

Climate Risk Assessment - Namibia Water Sector Infrastructure Support Program (NWSISP II)

Technical report
December 2025



GLOBAL
CENTER ON
ADAPTATION

AUTHORS & ACKNOWLEDGEMENTS

This report was developed by

Global Center on Adaptation

Partnerships: African Development Bank

Consultants: Global Factor

Acknowledgements:



GLOBAL
CENTER ON
ADAPTATION

African
Union



GLOBAL
CENTER ON
ADAPTATION

In Partnership with:



Consultants:



GLOBAL



ABOUT THE GLOBAL CENTER ON ADAPTATION

The Global Center on Adaptation (GCA) is an international organization, hosted by the Netherlands, which works as a solutions broker to accelerate action and support for adaptation solutions from the international to the local, in partnership with the public and private sector, to ensure we learn from each other and work together for a climate resilient future

AFRICA ADAPTATION ACCELERATION PROGRAM

GCA is providing technical assistance under the African Adaptation Acceleration Program (AAP), a joint initiative launched by the GCA and the African Development Bank in 2021



GLOBAL
CENTER ON
ADAPTATION

TABLE OF CONTENTS

ABBREVIATIONS	6
EXECUTIVE SUMMARY	7
INTRODUCTION	15
1 PART I. METHODOLOGY	16
1.1 CLIMATE CHANGE ANALYSIS	16
1.1.1 PURPOSE AND APPROACH	16
1.1.2 DATA SOURCES AND COVERAGE	16
1.1.3 SCENARIOS AND TIME WINDOWS	16
1.1.4 GEOGRAPHIC DOMAIN AND SPATIAL AGGREGATION	17
1.1.5 PRE-PROCESSING AND QUALITY CHECKS	17
1.1.6 CLIMATE INDICES	17
1.1.7 ENSEMBLE TREATMENT AND AGREEMENT	18
1.1.8 LIMITATIONS AND APPROPRIATE USE	18
1.1.9 VALIDATION AND UNCERTAINTY	19
1.2 CLIMATE HAZARD ASSESSMENT	19
1.2.1 STANDARDS AND TRACEABILITY	19
1.2.2 CLIMATE HAZARDS IDENTIFICATION	20
1.2.3 HAZARD LEVEL ANALYSIS	20
1.3 MULTI-HAZARD HOTSPOTS METHODOLOGY	26
1.4 CLIMATE EXPOSURE ASSESSMENT METHODOLOGY	27
1.5 CLIMATE VULNERABILITY ASSESSMENT METHODOLOGY	27
1.5.1 VULNERABILITY ASSESSMENT OF WASH ASSETS IN KUNENE AND OKAVANGO REGIONS	27
1.6 CLIMATE RISK ASSESSMENT METHODOLOGY	29
1.6.1 CLIMATE RISK CALCULATION METHOD FOR SCREENING WITH ASSET-SPECIFIC LIMITED DATA	29
1.6.2 CLIMATE RISK ASSESSMENT METHOD WHEN ASSET-SPECIFIC DATA IS AVAILABLE	30
2 PART II. CLIMATE CHANGE ANALYSIS RESULTS	34
2.1 TOPOGRAPHIC AND GEOGRAPHIC ANALYSIS	34
2.2 MAIN DRIVERS OF THE CLIMATE IN NAMIBIA	35
2.3 CLIMATE CHANGE IN NAMIBIA	35
2.4 CLIMATOLOGICAL ANALYSIS BY RIVER BASIN	39
2.4.1 CLIMATOLOGICAL ANALYSIS IN KUNENE RIVER BASIN	39
2.4.2 CLIMATOLOGICAL ANALYSIS IN OKAVANGO RIVER BASIN	45
3 PART III. CLIMATE HAZARDS ASSESSMENT: KUNENE AND OKAVANGO RIVER BASINS	52
3.1 INTRODUCTION	52
3.2 KUNENE AND OKAVANGO RIVER BASINS	52
3.3 CLIMATE HAZARD IDENTIFICATION	54
3.4 HAZARDS IN KUNENE RIVER BASIN	56
3.5 HAZARDS IN OKAVANGO RIVER BASIN	64
3.6 HOTSPOTS IN KUNENE AND OKAVANGO RIVER BASINS	72
3.6.1 HOTSPOTS IN KUNENE RIVER BASIN	72
3.6.2 HOTSPOTS OKAVANGO RIVER BASIN	73
3.7 HAZARD AND MULTI-HAZARD IMPLICATIONS FOR WASH PROJECTS IN KUNENE AND OKAVANGO RIVER BASINS	76
3.7.1 KUNENE BASIN HAZARD CONCLUSIONS	76
3.7.2 OKAVANGO BASIN HAZARD CONCLUSIONS	77
4 PART IV. CLIMATE EXPOSURE ASSESSMENT	80
4.1 EXPOSURE TO HEAT STRESS	80
4.1.1 KUNENE NORTH AND SOUTH	80
4.1.2 KAVANGO WEST AND EAST	80
4.2 EXPOSURE TO DROUGHT	80
4.2.1 KUNENE NORTH AND SOUTH	80

4.2.2.	KAVANGO WEST AND EAST	81
4.3	EXPOSURE TO PLUVIAL FLASH FLOODS	86
4.3.1.	KUNENE NORTH AND SOUTH	86
4.3.2.	KAVANGO WEST AND EAST	86
4.4	EXPOSURE TO FLUVIAL FLASH FLOODS	91
4.4.1.	KUNENE NORTH AND SOUTH	91
4.4.2.	KAVANGO WEST AND EAST	91
4.5	EXPOSURE TO WILDFIRE	96
4.5.1.	KUNENE NORTH AND SOUTH	96
4.5.2.	KAVANGO WEST AND EAST	96
4.6	WASH INFRASTRUCTURE IN HOTSPOTS BY REGION AND CONSTITUENCY	96
4.6.1.	KUNENE BASIN HOTSPOTS	96
4.6.2.	OKAVANGO BASIN HOTSPOTS	99
5	PART V. CLIMATE VULNERABILITY ASSESSMENT	103
5.1	TYPOLOGY-BASED VULNERABILITY ASSESSMENT	103
5.2	HEAT STRESS VULNERABILITY ASSESSMENT	105
5.3	DROUGHT VULNERABILITY ASSESSMENT	105
5.4	FLUVIAL FLASH FLOODS VULNERABILITY ASSESSMENT	106
5.5	PLUVIAL FLASH FLOODS VULNERABILITY ASSESSMENT	107
5.6	WILDFIRES VULNERABILITY ASSESSMENT	107
6	PART VI. CLIMATE RISK ASSESSMENT	109
6.1	HEAT STRESS RISK	109
6.2	DROUGHT RISK	110
6.3	FLUVIAL FLASH FLOODS RISK	111
6.4	PLUVIAL FLASH FLOODS RISK	112
6.5	WILDFIRE RISK	113
7	PART VII. PROJECT SITE CLIMATE RISK AND VULNERABILITY ANALYSIS	115
7.1	KAVANGO LINK- CAN WATER PROJECT	115
7.1.1	PROJECT SITE CONTEXT	115
7.1.2	WATER DEMAND	116
7.1.3	PLANNED INFRASTRUCTURE	116
7.1.4	CLIMATE HAZARDS	118
7.2	ASSESSMENT OF CLIMATE RISKS FOR THE KAVANGO LINK RAW-WATER TRANSFER	129
7.2.1.	PROPOSED SEGMENTATION FOR THE KAVANGO LINK	132
7.2.2.	IMPACT CRITERIA	139
7.3	RISK ASSESSMENT RESULTS	142
7.4	RURAL PROJECTS WITHIN 100KM RADIUS OF RUNDU PRELIMINARY CLIMATE RISK SCREENING	153
7.4.1	PROJECT SITE CONTEXT	153
7.4.2	IDENTIFIED RURAL AREAS	155
7.4.3	PLANNED INFRASTRUCTURE	156
7.4.4	CLIMATE HAZARD PROFILE AND HAZARD SPECIFIC HOTSPOTS	158
7.4.5	IMPLICATIONS FOR SITING, DESIGN AND OPERATIONS	165
	PART VIII : CONCLUSIONS	170
	BIBLIOGRAPHY	172
	TABLES AND FIGURES	175
	ANNEXES	180
	ANNEX 1. VULNERABILITY RATIONALE BY HAZARD	
	ANNEX 2. VULNERABILITY ASSESSMENT – METHODOLOGY, ASSIGNED VALUES AND MEANING	
	ANNEX 3. HOTSPOT TABLES FOR CLIMATE HAZARDS	
	ANNEX 4. SUMMARY OF ASSET EXPOSURE FOR KUNENE AND OKAVANGO RIVER BASINS	

