the skill and ability of climate models, we are able to improve understanding of important climate processes over East Africa and therefore provide more robust global estimates of important climate processes which influence surface water and groundwater supplies.

**While ensemble models are useful for understanding global climate, individual models perform better for specific geographies**. As part of a multi-phase model evaluation study, Dyer et al. (2020) evaluate the ability of Coupled Model Intercomparison Project Phase 5 (CMIP5) models to reproduce historic precipitation and temperature in Ethiopia. A range of performance metrics (seasonal biases, the annual cycle, trends and variability) are used to identify models within the CMIP ensemble with the most skill. Analysis identifies three models which may be good candidates to use in future climate impact studies: HadGEM2-AO, GFDL-CM3, and MPI-ESM-MR. However, even this subset of models struggles to capture the start and end of the rainy seasons. This indicates that projections are less reliable in certain months, hampering adaptation decision-making during key crop producing months in Ethiopia and the Awash basin.

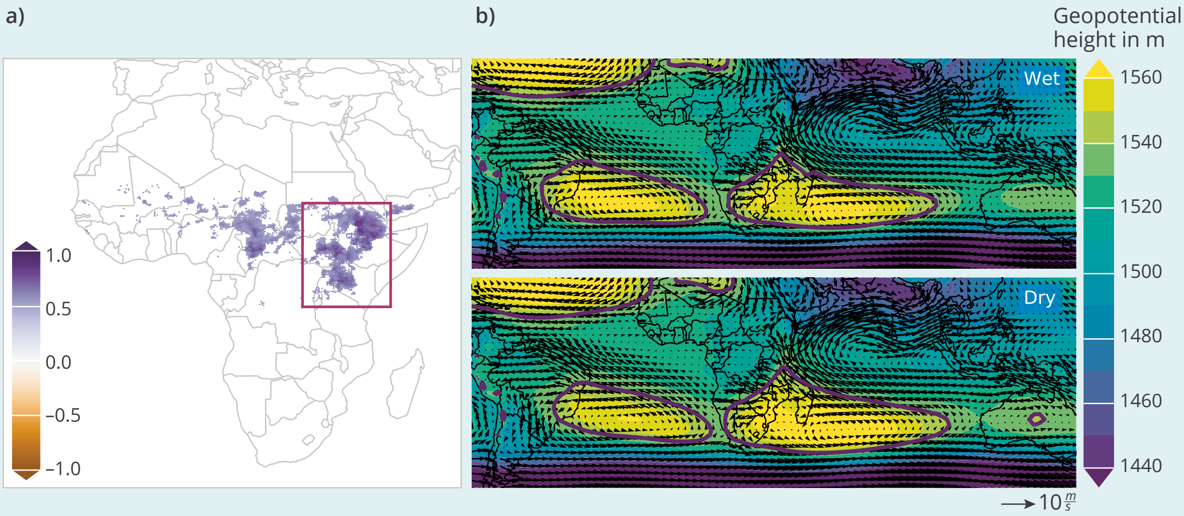
Figure 30: Rainfall in the Awash basin and northwest Ethiopia.



Annual rainfall cycles (mm/day) for coupled simulation models selected as a potential reduced ensemble for the Awash basin and northwest Ethiopia. Observational climatologies are shown in dashed lines, while individual model climatologies are shown as thin lines. The ensemble average is shown as a thick solid line. All rainfall was masked for the period 1981-2005. Models are selected based on their ability to reproduce the annual rainfall cycle, trends, variability and bias. The figure shows that biases remain in the reduced ensemble, highlighting the need for further process-based analysis to understand why the models struggle to reproduce the climatology in some months. Source: Dyer et el. (2020).

**Global climate teleconnections are a useful proxy for forecasting and risk planning**. The study by Dyer et al. (2021a, in review) evaluates the ability of CMIP5 and CMIP6 models to capture the Atlantic and Mascarene high pressure systems in the Atlantic and Indian Oceans, respectively. The authors explore the influence of these highs on rainfall over the Greater Horn of Africa in the July to September season. Results show that the relative strength of these two remote circulations is important: (i) increased Atlantic circulation results in an increase in rainfall over the Greater Horn of Africa, and (ii) increased Mascarene circulation is associated with decreased rainfall. Whilst model biases persist in the most recent CMIP6 ensemble, a significant relationship exists between changes in Greater Horn of Africa rainfall and the Atlantic-Mascarene circulation metric. There is an improvement in the relationship between rainfall and local features like the Turkana jet and central African westerlies that mediate the remote influence of the Atlantic High and Mascarene High. HadGEM2-AO, GFDL-CM3, and MPI-ESM-MR are also shown to be relatively skilful models, enhancing our confidence in their ability to represent important features for the Ethiopian climate.

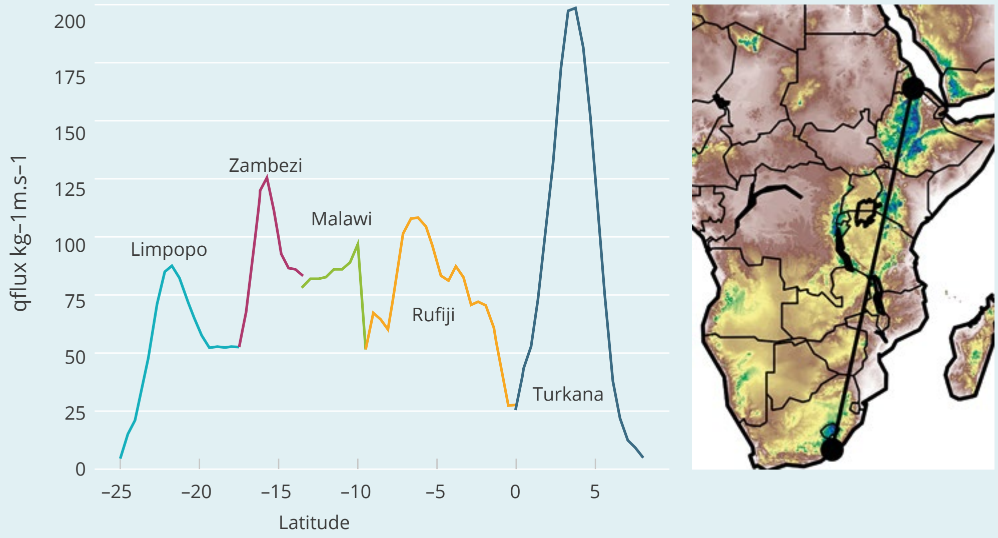
Figure 31: Influence of Atlantic and Mascarene highs on rainfall in the Greater Horn of Africa.



a) Masked region (red box) in the interior of Greater Horn of Africa used by Dyer et al. (2021a, in review) to examine the influence of the Mascarene and Atlantic highs on July-September rainfall. b) Wet and dry season circulation in the lower-troposphere in July-September. The figures depict the 850 hPa geopotential height (m), with a 1540m geopotential height contour overlaid with 850 hPa winds (m/s) for the wet and dry composites of masked rainfall. The 1540m geopotential height contour shows that the spatial extent of the Mascarene High is smaller in the wet composite than the dry composite. The opposite is true for the Atlantic High. Source: Dyer et al. (2021a, in review).