ABBREVIATIONS

Acronym	Definitions
AAAP	Africa Adaptation Acceleration Program
AfDB	African Development Bank
AR5	Fifth Assessment Report (IPCC)
AR6	Sixth Assessment Report (IPCC)
BAU	Business As Usual
CAN	Central Area of Namibia
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CN	Concept Note
CORDEX	Coordinated Regional Downscaling Experiment
CRA	Climate Risk Assessment
CRVA	Climate Risk and Vulnerability Assessment
ERA5	ECMWF Reanalysis 5th Generation (climate reanalysis dataset)
ESAP	Environmental and Social Assessment Procedures (AfDB)
ESIA	Environmental and Social Impact Assessment
ESMP	Environmental and Social Management Plan
GAP	Gender Action Plan
GCA	Global Center on Adaptation
GEF	Global Environment Facility
GVA	Gender Vulnerability Assessment
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
LDCF	Least Developed Countries Fund
MAWFLR	Ministry of Agriculture, Water, Fisheries and Land Reform
NAMCLIM	Namibia Climate Information Platform
NamWater	Namibia Water Corporation
NBS	Nature-Based Solutions
NDC	Nationally Determined Contributions
NMS	Namibia Meteorological Service
NPV	Net Present Value
OKACOM	Permanent Okavango River Basin Water Commission
PJTC	Permanent Joint Technical Commission
RCP	Representative Concentration Pathways
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SCCF	Special Climate Change Fund (GEF)
SDGs	Sustainable Development Goals
SSP2-4.5 / SSP5-8.5	Shared Socioeconomic Pathways – Climate scenarios used in IPCC AR6
ToR	Terms of Reference
VCA	Vulnerability and Capacity Assessment
WASH	Water, Sanitation and Hygiene
WRM	Water Resources Management
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

Namibia, the driest country in Sub-Saharan Africa, faces severe water security challenges driven by erratic rainfall, high climatic variability, and dependence on transboundary resources. To address these vulnerabilities, the Government of Namibia, with African Development Bank support, is implementing the **Namibia Water Sector Infrastructure Support Program Phase II (NWSISP II)** to strengthen climate-resilient water and sanitation services in the northern regions. The program includes rehabilitating critical conveyance systems, expanding rural supply, and integrating gender and social inclusion measures. Under the **Africa Adaptation Acceleration Program (AAAP)**, the Global Center on Adaptation (GCA) provides upstream technical support through a **Climate Risk and Vulnerability Assessment (CRVA)**, aiming to ensure that infrastructure design and financing strategies embed resilience to future climate hazards.

The objective of this assessment is to evaluate current and future climate risks to Namibia's water sector, focusing on the Kunene and Kavango basins, by identifying hazard patterns at national and regional scales and analyzing exposure, asset vulnerability, and risk at regional and local levels to highlight factors that threaten the resilience and sustainability of water infrastructure and services. At project level, the CRVA directly informs priority NWSISP II investments, in particular the Calueque–Oshakati system in the Kunene region and the Kavango Link bulk-water transfer and conceptual 100-km rural water-supply extensions around Rundu in the Okavango corridor.

This report is organized into eight parts to provide a clear and systematic assessment of climate risks. **Part I** outlines the methodological approach, detailing data sources, scenarios, and analytical steps. **Part II** presents climate change analysis results, followed by **Part III**, which assesses climate hazards across the Kunene and Okavango basins. **Parts IV to VI** examine exposure, vulnerability, and risk at sector and basin levels, while **Part VII** focuses on site-specific climate risk assessments for prioritized projects. Finally, **Part VIII** synthesizes findings and offers conclusions to guide climate-resilient planning and decision-making.

PART I. Methodological approach

This section explains the multi-level methodology underpinning the Climate Risk and Vulnerability Assessment, structured around five complementary components:

1. **Climate Hazard Assessment** identifies six key hazards—extreme heat, drought, pluvial flash floods, fluvial floods, strong winds and convective storms, and wildfires—prioritized using national and global climate risk evidence. Each hazard is analyzed through intensity and frequency metrics, combined into a single hazard level across time horizons, ensuring comparability and defensible decisions.
2. **Multi-Hazard Hotspot Analysis** highlights areas where multiple hazards co-occur at high intensity under the same scenario and time slice, based on multi-model projections for two emissions pathways (SSP2-4.5 and SSP5-8.5) and three-time horizons (2020–2039, 2040–2059, 2060–2079). Hotspots guide prioritisation of robust design measures and routing decisions at basin scale and along key corridors such as the Kavango Link and the 100-km Rundu rural water-supply concept, but always in combination with asset exposure, vulnerability and feasibility assessments.
3. **Climate Exposure Assessment** determines whether hazards can physically affect WASH assets and potentially cause damage. Geocoded assets—pipelines, reservoirs, boreholes, pump stations, treatment units, and distribution networks—are overlaid on hazard type maps for each scenario and time slice. Exposure is reported by constituency and asset type as the proportion of assets in High, Very High, and Extreme bands, with critical nodes flagged. Maps and tables depict spatial evolution of exposure and enable translation into design and operational implications, corroborated where possible with historical damage records.
4. **Climate Vulnerability Assessment** evaluates how WASH assets respond to hazards, considering sensitivity—physical infrastructure, service functionality, and operations—and adaptive capacity, which reflects institutional readiness and maintenance regimes. This ensures that exposure alone does not dictate risk, but asset behavior and resilience are factored in.
5. **Climate Risk Assessment (CRA)** Climate Risk Assessment (CRA) combines hazard likelihood and consequence into a 1–25 Risk Index, calculated separately for four impact dimensions: physical damage to assets, operational disruption, reduction in asset service life, and loss of service delivery. Scores are

mapped to qualitative levels (Low, Moderate, High, Extreme) for a near-future (2020–2039) and a distant-future (2040–2059) horizon under SSP2-4.5 and SSP5-8.5. Extreme risks demand redesign or relocation, while High risks require engineered and operational controls. The method is auditable, scalable, and adaptable as new climate data emerge, and is applied both at basin level and to the segment-level assessment of the Kavango Link project.

PART II. Climate Change Analysis Results

This section presents a detailed analysis of climate change trends and indices for Namibia, with focused assessments for the Kunene and Kavango river basins. Using multi-model climate projections across different emissions pathways and time horizons, the chapter identifies the key climate stressors shaping future hydrological regimes, water availability, and infrastructure reliability. The results provide a scientific foundation for assessing the evolving risks that water supply and sanitation systems will face over the coming decades. and are the basis for further hazard analysis.

National-Level Challenges in Namibia

Namibia's climate is characterized by persistent aridity, strong interannual variability, and a growing amplification of extremes due to climate change. Rising temperatures—projected to increase by 2–4°C by mid-century—are expected to intensify evapotranspiration and reduce effective rainfall, exacerbating chronic water scarcity. Drought frequency and duration are projected to worsen, especially across the central and northern regions where water demand is growing. Conversely, when rainfall does occur, it increasingly manifests as short, high-intensity storms that elevate the risk of flash floods and soil erosion. Together, these shifts may threaten agricultural productivity, groundwater recharge rates, and the long-term reliability of bulk water transfer systems on which both rural and urban populations depend.

Kavango (Okavango) Basin Challenges

The Kavango Basin—shared with Angola and Botswana—presents a contrasting hydrological regime, with comparatively higher rainfall but pronounced seasonal variability. Climate projections indicate rising temperatures and more erratic precipitation patterns, leading to increased uncertainty in the basin's flow regime. Reduced rainfall in the Angolan highlands, which generate most of the basin's discharge, could significantly diminish downstream flows, affecting water security, ecological integrity, and the resilience of communities that depend on floodplain agriculture. At the same time, extreme rainfall events could become more frequent, heightening risks of riverine flooding in low-lying settlements and compromising rural water supply infrastructure. These evolving hydrological pressures are particularly relevant for planned NWSISP II investments along the lower Okavango corridor, including the Kavango Link bulk-water transfer to the Central Area of Namibia and the planned expansion of water supply from Rundu to surrounding rural communities within the 100-km concept.