**Topography has a strong impact on the local and regional climate that needs to be considered to improve the reliability of forecasts and projections**. In Sub-Saharan Africa, model simulations and ground observations indicate that the topographic effect on water availability is large. Munday et al. (2021) investigated the role of African Low-Level Jets in transporting water vapour from the Indian Ocean to Central Africa via the East African Rift system. Results from the study identify a robust relationship between strengthened Low-Level Jets and drought in East Africa, and illustrate the importance of easterly moisture sources for tropical African convection. The research also shows that poor simulation of Low-Level Jets in global climate models can cause biases in rainfall climatology across the African continent, with results demonstrating the importance of using high resolution model simulations (<60km grid lengths) containing topographical features in analyses of rainfall climatology. The ongoing series of model experiments by Munday et al. (2021, draft) builds on this work, exploring the impact of river valleys in Kenya and East Africa on drought. The preliminary results suggest that the correct simulation of the river valleys in contemporary climate models is required if they are to provide a realistic view of climate change over the next century.

Figure 32: Transport of water vapour along the East African Rift system.



The relative contribution of rainfall by the five Low-Level Jets associated with transport of water vapour in the valleys along the East African Rift System. The jets are significant physical phenomenon with multiple implications for weather, climate and water availability. In East Africa water vapour transport is dominated by the Turkana Jet, which accounts for close to 30% of the total water vapour transport from eastern to central Africa across the line shown in the right figure. Adapted from: Munday et al. (2021).

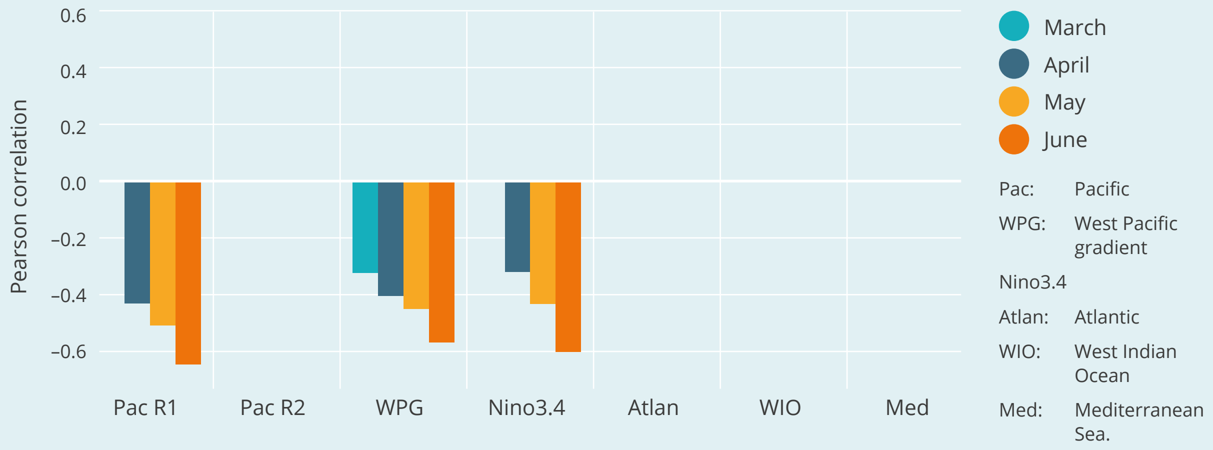
**Sub-seasonal analyses are critical for understanding regional climate**. By looking at extreme wet and dry seasons, Dyer and Washington (2021) showed that the most striking variability in the East African long rains is during the onset period. The authors identify regional climate processes associated with the Kenyan long rains' onset, peak and cessation periods to create a set of sub-seasonal diagnostics for model evaluation. In particular, the strength of easterlies over central Africa seem to influence rainfall with stronger easterlies in the mid-troposphere being associated with lower rainfall. This is consistent with results shown by Munday et al. (2021), highlighting the importance of moisture flow into the continent in the lower atmosphere. These diagnostics are now being applied to the CMIP6 ensemble to understand model biases and future projections in the East African long rains season.

Likewise, Taye et al. (2021) use sub-seasonal analysis to address the influence of large-scale climatic drivers, such as the East African Low-Level Jet, on patterns of rainfall over Ethiopia. Using correlation analysis, the authors establish a strong relationship between sea surface temperatures (SSTs) observed in March to May and rainfall in Ethiopia's main July–September (JAS, kiremt) rainy season. Using composite analysis, they show that drier kiremt seasons are associated with strong ENSO events and a positive Indian Ocean Dipole. Going beyond these well-known climate drivers the study uses objective regionalisation to identify different SSTs that affect rainfall in the upper and lower Awash.

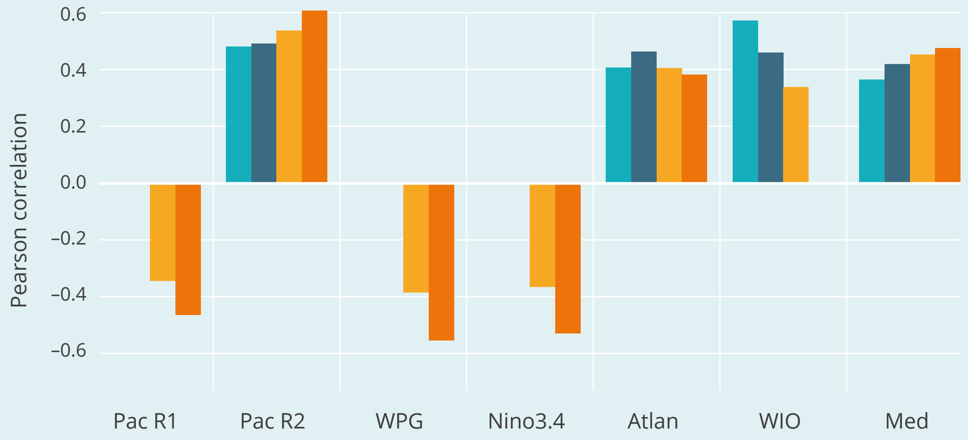
The additional potential predictability from the Atlantic and western Indian Oceans for the lower Awash indicates that these regionally specific metrics could add value to seasonal forecasting tools and assessments. Monitoring of the drivers identified by Taye et al. (2021) could inform seasonal management decisions at local and regional scales in Ethiopia and improve adaptation to potential weather-related extremes.

**Figure 33: Correlation of sea surface temperatures in seven global regions and rainfall in the Awash basin, Ethiopia.**

a) JAS Upper Awash correlations

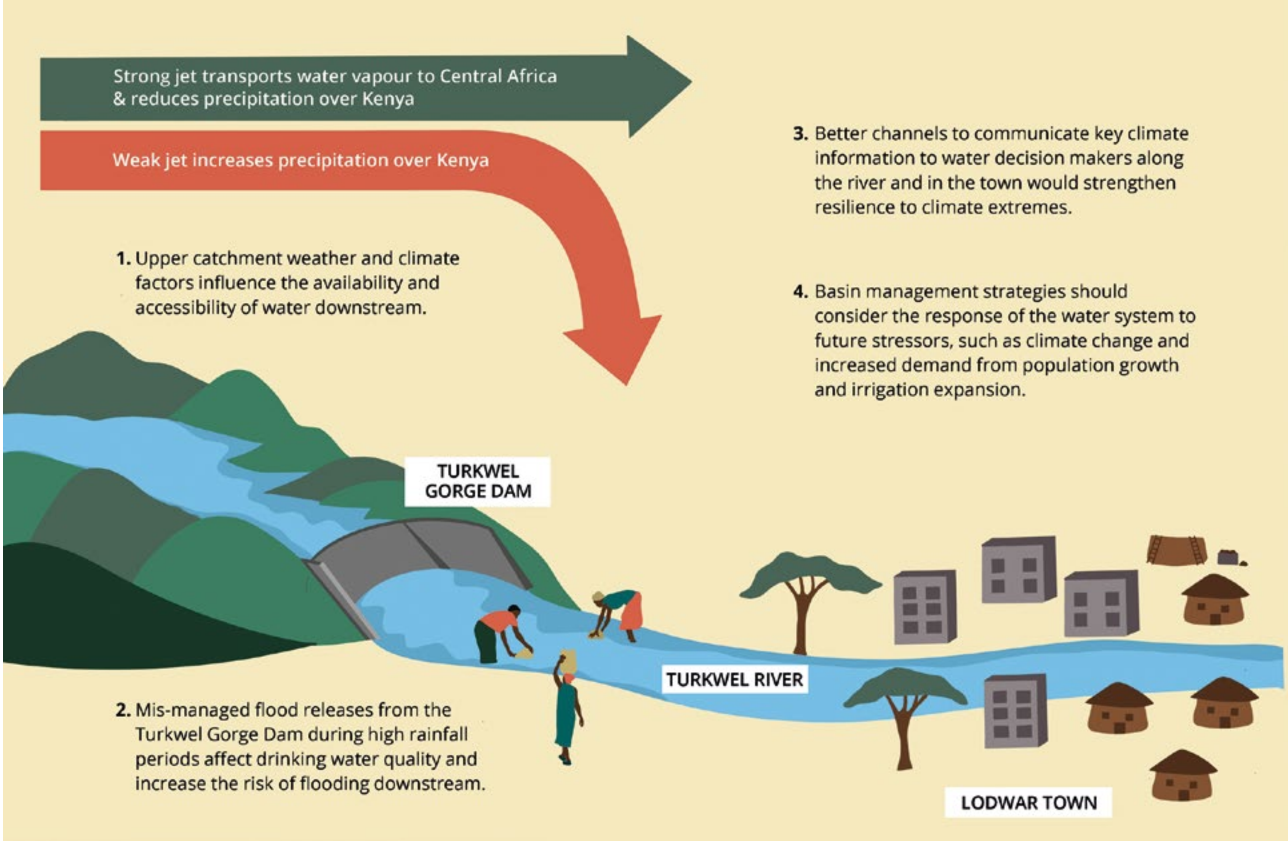


b) JAS Lower Awash correlations



Correlations of the upper a) and lower b) Awash basin June-August-September (JAS) rainfall with the preceding monthly sea surface temperatures (SSTs) in seven Global SST regions. Correlations are only shown for $p < 0.1$. The figures indicate that JAS rainfall in the upper Awash is negatively correlated with most of the Pacific Ocean SST region indicators, whilst the lower Awash has positive and negative correlations with SST. Source: Taye et al. (2021).

Figure 34: Turkwel Low Level Jet funnelled through the Turkana Channel in East Africa



## b. Climate information needs to be tailored to the context of the end user

**Ensuring decision-makers have access to appropriate climate information requires consideration of user needs and skill, but also to political aspects of information uptake**. For climate information to be useful, communication between information providers and users must be multidirectional so producers understand the needs and constraints of users, and users understand and are comfortable with the strengths and limitations of the products available to them.

**Political dimensions of climate information use are important as its incorporation into decision-making inherently involves an element of trust in the information and its producers** (Grasham et al. 2021, draft). Decision-makers take on liability risks when they use climate information for policy and practice. This can lead to pressure to restrict use to specific sanctioned products (e.g. national met service seasonal forecasts) which may limit the breadth of information available, either in representing the scientific understanding of climate in terms of teleconnections or topographical impacts or in representing the products needed by different types of water managers, or it can create a reluctance to use climate information altogether. In Kenya, including community leaders and providing space for indigenous knowledge has helped build credibility for the process of producing and disseminating weather-based advisories (Haines et al. 2017).

**Climate information needs to be targeted at user needs**. In northwest Kenya, Munday et al. (2020) report that sustained periods of high rainfall has caused reservoir levels in the Turkwel Gorge Dam to rise above historically observed levels. Overflow of the dam could cause surface water flooding and compromise drinking water quality for many settlements located downstream of the dam. In this instance, climate information on short-term forecasts and the increased likelihood of precipitation extremes could be used to inform better operational guidelines for the Turkwel Gorge Dam to address risks associated with the changing climate.

Figure 35: REACH is leading a fieldwork campaign in northwest Kenya to measure for the very first time the full diurnal cycle of the Turkana Jet, which as established is a critical player in the regional East African climate system. The data ensuing from the campaign will lend new insights into the old mystery of recurring East African drought, and will provide a much-needed benchmark against which to test climate, seasonal and weather forecast models. Photo: Callum Munday.

Similarly, drought managers have specific needs – for diverse, basin-wide climate information. The research presented by Haines et al. (2017) investigates the institutions involved in water decision-making in Lodwar town, Kenya, with a focus on their access to and use of weather and climate information. Individuals from a variety of climate and water sector institutions were interviewed about water security risks in the basin, including hydroclimatic variability, climate shocks, political decentralisation and competing priorities of water use. Drought is identified by interviewees as a key challenge to secure water supply, although definitions of what constituted as a drought event varied between participants. Numerous respondents stated that observations of rainfall and temperature from the Turkana region and border areas were important for drought planning, but that the availability and distribution of this information throughout the basin was insufficient.