Kunene Basin Challenges

The Kunene Basin is highly vulnerable due to its dependence on rainfall originating in Angola and the strong seasonality of runoff. Projections suggest substantial warming and increased drought likelihood, with potential reductions in river discharge that may threaten the stability of major hydraulic assets such as the Calueque–Oshakati canal system. Extreme rainfall episodes, although less frequent, may increase in intensity, raising concerns about erosion, slope instability, and damage to conveyance infrastructure. Variability in cross-border flows also poses strategic water management challenges, requiring coordinated bilateral operation and improved monitoring to secure consistent supply for northern Namibia's population centers.

PART III. Climate Hazard Assessment

This section presents the results of the Climate Hazard Assessment for the Kunene and Kavango basins, examining how key climate hazards evolve across scenarios and time horizons. Using multi-model projections, the analysis evaluates six priority hazards—extreme heat, drought, pluvial flash floods, fluvial floods, strong winds and convective storms, and wildfires—with a specific focus on identifying multi-hazard hotspots where

several hazards are projected to reach high or extreme intensity simultaneously. These hotspots highlight areas where WASH infrastructure is most likely to face recurrent or severe climate-related disruptions.

Climate Hazards and Potential Impacts on Water Infrastructure

The assessment identifies how climate hazards can disrupt water and sanitation systems, highlighting distinct mechanisms of impact:

- **Extreme Heat** accelerates material degradation, increases evaporation losses in canals and reservoirs, and reduces efficiency of pumps, treatment processes, and solar systems.
- **Drought** limits water availability, stresses groundwater-dependent systems, and increases competition for scarce resources, affecting service continuity.
- **Pluvial Flash Floods** overwhelm drainage systems, erode embankments, damage pipelines, and contaminate water sources with sediment and debris.
- **Fluvial Floods** threaten riverbank intakes, pumping stations, and floodplain settlements; prolonged inundation can disable electrical equipment and access roads.
- **Strong Winds and Convective Storms** damage elevated tanks, pipelines, power lines, and PV arrays, causing operational disruptions.
- **Wildfires** endanger exposed infrastructure—especially plastic pipelines and electrical components—and degrade catchment vegetation, increasing sediment loads after rainfall.

In that regard, climate hazards impose distinct design and operational challenges across the Kunene and Okavango basins. In the Kunene Basin, multi-hazard hotspots concentrate along the lower valley and across the north-central plains, intersecting existing and planned bulk-water schemes such as the Calueque–Oshakati system and related conveyance infrastructure. In the Okavango Basin, an elongated hotspot belt develops along the lower Okavango corridor with a pronounced cluster around the Rundu–Nkurenkuru urban area; this pattern coincides with the conceptual alignments of the Kavango Link and the 100-km rural water-supply extensions around Rundu. These overlaps indicate locations where drought, heat stress and fluvial and pluvial flooding are likely to interact over the asset life cycle, and therefore where conservative siting, elevated protection standards and redundancy in supply routes will be essential to secure long-term WASH service reliability.

- **Kunene Basin:** Heat stress becomes a dominant constraint by mid-century, reaching extreme levels later, while drought intensifies under high-emission scenarios, reducing dependable yields and increasing service volatility. Pluvial flash floods rise to high hazard, requiring robust drainage and access protection; fluvial floods remain localized but warrant site-specific checks. Wildfire persists as an extreme hazard throughout. Hotspots expand from the south-west to basin-wide coverage under SSP5-8.5, signaling compound drought–flood pressures. Recommended measures include flood-proof intakes, upsized storage, conservative groundwater yields, multi-source supply, and sealed, raised sanitation systems. Utilities should embed drought triggers in Water Safety Plans and adopt conjunctive surface–groundwater operations.
- **Okavango Basin:** Heat stress escalates from moderate to high hazard, while drought remains a persistent constraint. Pluvial and fluvial flood hazards stay high, demanding flood-safe siting and drainage upgrades; wildfire rises from moderate to high later in the century. Hotspots concentrate along the lower Okavango corridor and expand across Kavango East and West by late century. Adaptation priorities include resilient intakes, modular treatment plants, elevated storage, groundwater redundancy, and sanitation systems outside flood-prone zones. Critical assets should be phased outside hotspots or flood-hardened, supported by early-warning systems and multi-source supply strategies.

Multi-Hazard Hotspot Analysis

Hotspot patterns in both basins reveal a clear escalation of compound climate risks over time.

- **Kunene Basin:** Under SSP2-4.5, hotspots start as localized clusters in the south-west (2020–2039), expand along the corridor and interior plateau by mid-century, and consolidate into larger zones by

2060–2079. Under SSP5-8.5, intensification is faster and broader, with near-term clusters evolving into basin-wide coverage by late century, signaling widespread concurrence of drought and flood hazards.

- **Okavango Basin:** Under SSP2-4.5, hotspots progress from scattered patches in the southern basin to a discontinuous band along Kavango East by mid-century, expanding northward toward the river corridor by 2060–2079. Under SSP5-8.5, the shift is sharper: few hotspots early, but extensive coverage across Kavango East and West—including Rundu, Nkurenkuru, and the floodplain—by late century.

PART IV. Climate Exposure Assessment

This section presents the Climate Exposure Assessment, which examines how existing WASH infrastructure - including bore holes, dams, wells, public taps, water tanker service points, and water pump stations - in the Kunene and Kavango basins overlaps with areas projected to experience high-intensity climate hazards. By spatially intersecting geocoded WASH assets with hazard-class maps across scenarios and time horizons, the analysis identifies where infrastructure is currently exposed—and will likely remain exposed—to droughts, extreme heat, pluvial and fluvial flooding, strong winds, and wildfires. The assessment is carried out at both regional and constituency levels, providing a detailed view of exposure patterns and highlighting priority hotspots that require targeted climate-resilient design and operational measures.

Exposure of WASH Infrastructure to Climate Hazards

The analysis shows near-universal exposure of WASH assets to multiple hazards across both basins, with severity increasing over time and under high-emission scenarios:

- **Heat Stress:** Already near-universal in the near term; by mid-century, all assets in Kunene and Okavango reach Extreme exposure under both SSP2-4.5 and SSP5-8.5, signaling system-wide thermal stress.
- **Drought:** Exposure intensifies progressively. In Kunene, Opuwo, Khorixas, and Outjo reach Extreme levels by late century, with boreholes and tanker points often at 100% in High+ bands. In Okavango, Mpungu, Kahenge, and the Rundu corridor escalate from Moderate to Very High/Extreme, affecting both production and distribution nodes.
- **Pluvial Flash Floods:** High exposure is widespread from the near term in Kunene and expands basin-wide by mid-century; by 2060–2079, nearly all asset classes—including pump stations—are flagged High under SSP5-8.5. In Okavango, High exposure dominates the Rundu corridor early and spreads to surrounding constituencies by late century.
- **Fluvial Floods:** Persistent High exposure across both basins from the outset, with localized escalation to Very High or Extreme under SSP5-8.5, particularly in river-adjacent constituencies (Opuwo, Epupa, Khorixas, Rundu corridor).
- **Wildfire:** Emerges as a basin-wide Extreme hazard in all periods and scenarios, with near-complete coverage across asset types by mid-century, shifting the planning focus from spatial avoidance to operational resilience.

Regional Summary of Exposure of WASH Assets

Across both basins, boreholes, pipelines, and pumping stations emerge as the asset types most exposed to climate hazards. In the Kavango Basin, flood-prone zones overlap significantly with linear infrastructure, increasing the likelihood of physical damage during extreme rainfall events. In the Kunene Basin, exposure is driven primarily by hydrological scarcity and thermal stress, affecting both groundwater-dependent systems and components of major conveyance infrastructure.

The overall exposure patterns highlight the need for integrated resilience measures—ranging from hydraulic design adjustments and improved drainage protections to operational redundancies and climate-informed asset management—to ensure that WASH infrastructure remains functional and reliable under future climate conditions.

PART V. Climate Vulnerability Assessment

This section evaluates the intrinsic susceptibility of WASH (Water, Sanitation, and Hygiene) infrastructure to climate hazards, complementing the exposure analysis by examining how assets perform under stress. Using a typology-based default methodology, vulnerability is quantified across four engineering dimensions—**Physical Damage (PD)**, **Operability (OP)**, **Service Life (SL)**, and **Productivity (PR)**—to capture both structural fragility and service continuity. For each hazard, differentiated parameter sets reflect the dominant mechanisms of impact

The **Vulnerability Index** for each asset type by hazard is computed using fixed weights and classified into reporting bands (Low, Moderate, High, Very High) to ensure comparability across typologies and locations. These results provide actionable insights for design and operational planning—highlighting which assets require flood-proofing, heat-tolerant materials, redundancy measures, or enhanced maintenance protocols. By making assumptions explicit and auditable, the approach offers a pragmatic bridge from limited data to defensible vulnerability estimates, supporting climate-resilient investment decisions.

This section evaluates how WASH infrastructure responds to the identified climate hazards. The vulnerability of each asset is influenced by both its **sensitivity** to specific climate impacts and its **adaptive capacity** to manage or recover from these stressors.

The sensitivity of infrastructure refers to how susceptible each asset is to damage or reduced functionality due to specific climate impacts. For example:

- **Boreholes and wells** are sensitive to drought and heat stress, as these hazards can decrease groundwater levels and increase evaporation losses.
- **Pipelines** face heightened vulnerability from flooding and wildfires, which may cause physical damage, erosion, and contamination, leading to service interruptions.
- **Pump stations** are at risk from extreme heat, which reduces efficiency, and from fluvial flooding, which can disrupt the electrical systems and infrastructure.

Adaptive capacity is the ability of an asset to resist, absorb, or recover from the impacts of climate hazards. This is influenced by:

- **Operational flexibility**, such as the ability to switch between water sources in times of drought.
- **Maintenance regimes**, including the frequency and quality of infrastructure upkeep to mitigate damage from extreme weather.
- **Institutional readiness**, such as planning for climate-resilient water systems and emergency protocols for asset failure.

The vulnerability assessment highlights areas where WASH assets are most at risk and where resilience measures are urgently needed. These include:

- **Reinforced infrastructure**: Protecting critical assets such as pipelines, boreholes, and pumping stations from flooding, heat stress, and wildfires by incorporating heat-resistant materials, flood-proofing measures, and fire-resistant components.
- **Redundancy measures**: Building redundancy into the water supply network by ensuring alternative water sources and backup systems to maintain service continuity during extreme droughts or floods.
- **Enhanced maintenance protocols**: Implementing regular inspection and maintenance routines to address the impacts of heat, drought, and floods on infrastructure, ensuring that assets remain functional throughout their service life.

PART VI. Climate Risk Assessment

The Climate Risk Assessment (CRA) integrates the findings from the Climate Hazard, Exposure, and Vulnerability Assessments to evaluate the overall climate risk faced by water, sanitation, and hygiene (WASH) infrastructure in the Kunene and Kavango basins. This assessment quantifies risk by combining the **likelihood** of each identified climate hazard with the **consequences** on infrastructure performance. The **Risk Index** generated from this methodology is classified into four levels: **Low**, **Moderate**, **High**, or **Extreme**.

The CRA results for the Kunene and Kavango basins reveal significant climate risks for key infrastructure. The following summarizes the primary climate risks for both regions:

Kunene Basin

- **Heat Stress:** Extreme heat is projected to become a dominant risk in the Kunene Basin, especially for **reservoirs, pipelines, and pump stations**, due to increasing temperatures and evaporation losses. The risk level is classified as **High**.
- **Drought:** Drought risk is significant, particularly for **groundwater-dependent systems** such as **boreholes and wells**, which are projected to face **Extreme** risk by mid-century (2040–2059). Reduced water availability and increased competition for resources will exacerbate water scarcity.
- **Pluvial and Fluvial Floods:** **High to Very High** risks for infrastructure in flood-prone areas, such as **pipelines, drainage systems, and pump stations**. These risks increase significantly with rising rainfall intensity under high-emission scenarios.
- **Wildfire:** **Extreme** risk to exposed infrastructure, particularly **plastic pipelines and solar PV systems**, due to increased temperatures and prolonged drought conditions.

Kavango Basin

- **Heat Stress:** **Pump stations and water treatment plants** are classified as **High** risk due to rising temperatures affecting operational efficiency and water treatment processes.
- **Drought:** **Moderate to High** risk for **boreholes and water supply systems** in areas like the **Rundu corridor**, which are vulnerable to decreased water availability during prolonged dry spells.
- **Pluvial Flooding:** **High** risk to infrastructure such as **pipelines and pumping stations** in flood-prone areas, particularly along the Okavango River corridor, which faces higher rainfall intensity.
- **Fluvial Flooding:** **Extreme** risk to infrastructure located along riverbanks, including **intake structures, pumping stations, and treatment facilities**, with significant potential damage from flood events.
- **Wildfire:** **Moderate to High** risk for **solar-powered systems and exposed infrastructure**, with an increasing risk of fires due to rising temperatures and prolonged dry conditions.

The CRVA highlights the urgent need for climate-resilient infrastructure and adaptive management strategies across the Kunene and Kavango basins. Key recommendations include:

- **Climate-proofing critical assets:** Implementing robust design measures such as **flood-proofing**, using **heat-resistant materials**, and **fireproofing** critical infrastructure like **pipelines, pump stations, and reservoirs**.
- **Building redundancy:** Ensuring **alternative water sources, backup power systems, and emergency preparedness** to guarantee service continuity during extreme events such as droughts, floods, and wildfires.
- **Enhanced operational flexibility:** Incorporating **adaptive management** practices into water systems to address future climate risks, including **early warning systems** and improved **maintenance protocols** to reduce vulnerability.

PART VII: Project Site Climate Risk and Vulnerability Analysis

This chapter assesses the climate risks and vulnerabilities affecting project sites identified under NWSISP II, with the objective of determining how planned WASH infrastructure may perform under current and future climate conditions. The intention of this analysis is to ensure that the design, siting, and operation of project components integrate climate-resilient measures from the outset. Although the initial project portfolio considered multiple planned investments, a full assessment requires highly detailed information at the asset level. Given the level of data available for the intended NWSISP II infrastructure projects at the time of the assessment, this chapter presents the complete climate risk and vulnerability analysis for the **Kavango Link Project**, which currently offers the necessary technical documentation, design parameters, and asset specifications to apply the CRA methodology in full. Additionally, a preliminary climate screening for the **Rundu 100-km rural water supply extensions** is provided.

Kavango Link Project

The Kavango Link Project is a strategic water transfer initiative designed to secure long-term water supply for Namibia's Central Area (CAN), including Windhoek and surrounding towns.

This infrastructure will connect key production and distribution nodes across a 277 km corridor, improving service reliability and addressing seasonal shortages. The project responds to projected increases in water demand driven by population growth and service expansion, under a Design–Build (DB) contract ensuring compliance with NamWater operational standards.

By 2050, water demand in the CAN region is expected to reach 68.8 Mm³/year, while existing supply capacity will remain below 39 Mm³/year, creating an annual deficit of 30 Mm³. To close this gap, the Kavango Link will deliver 35 Mm³/year, primarily serving Windhoek. Abstraction will be limited to 180 days/year during high-flow periods to minimize environmental impacts.

The Kavango Link Project is exposed to several climate hazards projected to intensify in the coming decades. **Fluvial flooding** represents a significant risk due to the site's proximity to major river channels and floodplain systems, where increased rainfall intensity may lead to inundation of low-lying sections of the alignment. **Pluvial flash floods** pose additional risks to above-ground or shallow-buried assets, potentially causing erosion, sediment accumulation, and damage to pipeline segments or access roads. The project site is also exposed to **rising temperatures and heat extremes**, which can reduce pump efficiency, stress mechanical components, and accelerate material degradation. While **drought** has a relatively lower direct impact on linear infrastructure, it may reduce water availability for abstraction, complicating operational reliability during prolonged dry periods. Together, these hazards create a multi-dimensional risk environment that must be addressed during design, construction, and operation.