Research uptake and policy / practice impact

**REACH Partnership with Kenya's National Drought Management Authority**

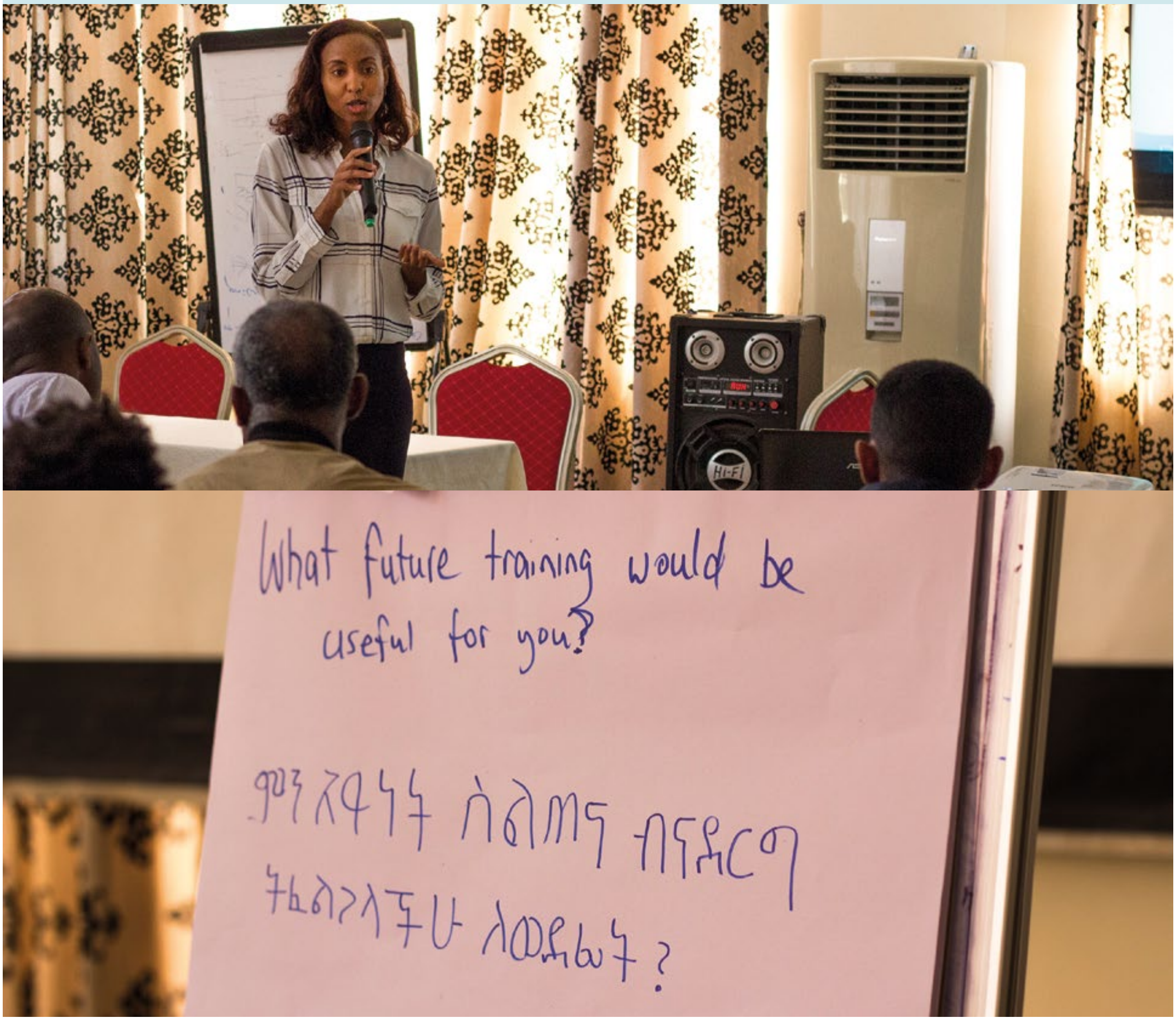
The REACH Kenya Programme has maintained its partnerships with Kenya's National Drought Management Authority (NDMA). REACH is a member of the Turkana County Steering Group which is coordinated by the NDMA to discuss development issues and programs at the county level to address impacts of drought. The REACH programme has been using this platform to provide updates on water security from groundwater studies, socio-economic studies, and infrastructural analysis in the Turkana region. Work by REACH has been important in strengthening water sector planning and environmental policy development in Turkana County.

The main partnership between NDMA (Turkana Office) and the REACH programme has been information exchange. REACH has shared results from studies implemented in Turkana to help NDMA in drought response, planning, and mitigation. The NDMA has been actively supporting REACH research activities by sharing early warning drought bulletins, food and nutrition security reports, flood reports, and providing key information whenever requested during field studies.

**Co-production of climate information with users is needed to tailor outputs to support improved decision making in water management**. Poor alignment between those who produce and use climate information can present a barrier to uptake. The FCFA FRACTAL project (Bharwani et al. 2019) found that meteorologists can overestimate policy makers' grasp of climate science. Whereas, a study by Mwangi et al. (2020) showed that farmers have a better understanding of forecast uncertainty than meteorologists expected and that they would prefer information about uncertainty to help them make better decisions. Engagement with stakeholders in Ethiopia has identified a lack of clarity on how forecasts are created and how they can be applied to suit the needs of the basin development office, this includes a lack of regionally disaggregated information that corresponds with their basin.

Ongoing work by Dyer et al. (2021b, draft) maps climate information flows in the Awash basin, Ethiopia, with an aim to understand (i) how climate information is used in the water sector, and (ii) how it is created and transformed. The research investigates barriers to climate information use for decision making, along with good practices that can be scaled up. This study focuses on seasonal-forecast information which is more widely available and actively disseminated than long-term projections of climate change. However, the goal is to take lessons about challenges or successes in communicating seasonal forecasts within the water sector that can then be applied to future efforts to create and disseminate information about long-term climate change.

Figure 36: Dr Meron Teferi Taye presents REACH results to members of the Awash Basin Development Office in Adama, Ethiopia, in November 2018. Photos: Alice Chautard.



## Research uptake and policy / practice impact

### Improvement of WEAP model for decision making in Ethiopia's Awash basin

The Awash Basin Development Office (AwBDO) has a WEAP model for water allocation in the basin developed for their planning purposes. However, access to good quality real-time data on flow or rainfall across the basin is lacking, and modelling capabilities are restricted with an underdeveloped water allocation model and no pollution models.

Partnerships with AwBDO and Ministry of Water, Irrigation and Electricity (MoWIE) have led to the development and uptake of a refined model of water allocation, which is expected to improve water security for the 18.3 million people who live in the basin, as well as for irrigation and industry. The model allows the evaluation of water allocation plans for different future scenarios, to ensure a more resilient basin to climate variability and extremes.

# 5. Recommendations: Improving water security to build climate resilience

REACH research reveals that climate and water risks are experienced unequally, with complex physical, political, social, behavioural and environmental mechanisms influencing the water security of urban, peri-urban and rural communities. Because of this, building climate resilience in water systems for vulnerable communities relies on a multitude of factors. This section outlines three recommendations to improve water security of vulnerable water systems and thereby increase resilience to existing and future climate risks.

## a. More accurate and granular analysis of climate risk is needed to make climate information relevant to specific users

**Water security is underpinned by understanding and translating climate risks into effective and actionable information for specific users**. Whilst considerable progress has been made in this area, we must continue developing modelling tools and monitoring systems that help to improve understanding of important climate processes and threats from climate change. Better information will be available for decision-making about water system operation and management if research: (i) targets inequalities in access to existing high quality climate information, and (ii) creates climate information products that cover a wide range of temporal and spatial scales, and respond to regional water-related climate risks. As Hirpa et al. (2019) establish, climate change driven decreases in extreme high flows in the Greater Horn of Africa may result in a potential reduction in groundwater recharge. If water use practices continue as normal without regard for the changing climate, groundwater sources will be depleted and livelihoods of agricultural and pastoral communities reliant on groundwater supplies will be exposed to higher levels of water insecurity. Better information on rates of aquifer recharge will help to inform sustainable groundwater use in water insecure communities and therefore safeguard existing water supplies.

**Reliable climate information from robustly evaluated climate models will help to build resilience to hazards of anthropogenic climate change**. For example, ensembles of future climate scenarios can be used alongside water resource systems models to (i) understand evolving water-related risks, (ii) examine portfolios of adaptation options, and (iii) identify and implement adaptation pathways that equitably manage water-related risks. Many REACH projects have demonstrated the utility of scenario-based analyses when planning for climate resilience, including Bussi et al. (2016), Ramos et al. (2020), Birhanu et al. (2021), Taye et al. (2018) and Borgomeo et al. (2018). As an alternative to planning for a limited number of possible futures and risking maladaptation, water planners can use a scenario ensemble approach to identify adaptation portfolios that are robust to a wide range of future trajectories. Water resource systems models, such as the Water Evaluation and Planning System (WEAP), also enable analysis of future risks to different actors in a basin, and therefore help to equitably manage distributional water-related risks.