To systematically assess climate risk, the project area is segmented into CRA zones that reflect differences in hazard intensity, exposure, and vulnerability of the associated assets. Each segment includes specific assets and associated design checks required to ensure resilience under future climate conditions.

- **Segment 1: High Flood Exposure Corridor**
Includes assets located closest to river channels or within areas historically affected by flooding. This segment covers the river abstraction pump station at Rundu, the initial 15 km of pipeline alignment near the Okavango River, and associated intake structures. Key design-check implications include elevating critical components, reinforcing pipeline anchoring, improving drainage and culvert capacity, and protecting embankments against erosion and scour.
- **Segment 2: Flashflood and Surface Runoff Zone**
Comprises areas exposed to intense pluvial flooding resulting from short-duration, high-intensity rainfall events. Assets may include pipeline sections crossing ephemeral streams and road crossings between Rundu and Grootfontein, as well as minor pump facilities near low-lying terrain. Recommended design considerations include increased burial depth, protective trenching, slope stabilization, and installation of diversion structures to manage concentrated runoff.
- **Segment 3: Heat- and Drought-Stressed Sector**
Encompasses above-ground facilities or pumping units situated in locations with high projected temperature increases. Assets typically include the base pump station, three booster pump stations, and associated electrical and mechanical equipment along the mid- and southern alignment. Design checks focus on heat-resistant materials, enhanced ventilation, pump derating considerations, and redundancy for power supply and cooling systems.
- **Segment 4: Low Vulnerability/Moderate Hazard Zone**
Covers areas where hazards are less intense or where asset vulnerability is inherently lower due to underground placement or protective siting. Assets may include deeply buried pipeline sections in stable terrain and network interconnections near Uitzicht. Design implications center on ensuring stability under fluctuating temperatures and incorporating routine monitoring to detect early structural stresses.

Each segment provides a clear basis for determining site-specific engineering measures and operational safeguards. The CRA framework allows project teams to prioritize interventions according to hazard intensity, asset criticality, and the potential consequences of failure, ensuring that resilience considerations are fully integrated into the project's lifecycle.

Rural Projects within 100Km radius of Rundu preliminary climate risk screening

The 100 km corridor surrounding Rundu represents a conceptual extension of rural water-supply systems under NWSISP II, aimed at improving access for dispersed communities along the Okavango River and its hinterlands. This area is strategically important because it supports domestic water supply, small-scale irrigation, and livestock watering in regions characterized by high poverty and limited WASH coverage. Its development is essential to reduce vulnerability to climate shocks in communities that currently depend on shallow boreholes and seasonal streams.

The climate risk profile of this corridor is shaped by five major hazards projected to intensify over time: heat stress, drought, pluvial flash floods, fluvial floods, and wildfires. Heat stress emerges as a pervasive constraint, escalating to high or extreme levels by mid-century under both emissions scenarios. Prolonged warm spells and frequent days exceeding 35°C will impose thermal stress on pumps, solar systems, and plastic pipelines, reducing operational efficiency and accelerating material degradation. Drought remains a persistent high hazard throughout the century, with SPEI and CDD indices indicating longer dry spells and multi-season deficits that undermine groundwater reliability and increase pressure on surface sources. Pluvial flash floods pose a recurrent threat due to short, intense storms that can wash out culverts, erode rural roads, and destabilize shallow-buried pipelines. Fluvial flooding along the Okavango River corridor adds further complexity, exposing intakes, pump stations, and low-lying kiosks to inundation and sediment loads. Wildfire risk, while moderate in the near term, rises to high levels later in the century as heat and dryness intensify, increasing ignition potential and spread rates.

Design and operational implications for the potential projects to be incorporated under NWSISP II include elevating intakes and pump houses, reinforcing embankments, sizing culverts for multi-day rainfall events, and installing diversion channels to manage flood risk. Heat resilience requires heat-resistant materials, improved ventilation in pump houses, derating of motors, and protection of PV arrays. Drought adaptation strategies should prioritize conservative groundwater yields, emergency storage, and conjunctive use of surface and groundwater sources. Wildfire protection calls for defensible space, fire-resistant enclosures, and backup power systems. Operational safeguards such as early warning systems for rainfall and river stage, drought triggers in Water Safety Plans, and pre-season maintenance of drainage and firebreaks are essential to maintain service continuity.

Risk prioritization places fluvial flooding at river-adjacent intakes and pump stations in the extreme category, while heat stress and drought rank as high risks across all asset classes. Pluvial flooding at culverts and kiosks also constitutes a high risk, whereas wildfire and localized erosion hazards are assessed as moderate. These findings underscore the need for integrated, climate-resilient design and adaptive management to secure reliable water services in the Rundu corridor under future climate conditions.

INTRODUCTION

The Global Center on Adaptation (GCA) is providing targeted technical support under the Africa Adaptation Acceleration Program (AAP) to the Government of the Republic of Namibia (GRN) and the African Development Bank (AfDB) for the implementation of the Namibia Water Sector Infrastructure Program Phase II (NWSIP II).

Namibia is the driest country in Sub-Saharan Africa, characterized by extremely limited water availability, high climatic variability, low and erratic rainfall, and a strong reliance on groundwater and transboundary water resources. These conditions, coupled with aging water infrastructure, growing population pressures, rapid urbanization, and structural gaps in sanitation, pose critical challenges for the country's water security.

To address these vulnerabilities, the Government of Namibia, with the support of the African Development Bank (AfDB), is implementing the **Namibia Water Sector Infrastructure Support Program – Phase II (NWSIP II)**. This strategic investment aims to improve access, quality, and resilience of water and sanitation services across the most climate-vulnerable northern regions. The program prioritizes climate-resilient infrastructure, including the rehabilitation of the Calueque-Oshakati raw water canal, development of the Abenab borehole scheme, expansion of rural water supply systems, and construction of climate-smart sanitation facilities. It also integrates objectives and intervention to ensure gender mainstreaming and social inclusion in the implementation of the NWSIP.

In this context, the Global Center on Adaptation (GCA) is providing upstream technical support to integrate climate resilience into the program. Through its Climate Resilient Water Services (CRWS) line of work under the **Africa Adaptation Acceleration Program (AAP)**, GCA is leading the **Climate Risk and Vulnerability Assessment (CRVA) and adaptation planning process** to inform project design and climate financing strategies.

By integrating climate change considerations and resilience-building measures into water infrastructure investments, this CRA aims to contribute to sustainable water security in Namibia. It seeks to ensure that the AfDB-financed interventions generate long-term, inclusive benefits—especially for women, girls, rural communities, and historically underserved groups—within a context of increasing climate uncertainty.

The CRVA will focus on investment locations in Northern Namibia as well as the broader Kunene and Kavango River basins, assessing current and future risks under different climate scenarios and time horizons. The assessment will support evidence-based decision-making to ensure the long-term sustainability of water and sanitation infrastructure and services in the face of intensifying climate impacts.

The first objective focuses on understanding current and future climate risks affecting the water sector in Namibia, focusing on the Kunene and Kavango basins. This includes the identification of hazard patterns, exposure, and vulnerabilities at national, regional, and local levels. The climate risks and vulnerabilities that threaten the sustainability of water infrastructure and services. This involves evaluating how both surface and groundwater systems, storage facilities, and supply networks—particularly those in rural and peri-urban areas—are exposed and sensitive to climate-related hazards under various future scenarios.

1 PART I. METHODOLOGY

1.1 Climate Change analysis

The climate change analysis chapter characterizes the recent climate and projected future changes at national level and for Namibia's Kunene and Okavango basins to support the Climate Risk and Vulnerability Assessment (CRVA) and the NWSSIP II planning windows.

Namibia is recognized as one of the most climate-vulnerable countries in Sub-Saharan Africa, with the Kunene and Okavango basins particularly exposed due to their geographic location and socio-ecological characteristics. These areas already experience considerable interannual climate variability, frequent droughts, erratic rainfall patterns, and high evapotranspiration rates—factors that are projected to intensify under future climate change scenarios.

1.1.1 Purpose and approach

The first step of the Climate Risk Assessments is to evaluate the projected changes for the most relevant climate variables (climate indices) that may have an impact on the assets of interest. For this evaluation, it is first necessary to characterize the climatology of Kunene and Okavango River basins (the area of interest) using climatological data from the World Bank Climate Change Knowledge Portal (CCKP).

1.1.2 Data sources and coverage

CCKP provides bias-adjusted CMIP6 projections on a regular grid of approximately 0.25°, together with historical climatologies derived from widely used observational and reanalysis datasets. We use portal outputs in two complementary ways.

First, absolute climatologies for specified periods (historical or future) are taken as the basis for maps and basin summaries. Second, anomalies and pre-computed climate indices are used directly when supplied by CCKP portal, always stating the reference period used in its computation.

The objective is to deliver a rigorous method that is, reproducible while remaining technically sound for engineering screening. Additionally, CCKP uses the Coordinated Regional Climate Downscaling Experiment (CORDEX) to provide higher-resolution climate projections. For Africa, the CORDEX-Africa initiative has developed datasets at a spatial resolution of approximately 0.44° (50 km), covering the entire mainland continent with a domain size of 194 x 201 grid points. These downscaled products significantly improve the ability to capture local climate features relevant for impact assessments, such as rainfall variability, extreme temperature events, and seasonal shifts.

1.1.3 Scenarios and time windows

Future projections are reported for two CMIP6 scenarios, SSP2-4.5 and SSP5-8.5, to bracket a stabilization pathway and a high-emissions pathway. To align with decision horizons, four future windows are used:

- (i) 2020-2039 as the near-term scenario (NF).
- (ii) 2040-2059 as the mid-term or mid-century period (MTF).
- (iii) 2060-2079 as a long-term or late-century period (LTF).
- (iv) Historical climatologies and anomalies are referenced to 1995–2014 as the Reference Period (RP).

These time horizons allow the project to assess near-term (2020-2039), midterm or mid-century (2049-2059) and long-term or late-century (2060-2079) anchors for planning and design envelopes. Covering the minimum and maximum expected lifespan of key infrastructure components under the Namibia Water Sector

Infrastructure Support Programme Phase II (NWSSIP II). Using near, mid, and long-term horizons allows the project to assess climate risks across the full asset life cycle:

- Shorter-lived elements such as solar-powered water pumps and purification systems may operate within a 10–15-year window.
- Long-lived investments like reservoirs and transmission pipelines may remain in service for up to 50 years or more. and to plan
- for the complete range of plausible future conditions.
- Additionally, the inclusion of the long-term horizon (2060–2079) is also aligned with the African Union’s continental vision, *Agenda 2063: The Africa We Want*, which calls for forward-looking infrastructure planning and resilience through 2063.

The emission scenarios used are:

- SSP2-4.5 (Stabilization scenario) representing a “middle-of-the-road” or business-as-usual pathway
- SSP5-8.5 (High emissions, worst-case scenario) representing a high-emissions worst-case pathway.

This dual-scenario approach provides a robust basis for stress-testing infrastructure performance under different climate futures, supporting the identification of no-regret and flexible adaptation strategies.

These trends and projections will serve as the foundation for the climate hazard mapping in subsequent phases of the assessment. Downscaled data and historical baselines will be cross validated using local meteorological records when available. The analysis will focus on identifying threshold conditions critical to the functionality and resilience of water supply, sanitation, and supporting infrastructure systems in the two river basins.

1.1.4 Geographic domain and spatial aggregation

All results are reported for two nested domains:

- The National extent of Namibia.
- At river basin level of the Kunene and Okavango basins. Portal grid cells are intersected with these polygons. Basin time series, indicator counts and summary values are computed as area-weighted means over each basin mask. When displayed as maps, values are shown at the native resolution of the underlying portal grid; when reported in tables, they represent spatial means over the relevant mask.

1.1.5 Pre-processing and quality checks

The analysis accepts the portal pipelines and applies consistency checks to ensure the CRVA purpose. These checks include: (i) examination of seasonal cycles and spatial gradients for climatological plausibility; (ii) verification that ensemble warming signals fall within ranges documented for Namibia; (iii) inspection that heavy-rainfall indicators peak in the north and northeast in line with wet-season maxima; (iv) confirmation that dry-spell metrics increase coherently in western and southern arid zones. These steps do not replace station-level validation but ensure that portal outputs are coherent and interpretable for screening-level risk work.

1.1.6 Climate indices

The index suite is aligned with ETCCDI/WMO practice and with the Namibia hazard framework so that results flow directly into the CRVA matrices:

- Heat and temperature stress are characterized by TXx (annual maximum of daily maximum temperature), WSDI (warm spell duration), and operational thresholds such as days with $T_{max} \geq 35^{\circ}\text{C}$ and, where relevant, $\geq 40^{\circ}\text{C}$.
- Short-duration heavy rainfall relevant to pluvial flash flooding is represented by Rx1day and, where available, counts of days with ≥ 50 mm.
- Multi-day rainfall relevant to fluvial responses is represented by Rx5day and counts of days with ≥ 20 mm.

- Dryness and meteorological drought are represented by CDD (maximum consecutive dry days) and SPEI 12-month accumulation windows.

Changes are computed with respect to the harmonized 1995–2014 baseline for the same indicator. All the climate indices used in the study are compiled in **table 1**.

Table 1. Climate indices used in the study.

Abbreviation	Climate indices name	Definition / Unit	Primary use (hazard)
TXx	Annual Maximum of Daily Maximum Temperature	Hottest daily Tmax each year; Δ vs RP in °C	Heat
TX90p	Warm Days (90th Percentile of Tmax)	Share of days with Tmax > RP 90th percentile (%)	Heat
WSDI	Warm Spell Duration Index	Days in spells ≥ 6 days with Tmax > RP 90th percentile (days/yr)	Heat
Rx1day	Maximum 1-day Precipitation	Wettest 1-day total in a year (mm) or Δ vs RP (%)	Fluvial
Rx5day	Maximum 5-day Precipitation	Wettest consecutive 5-day total (mm) or Δ vs RP (%)	Fluvial
R20mm	Very Heavy Precipitation Days	Days with precipitation ≥ 20 mm (days/yr)	Fluvial (frequency)
R50mm	Extremely Heavy Precipitation Days	Days with precipitation ≥ 50 mm (days/season)	Pluvial (frequency), Storms (frequency)
SDII	Simple Daily Intensity Index	Total precip on wet days / number of wet days (mm/day)	Pluvial, Storms
CDD	Consecutive Dry Days	Longest run of days with precip < 1 mm (days)	Drought, Wildfire
SPEI-12	Standardized Precipitation–Evapotranspiration Index	Standardized anomaly of (P–PET) over 12 months (σ)	Drought, Wildfire
SPI-12	Standardized Precipitation Index	Standardized anomaly of precipitation over 12 months (σ)	Drought (corroboration)

1.1.7 Ensemble treatment and agreement

All maps and tables summarize multi-model ensembles. Unless otherwise noted, the central tendency is the ensemble mean.

Basin-level figures report spread using interquartile ranges and the full model range. Maps or captions indicate areas of high or low model agreement to distinguish robust signals from areas where scenario or model differences are significant. No bespoke model weighting or performance-based selection is applied, as the portal ensembles are intended to be representative and ready for screening applications.

1.1.8 Limitations and appropriate use

Spatial detail is limited by the resolution of CCKP and very localized phenomena such as site-specific wind gusts. Some indicators, particularly wind, are not available across the portal, in which case qualitative engineering implications are provided with explicit notes on data availability.

For basin-scale screening and program planning, the portal-based ensemble provides transparent, reproducible evidence suitable for decision support. For engineering design at specific sites, these results should be paired with hydrologic or hydraulic studies and local observations.

Maps present either absolute climatology for the reference period or change relative to 1995–2014 for projections, always identifying the scenario and future window.

Basin tables and time series represent area-weighted means or counts over the Namibia portions of the Kunene and Okavango basins.

Climate indices maps and summaries indicate ensemble spread; where agreement is low, captions flag that results should be interpreted with caution. A cross-walk in the results section translates each index into the hazard classes and thresholds used by the CRVA so planners can move directly from projected change to a hazard level relevant for infrastructure decisions.