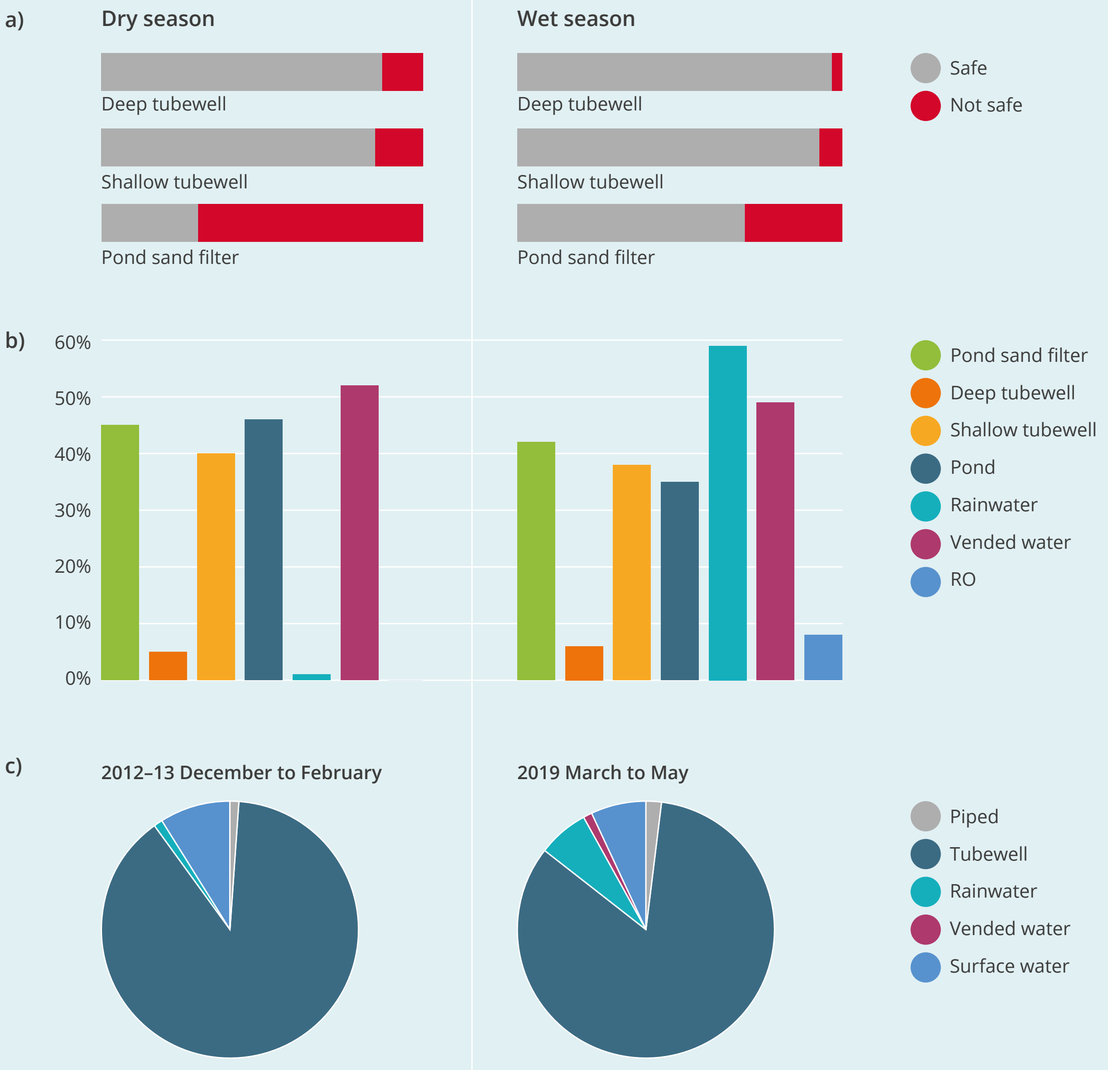
**Climate resilient water systems need to be developed based on access to appropriate climate information, which has financial implications**. To build climate resilience into water systems across scales, from dams to drinking water, requires investment to ensure access to climate information that is appropriate for the local context. The cost of providing this information has to be considered in financing plans for the water sector.

## b. Metrics for monitoring climate resilience in water systems are critical to track progress and inform investments for water security

**Climate change threatens the Sustainable Development Goal (SDG 6.1) of achieving universal access to drinking water (Charles et al. 2020), however there are no measures in place to track the variability in access to safe water**. Increasing temperatures and changing rainfall patterns impact both the quantity and quality of water supplies, often forcing households create resilience through multiple water sources of differing safety and affordability.

**Measurements of climate resilience in water systems need to address seasonality in water safety and security**. Water quality varies seasonally in natural water systems, at the point of collection, including for improved water sources, and at the point of use. The climatic conditions experienced when sampling is conducted strongly influences the observed water quality (Charles et al. 2021, draft). Comparisons between the 2012/13 MICS5 study in Bangladesh, in which more than 75% of samples were collected during cooler months, and the 2019 MICS6 study, which collected two thirds of samples in the hot season, highlight increases in *E. coli* contaminated samples from point of use and point of collection samples that are in contrast to improvements in other WASH indicators (Bangladesh Bureau of Statistics, 2021, draft). The observed increase between studies is a likely consequence of the warmer temperatures and increased precipitation experienced during the fieldwork period in MICS6. The results highlight the importance of using seasonal measurements of microbial water quality instead of one-off grab samples which provide little insight into the resilience of water systems to climatic changes. One-off samples such as used in MICS are often undertaken in the dry season, when faecal contamination risk is lowest.

## Figure 37: Seasonal variability in water quality and water use underscores the complex relationships between environmental conditions, infrastructure and management that inform climate resilience in water systems.

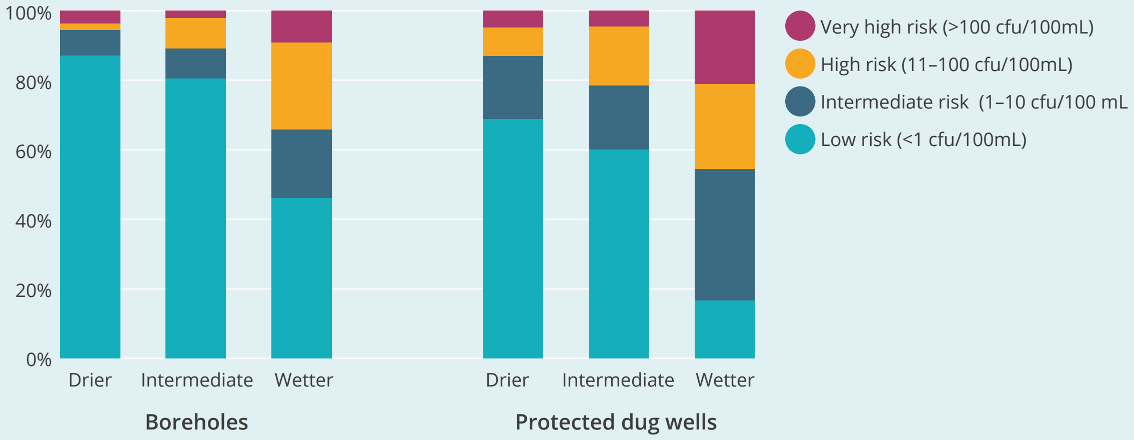


a) Water quality in all system types are vulnerable to heavy rainfall: proportion of samples with no E. coli detected in Polder 29 in coastal Bangladesh based on source type in the dry season (January, left) and the wet season (June, right) (Hope, Fischer, et al. 2021). b) Households use multiple water sources: proportion of water diary households reporting using different water sources by season in Polder 29 in coastal Bangladesh (Hoque et al. 2021). c) Comparison of main sources of drinking water reported in MICS 2012-13 (Dec-Feb) and MICS 2019 (Mar-May) for rural areas of Khulna.