1.1.9 Validation and uncertainty

The climate information used in the CRVA comes from the World Bank Climate Change Knowledge Portal (CCKP) CMIP6 0.25-degree dataset, which is based on a multi-model CMIP6 ensemble that has been bias-corrected and downscaled using ERA5 for the 1995–2014 historical reference period. The analysis uses primarily the ensemble median as the central estimate for most indicators and time slices, and the 90th percentile for selected variables and horizons where a conservative, high-impact view is needed for stress-testing (for example, extreme rainfall indices). Beyond the bias correction and downscaling already applied in the CCKP dataset, no further statistical adjustment or formal comparison with national station records has been carried out in this study, due to limited and non-systematic access to national meteorological data. Instead, we have verified that the projected patterns and trends are physically plausible at basin and regional scale, and that related indicators (for example, temperature and hot-day counts, or rainfall and drought indices) behave consistently with each other.

Uncertainty is due to model structural differences, internal variability, scenario choice and the translation of continuous indicators into discrete hazard classes. The CCKP partly captures this through 10th–90th percentile ranges around the median, which indicate the spread of model results. In this context, the CRVA is designed to provide robust, decision-oriented ranges for key hazards—sufficient to support climate-resilient siting, design and prioritisation of NWSISP II investments.

1.2 Climate hazard assessment

This chapter sets out the methodology used to assess climate hazards and derive decision-ready risk evidence for water and sanitation (WASH) infrastructure in Namibia, with emphasis on the Kunene and Okavango river basins. It includes:

- Hazard identification and prioritization for the WASH sector in northern Namibia.
- Hazard intensity and hazard frequency calculations.
- Hazard labeling considering intensity and frequency into a single hazard level and time horizon.

The methodology is aligned with international standards for climate-risk assessment and water utility management, and it is suitable for due diligence under the African Development Bank (AfDB) Climate Safeguards System (CSS) and the Updated Integrated Safeguards System (ISS). [18,19,1,2,3,9]

1.2.1 Standards and traceability

This assessment conforms to:

- ISO 14091:2021 on adaptation to climate change—guidelines for vulnerability, impact and risk assessment.
- ISO 14090:2019 on adaptation principles and requirements.
- ISO 31000:2018 on risk management.
- ISO 31010:2019 on risk assessment techniques.
- Sector-specific guidance is drawn from ISO 24510:2007 (service to users), ISO 24511:2007 (management of wastewater utilities), ISO 24512:2007 (management of drinking water utilities), ISO 24516-1:2016 (asset management of drinking-water distribution networks) and ISO 24518:2015 (crisis management of water utilities).

These standards frame the CRVA definitions, classification logic, assumptions and limitations. [1,2,3,4,5,6,7,8].

1.2.2 Climate Hazards identification

Northern Namibia is arid to semi-arid, with high inter-annual rainfall variability and strong transboundary influences from Angola and Zambia. For WASH systems, the most relevant climate hazards are extreme heat, drought, pluvial flash floods, fluvial floods, strong winds and convective storms and wildfires. These hazards were prioritized based on the national climate-risk evidence based in Namibia's Fourth National Communication to the UNFCCC, the World Bank Climate Risk Country Profile for Namibia, UNDRR Disaster Risk Profile, global screening (GFDRR ThinkHazard), combined with infrastructure exposure patterns in the NWSSIP II pipeline. [14,16,15,17].

1.2.3 Hazard level analysis

Each hazard is represented by a pair of measurable components: intensity and frequency components. The intensity component measures how strong the hazard is with respect to the RP; the frequency component measures how often events of concern occur within a season, year or decade. Both components are computed from the indices listed in Table 1, using thresholds that are locally calibrated and widely adopted in the extreme's literature and WMO/ETCCDI guidance. The following subsections make every calculation explicit and justify each threshold. [12,10,11,3]

1.2.3.1 Heat Stress

Extreme heat affects WASH assets via higher evaporation in open storage and conveyance, softening of polymers and linings, accelerated disinfectant decay, reduced oxygen solubility for biological processes, and derating/overheating of pump/VSD and electro-mechanical equipment; it also reduces PV efficiency and worker productivity and safety. [1]

The hazard of extreme heat events is assessed by combining intensity and frequency using suitable climate indices. Intensity is quantified from the annual maximum of daily maximum temperature (TXx) and warm days above the 90th percentile (TX90p); frequency is measured with the Warm Spell Duration Index (WSDI). TXx and WSDI are ETCCDI indices designed for robust detection of heat-related extremes and persistence. Heat thresholds interface directly with ISO 24512/24516 asset management for temperature-sensitive components and ISO 24518 crisis readiness for staff safety and process stability. [12,7,8]

- **Low-intensity** events were defined as a +0.0–0.7 °C increase in the annual maximum of daily temperature (ΔTXx) versus the reference period (RP). This band reflects temperature changes unlikely to materially affect asset performance beyond routine design margins.
- **Moderate-intensity** events were assigned for +0.8–1.7 °C (ΔTXx), recognizing non-linear sensitivity of WASH systems: higher reservoir and canal evaporation, faster disinfectant decay and biofilm growth, reduced oxygen solubility for biological processes, and increased risk of motor/VSD overheating in poorly ventilated pump houses.
- **High-intensity** events were identified for $\geq +1.8$ °C (ΔTXx). At this level, cumulative effects (thermal stress on polymers/linings, higher head loss with warmer water, process instability in sludge/biological treatment, and elevated O&M cooling needs) can materially degrade service reliability without targeted adaptation.

Frequency is measured as the number of days per year in warm spells above the 90th percentile of the reference period (WSDI):

- **Low-frequency** events were defined as ≤ 29 days/year in warm-spell conditions ($\leq p90$ exceedance days), consistent with isolated heatwaves manageable through operational measures.
- **Moderate-frequency** events were set at 30–58 days/year, indicating recurrent heatwaves that materially increase O&M burden (shift scheduling, ventilation/cooling, reservoir level management).
- **High-frequency** events were > 58 days/year, reflecting persistent heat stress that elevates failure likelihood in electro-mechanical equipment and increases evaporative losses from open storage and conveyance.

We assign the heat-stress hazard level by combining intensity and frequency in a 3×3 matrix. Frequency is evaluated with WSDI and expressed as days per year of warm spells: low frequency is ≤ 29 days/year, medium frequency is 30–58 days/year, and high frequency is > 58 days/year.

- **When intensity is low**, the hazard is low if warm spells are infrequent, moderate when they occur with medium frequency, and high when they are frequent.
- **When intensity is moderate**—defined as an increase between 0.8 and 1.7 °C in the annual maximum of daily temperature—the hazard is moderate under low frequency, high under medium frequency, and very high under high frequency.
- **When intensity is high**—defined as an increase of at least 1.8 °C—the hazard is high under low frequency, very high under medium frequency, and extreme under high frequency.

All metrics are calculated for each location and each future horizon. The ensemble median is reported as the central estimate, and the interquartile range (IQR) quantifies the associated uncertainty. The heat-stress hazard levels are reported for each grid cell area and scenario.

Table 2. Hazard level matrix to assess Heat stress.

Hazard intensity	Hazard Frequency		
	Low 29 days or less	Moderate 30-58 days	High More than 58 days
High intensity 1.8°C - more	High	Very High	Extreme
Moderate intensity 0.8 - 1.7 °C	Moderate	High	Very High
Low intensity 0.0- 0.7 °C	Low	Moderate	High

1.2.3.2 Drought

The drought hazard level is quantified by intensity and frequency from standardized hydro-climatic indices and hydrologic indicators relevant to surface and groundwater that supply WASH services, relative to the historical reference period (RP). Intensity is assigned using a multi-indicator approach centered on the 12-month Standardized Precipitation–Evapotranspiration Index (SPEI-12) as the primary signal, with Consecutive Dry Days (CDD) anomalies characterizing dry-spell persistence. For each asset, the strongest indicator available sets the intensity, with the other used for corroboration. Heat and drought thresholds interface with ISO 24512/24516 asset management for water utilities and ISO 24518 crisis readiness for staff safety and process stability. [12,7,8].

- **Low-intensity** drought corresponds to mild hydro-climatic deficits (e.g., SPEI -0.5 to -0.99 or small CDD anomalies, ≤ +4 days) typically absorbed by operational storage and demand management.
- **Moderate-intensity** drought is set at SPEI -1.0 to -1.49 or CDD anomaly +5–15 days.
- **High-intensity** drought is SPEI ≤ -1.5 or CDD anomaly ≥ +16 days.