Women, men and children need affordable, reliable and safe drinking water services every day. The seasonality of water sources means that individuals adapt their water source choices to weather patterns, with implications for water quality and cost. Similar variability has been demonstrated in Kenya (Hoque and Hope, 2018).

**Future work must account for temporal changes in household water source and recognise that water quality risks differ for alternative sources**. Households meet their water needs from multiple sources throughout the year, yet measurement of water access often focuses on a 'main' water source. Water surveys are mostly conducted in the dry season when travel is easier, however households often use multiple sources to address issues of reliability and seasonality. Hoque and Hope (2020) observe considerable temporal variability in household water sources in a coastal polder in Bangladesh, with many households relying on surface water (e.g. pond) for non-consumptive uses and on groundwater (e.g. tubewells) for drinking and cooking. In the Bangladesh MICS 2019 data for rural areas of Khulna district, 83.4% of the population reported using tubewells as their main drinking water source, while 6.6% used rainwater. The proportion of rural households using tubewells is higher here than the Hoque and Hope study, where it ranged from around 35% to 55%, while rainwater use varied from zero up to 70%. In Kitui, Kenya, while boreholes provide more reliable access to water, high natural salinity in groundwater means people prefer to use (untreated) surface water when it is available. Likewise, in Bangladesh's Shyamnagar upazila, Hossain et al. (2016) find that households use unfiltered pond water in the dry season when rainwater is unavailable, despite higher risk of microbial contamination and greater salinity. While use of multiple water sources can increase resilience to variability in water availability, water quality risks can increase.

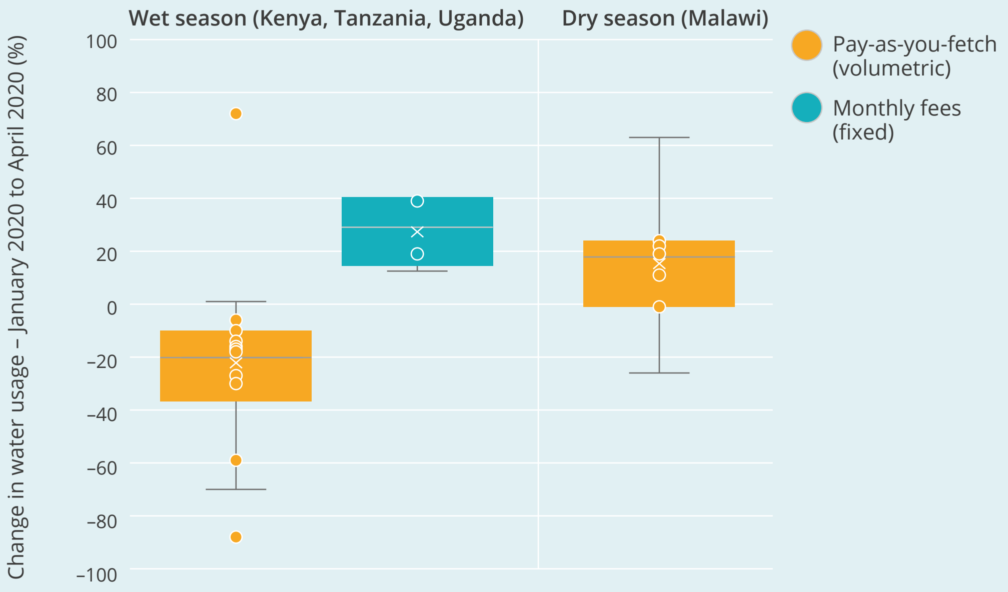
Figure 38: A longitudinal study of water quality from 30 boreholes and 41 protected dug wells in Tanzania highlights the importance of the type of infrastructure for groundwater resilience. While water quality in boreholes does deteriorate in wet weather, boreholes have better water quality in all weathers than protected dug wells. Source: Charles et al. (2021, draft)



**Routine monitoring of metered water usage and weather conditions can improve water security and therefore the resilience of rural water service providers to shifts in climate**. In rural piped schemes in four Sub-Saharan Africa countries, Armstrong et al. (2021) find that changes in water usage rates align with transitions between wet and dry seasons. In Malawi, for example, decreases in rainfall and reduced availability of rain-fed sources result in increased usage of piped water schemes. In the Kenyan, Tanzanian and Ugandan study regions, monthly water use of 'Pay-As-You-Fetch' (PAYF) piped schemes decrease as rainfall increases, caused by users shifting to alternative (free) rain-fed sources.

During key seasonal transition periods, the authors find that rural piped water schemes become more exposed to revenue risk and may struggle to sustain operations. Financial support for routine monitoring of metered water usage and rainfall could help to manage this risk, providing the information necessary for local water managers to design short-term water tariffs and performance-based subsidies based on observed trends.

**Figure 39: Changes in water usage rates between January and April 2020 in rural Kenya, Uganda, Tanzania and Malawi. The observed changes align with transitions between wet and dry seasons, and reflect patterns of rural water source choice and payment behaviour. Where 'Pay-As-You-Fetch' payment modality is employed, increased rainfall during the wet season buffers water demand from rural piped schemes. Source: Armstrong et al. (2021).**



**The variability in quality, source use and implications for sustainability all highlight the need to strengthen climate resilience in water supplies, but they also underline the need to be able to measure the impact of climate change on water access** (Charles et al. 2020). As the SDG target of universal access to drinking water (SDG 6.1) is progressively achieved, the importance of the future sustainability of safe drinking water supplies becomes increasingly apparent – many of those currently considered to have access to safely managed drinking water might experience a reduction of the level of service, or a loss of service. Climate resilient water supplies must ensure service water safety is sustained throughout the year against the range of weather conditions expected in the region's variable and changing climate.

Achieving and sustaining universal access to safe drinking water will require investment in additional monitoring that can inform decision making on whether services are managed to ensure safety and security of access to climate risks.

## c. New institutional models that improve water security will be critical for climate resilience

**While climate information is necessary to build climate resilience for water security, the institutional processes and practices which determine water policy choices and investment priorities should be informed by a wide set of social and political considerations**. Approaches to build water secure, climate resilient institutions need to consider the structural inequalities and individual choices of water users to climate risks, as well as the motivations and barriers to integrating climate data in decisions at different scales. As highlighted in the previous section, many drinking water systems lack climate resilience as a result of poor water security, experiencing deteriorations in water quality and water availability, resulting in households using multiple sources, with implications for affordability and financial sustainability. In response, REACH has collaborated with government partners in Bangladesh and Kenya to advance results-based models to improve water security, which are climate resilient and financially sustainable.

**Figure 40: FundiFix technicians fixing handpump in Kitui County, Kenya, during the**

**COVID-19 pandemic. Photo: Cliff Nyaga.**

**Institutional models have been demonstrated that improve the functionality and climate resilience of rural water supply infrastructure**. In Kenya, the FundiFix company has been incubated since 2016 to address the primary issue of service reliability (Smith School and Rural Focus Ltd., 2014; Thomson and Koehler, 2016). During the dry season and droughts, water sources in Kitui dry up, leaving more pressure on fewer sources which can exacerbate breakdowns. The impact on women and girls, who are generally responsible for water collection, in terms of psychosocial distress and the time burden was highlighted above in the work of Balfour et al. (2020). FundiFix has reduced downtime of waterpoints from a month or more to less than three days. The services are guaranteed under an affordable tariff with a results-based payment providing a subsidy through the Kitui Water Services Maintenance Trust Fund. The Trust Fund has increased private sector funding so donor support is now in a minority. Further, the FundiFix team has joined the Uptime Consortium with similar water service providers operating a results-based model in Burkina Faso, Central African Republic and Uganda with a total of 1.3 million paying water users. During the COVID-19 pandemic, dry seasons and conflict all the providers have continued to provide reliable infrastructure. New work is scoping a strategy to expand to 100 million users by 2030 supported by the REACH programme.

**New work in Bangladesh with SafePani is further developing institutional models of rural water supply management to address water safety and the impacts of extreme events**. One challenge for the Uptime consortium is to develop a consistent approach to improve water safety (Charles et al. 2020; Nowicki et al. 2020). In response, REACH has worked with UNICEF and the Government of Bangladesh to develop the SafePani (safe water) model based on research and discussion since 2016 (Fischer et al. 2020; Hope, Fischer, et al. 2021; Hoque et al. 2019; Hoque and Hope, 2019). Seasonal variability and extreme events pose water quality risks (Bangladesh Bureau of Statistics, 2021, draft; Charles et al. 2021, draft). SafePani will work to address these climate risks through climate resilient water safety planning in the coastal region where over 20 million people face risks from increasingly saline aquifers, seasonal water scarcity and faecal contamination, and flooding from the monsoon and storm surges from cyclones affecting water quality and damaging water infrastructure.

**Legal and policy reform is essential to support service delivery models that can advance water security for climate resilience, which REACH has been advancing in Bangladesh and Kenya**. The Government of Kenya's 2016 Water Act recognised for the first time the role of private service providers in rural areas, acknowledging that community-based management is not delivering resilient services, and supporting new thinking in the policy reform process for the 47 county governments. In Kitui, REACH has worked with the county government to support its first Water Bill which has proposed provision for professional service providers, funding for maintenance of water supply infrastructure, and improved water service regulation and monitoring. In Bangladesh, the 1998 National Water Policy is under review with REACH supporting the process including discussion of salient elements of the SafePani model to rethinking how the government allocates risks and responsibilities between the state, the market (service providers) and communities.

**Service delivery models must recognise seasonal behaviour and affordability to be financially sustainable**. To ensure sustained access to safe drinking water, water prices should reflect the water user's ability to pay and be priced at affordable thresholds that encourage regular use and user payments, even in wet periods. The revenue generated by payments should be re-invested in water services to guarantee timely repairs and maintenance of the water infrastructure.

Figure 41: Politicised approaches to building climate resilience, whether in urban or rural areas, at any scale, are necessary for meaningful change.

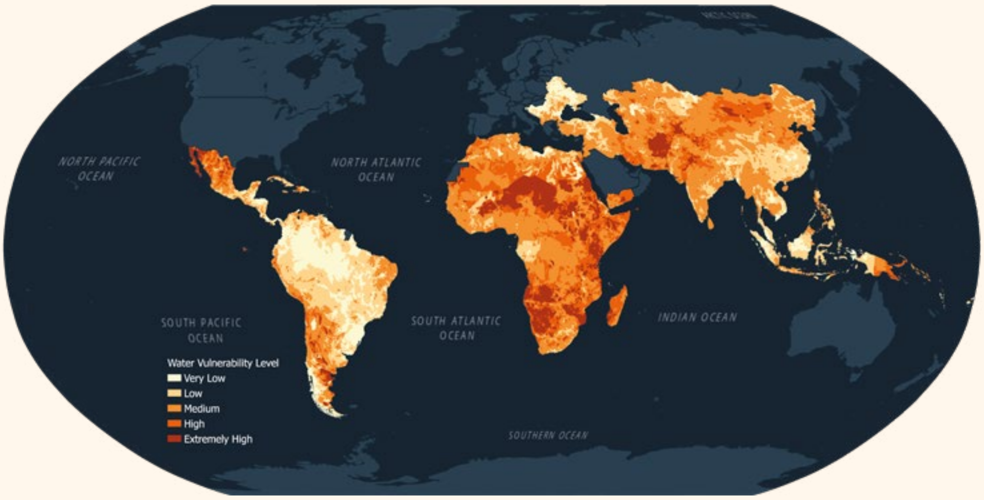
A holistic approach, that engages with context-specific governance structures and institutional norms is necessary to ensure climate resilient water security in fragile environments (Grasham et al., 2021). Such a contextual approach avoids top-down, technocratic interventions that attempt to work around power relations, undermining indigenous knowledge and compromising community resilience. Grasham et al.'s roadmap to re-politicise climate resilience reasons that water institutions must identify actions that address current climate risks whilst navigating sensitive local institutional norms, socio-cultural and political processes. As REACH research has shown, climate vulnerability varies with age, gender, socio-economic status and location and greater consideration of context specific values will ensure that adaptation actions will benefit marginalised communities most vulnerable to climate risks.

The roadmap aims to meaningfully engage with the politics of climate resilient water security and support efforts towards achieving Sustainable Development Goal 6 – water and sanitation for all. With six key elements of resilience, the roadmap strengthens the ability of all to mitigate vulnerability to risks from, and adapt to, changing patterns in climate hazards and variability. In summary, the roadmap offers a politicised and human approach to engaging in efforts to reduce vulnerability.

Photo by Alice Chautard

## Water Security for All. New initiative of REACH's partner UNICEF

In March 2021, UNICEF launched their report "Water Security for All", presenting an analysis of the relationship between physical water scarcity risks and water service levels which contribute to water vulnerability. The analysis indicated that 1.42 billion people, including 450 million children, live in areas of high or extremely high water vulnerability.



Produced by United Nations Geospatial

Figure 42: Distribution of areas of water vulnerability. Source: UNICEF.

Climate change is exacerbating water scarcity risks, contributing to increased collection times, reduced water quality, increased water demand and competition, as well as migration and conflict.  While ensuring access to increasingly higher levels of WASH services reduces the vulnerability to climate change, as this report highlights simply ensuring access to a WASH service does not guarantee resilience to the varied impacts of climate change. To address the complex, yet important relationship between access and resilience, REACH programme partner UNICEF launched the Water Security For All Initiative, comprised of four key dimensions:

1. **Safe and affordable drinking water services**. Provide access to a safe and affordable water service that is sustainable, close to home and managed professionally.
2. **Climate-resilient WASH services and communities**. Ensure that all WASH services have been designed to withstand climate-related events, strengthen the resilience and adaptive capacities of vulnerable communities, and operate using low-carbon energy sources, such as solar power.
3. **Prevention of water scarcity crises through early action**. Avert water scarcity crises through water resources assessments, sustainable water withdrawal, efficient use, and early warning and early action to prevent situations where water supplies are fully depleted.
4. **Water cooperation for peace and stability**. Work with communities and key stakeholders so that equitable management of water resources and WASH services contribute to increased social cohesion, political stability and peace; and in conflict zones to prevent attacks on water and sanitation infrastructure and personnel.

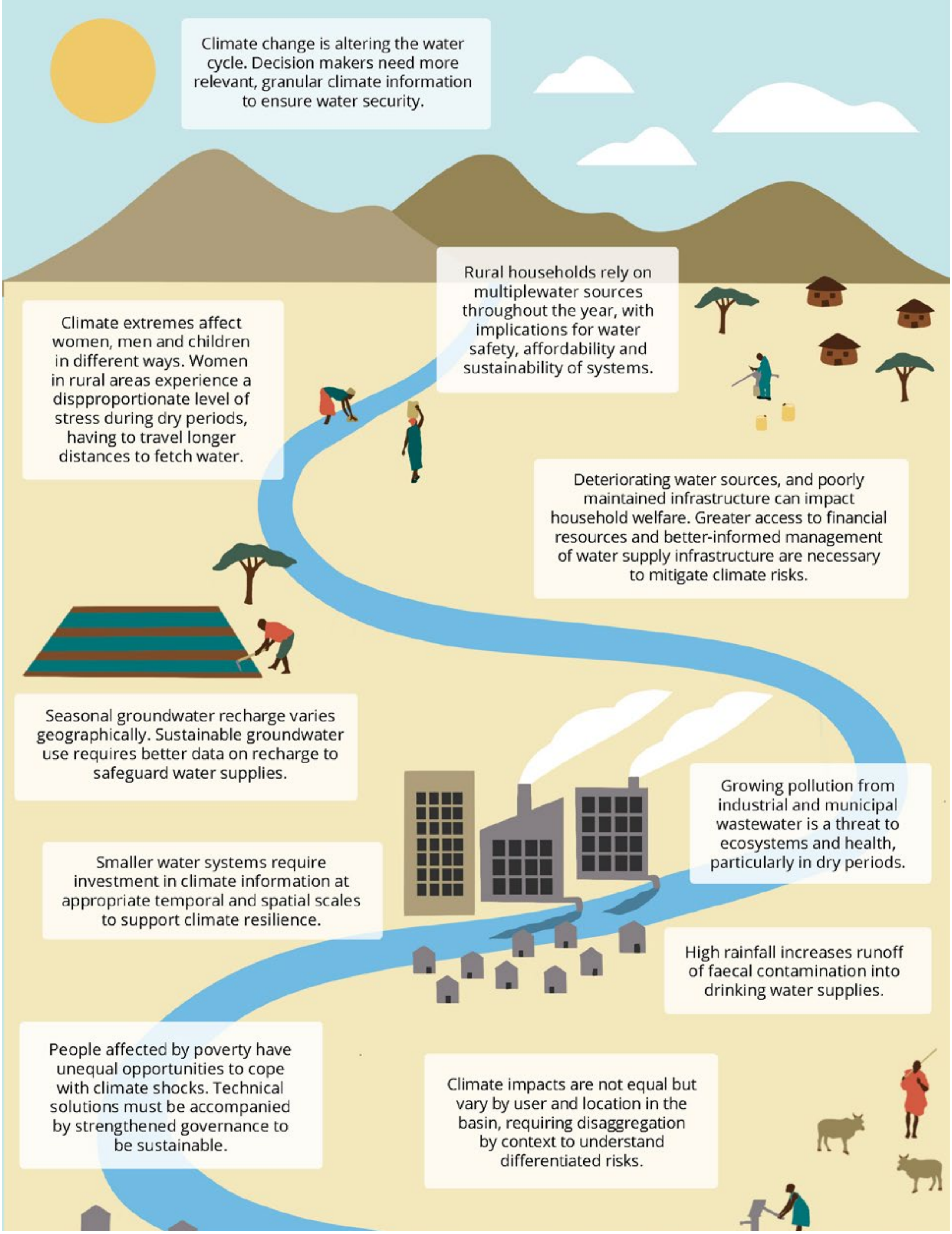
Implementing all of these dimensions into a comprehensive WASH programme is critical for the sustainability, affordability, equity, safety and resilience of WASH services.

# 6. Concluding remarks

REACH recognises that water institutions are working to build climate resilient water systems by managing risks from climate shocks and variability. However, improved water policy and practice is critical to support equitable and sustained climate resilience for water security. Research presented in this report shows that the impacts of climate are experienced unequally between water users and communities in a basin, and that exposure to these risks is a product of how they are managed and financed by governance and institutions. Improved understanding and translation of climate risks into effective and actionable information will help to build climate resilience in the most vulnerable communities, and therefore fairly and effectively allocate climate risks and responsibilities. These inequalities in experiences of climate risk and the need for investment in climate information to support development of climate resilient institutions highlight the need for a rethink of how we finance climate in the water sector.

Interdisciplinary science by REACH has advanced understanding of the diverse and complex impacts of climate and weather on water security, and has provided actionable evidence to support adaptation decisions that aim to protect communities most vulnerable to these impacts. The REACH programme will continue research to address current gaps in the knowledge and understanding of climate-water interactions in partnership with climate scientists, water managers and policy makers, building institutions which improve water security fairly, reliably and universally.

Figure 43: The impacts of climate on water security vary across time and space. They are experienced differently by users across the basin, and are affected by the local hydro-climatic conditions of the area. Improving our understanding of how current and future climate affect water security is critical to building resilience.



Climate change is altering the water cycle. Decision makers need more relevant, granular climate information to ensure water security.

Rural households rely on multiplewater sources throughout the year, with implications for water safety, affordability and sustainability of systems.

Climate extremes affect women, men and children in different ways. Women in rural areas experience a dispproportionate level of stress during dry periods, having to travel longer distances to fetch water.

Deteriorating water sources, and poorly maintained infrastructure can impact household welfare. Greater access to financial resources and better-informed management of water supply infrastructure are necessary to mitigate climate risks.

Seasonal groundwater recharge varies geographically. Sustainable groundwater use requires better data on recharge to safeguard water supplies.

Growing pollution from industrial and municipal wastewater is a threat to ecosystems and health, particularly in dry periods.

Smaller water systems require investment in climate information at appropriate temporal and spatial scales to support climate resilience.

High rainfall increases runoff of faecal contamination into drinking water supplies.

People affected by poverty have unequal opportunities to cope with climate shocks. Technical solutions must be accompanied by strengthened governance to be sustainable.

Climate impacts are not equal but vary by user and location in the basin, requiring disaggregation by context to understand differentiated risks.

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REACH research is indicated in **bold text**.

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