Frequency counts years per decade with at least one event meeting the relevant intensity threshold: low frequency is ≤ 1–2 years/decade; moderate frequency is 2–3 years/decade; high frequency is ≥ 4 years/decade or multi-season drought.

We assign the drought hazard level by combining intensity and frequency in a 3 by 3 matrix:

- **When intensity is low**, the hazard is low under low frequency, moderate under moderate frequency, and high under high frequency.
- **When intensity is moderate**, the hazard is moderate under low frequency, high under moderate frequency, and very high under high frequency.
- **When intensity is high**, the hazard is high under low frequency, very high under moderate frequency, and extreme under high frequency.

All metrics are calculated for each location/asset and for each future horizon. The ensemble median is reported as the central estimate, and the interquartile range (IQR) quantifies the associated uncertainty. Drought hazard levels are reported for each grid cell area and scenario.

Table 3. Hazard level matrix to assess droughts.

Hazard intensity	Hazard Frequency		
	Low ≤ 1–2 yrs/dec	Moderate 2–3 yrs/dec	High ≥ 4 yrs/dec
High intensity SPEI ≤ -1.5; CDD ≥ 16	High	Very High	Extreme
Moderate intensity SPEI -1.0 to -1.49; CDD 5–15	Moderate	High	Very High
Low intensity SPEI -0.5 to -0.99 or minor anomalies; CDD ≤ 4	Low	Moderate	High

1.2.3.3 Pluvial flash floods (short-duration, high-intensity rainfall)

Convective storms can damage elevated tanks, kiosks, solar frames, and pump-station electrical systems (including lightning/surge), and trigger flash-flooding that undermines rural distribution lines, latrines, kiosks, compound drainage, and access roads. Where wind fields are unavailable, precipitation extremes are used as severity proxies. The indicators used are:

- Seasonal maximum 1-day precipitation (Rx1day).
- 50th/95th percentile of Rx1day from the baseline (P95).
- Simple Daily Intensity Index (SDII) as the total precipitation on wet days divided by the number of wet days.
- Count of days with ≥50 mm in the rainy season (R50mm).

We classify intensity by comparing observed storm metrics to a fixed climatological baseline at the station/grid-cell level:

- **Low intensity** (Rx1day ≤ P50) is unlikely to exceed local drainage capacity or destabilize soils around latrines, kiosks, or shallow-buried pipelines.
- **Moderate intensity** (Rx1day > P50–P95 of RP, or SDII +5–10%) captures events that overload compound drainage, erode access roads, and expose shallow pipelines.
- **High intensity** (Rx1day > P95 of RP, or ≥50 mm/day, or SDII > +10%) is consistent with pit latrine collapse, infiltration/inflow surges, and washouts at culverts and small-stream crossings. [12,10,11]

We compute frequency per rainy season by counting the number of days with ≥50 mm of rainfall (R50mm) at the site or area. For multi-year analysis we summarize by season (how many seasons fall in each band) or use the average R50mm per season to capture recurrence [12,11]:

- **Low frequency:** R50mm = 0–1 days/season (isolated shocks).
- **Moderate frequency:** R50mm = 2–3 days/season (recurrent O&M disruption).
- **High frequency:** R50mm ≥ 4 (regular failures without drainage upgrades).

Percentile-based Rx1day and SDII are the recommended ETCCDI tools for short-duration extremes; the ≥50 mm/day marker is widely used in impact studies and provides a clear O&M-relevant trigger compatible with ISO 24518 emergency procedures [12,7]:

We assign the pluvial flash-flood hazard level by combining intensity and frequency in a 3 by 3 matrix.

- **When intensity is low**, the hazard is low under low frequency, moderate under moderate frequency, and high under high frequency.
- **When intensity is moderate**, the hazard is moderate under low frequency, high under moderate frequency, and very high under high frequency.
- **When intensity is high**, the hazard is high under low frequency, very high under moderate frequency, and extreme under high frequency.

All metrics are calculated for each location and each future horizon. The ensemble median is reported as the central estimate, and the interquartile range (IQR) quantifies the associated uncertainty. Pluvial flash-flood hazard levels are reported for each grid cell or service area and scenario.

Table 4. Hazard level matrix to assess pluvial flash floods

Hazard intensity	Frequency		
	Low R50=0–1	Moderate R50=2–3	High R50 ≥ 4
High Intensity Rx1day >P95 or ≥50 mm or SDII > +10%	High	Very High	Extreme
Moderate Intensity Rx1day >P50 or SDII +5–10%	Moderate	High	Very High
Low Intensity Rx1day ≤P50	Low	Moderate	High

1.2.3.4 Fluvial floods

Flood hazard to WASH assets (intakes, canals, borehole heads, pump houses, access roads, elevated tanks) is assessed via precipitation extremes and, where available, hydrologic response. Fluvial floods are relevant to intakes, river crossings, canal embankments, elevated tanks near floodplains, and access/SCADA rooms vulnerable to inundation.

Maximum 5-day precipitation (Rx5day) is used as a precipitation-extreme proxy.

Intensity is calculated in the reference period (RP) using station/grid-cell climatology and, where available, hydrologic response:

- **Low intensity** was set at Rx5day ≤ P50 of the reference period, typically within channel capacity and existing protection for intakes and canals.
- **Moderate intensity** (Rx5day > P50–P75 of RP) reflects events with meaningful siltation/contamination risk at intakes and localized overtopping of canals or access road inundation. [12,10,11]
- **High intensity** (Rx5day > P75 of RP) indicates conditions capable of structural damage (borehole heads, pump houses), widespread water-quality deterioration, and supply interruptions without additional protection. [12,10,11]

Frequency measures:

- Number of very heavy precipitation days (R20mm) per year (count of days with ≥20 mm).
- Multi-year summary using either seasonal counts (how many seasons fall in each band) or the average R20mm per season.

Frequency calculation. We take the more conservative of two measures: (i) R20mm (days with ≥20 mm/year) classed as Low (0–2), Moderate (3–5), High (≥6). [12,11]

Justification. Multi-day precipitation percentiles are standard proxies for fluvial hazard. [8,3]

We assign the fluvial-flood hazard level by combining intensity and frequency in a 3 by 3 matrix:

- **When intensity is low**, the hazard is low under low frequency, moderate under moderate frequency, and high under high frequency.
- **When intensity is moderate**, the hazard is moderate under low frequency, high under moderate frequency, and very high under high frequency.
- **When intensity is high**, the hazard is high under low frequency, very high under moderate frequency, and extreme under high frequency.

All metrics are calculated for each location and each future horizon. The ensemble median is reported as the central estimate, and the interquartile range (IQR) quantifies the associated uncertainty. Fluvial-flood hazard levels are reported for each grid cell or service area and scenario.

Table 5. Hazard level matrix to assess fluvial floods.

Hazard intensity	Frequency		
	Low R20=0–2	Moderate R20=3–5	High R20≥6
High intensity Rx5day >P75	High	Very High	Extreme
Moderate intensity Rx5day >P50–P75	Moderate	High	Very High
Low intensity Rx5day ≤P50	Low	Moderate	High

1.2.3.1 Storms

Convective storms can damage elevated tanks, kiosks, solar frames, pump-station electrical/SCADA rooms, telemetry masts, river/canal crossings and access roads. Lightning surge can compromise electrical systems, and wind-driven rain can force water into equipment housings and control rooms.

We classify intensity against a fixed reference period using wind-first metrics where wind fields are available. Where wind is missing, precipitation-based proxies are applied.

Precipitation-based proxies (when wind fields are unavailable or incomplete) [12,10,11] are: Maximum 1-day precipitation (Rx1day) and Maximum 5-day precipitation (Rx5day).

- **Low intensity** when Rx1day/Rx5day ≤ P75 (usually within drainage and structural capacity).
- **Moderate intensity** when Rx1day/Rx5day > P75–P95 (storm runoff, localized overtopping and erosion).
- **High intensity** when Rx1day/Rx5day > P95 (likely structural/erosion damage, widespread service disruption).

For frequency we count how many “stormy” or “very heavy” days a season produces and classify that count. Wind-based counts are used when available; otherwise, rainfall proxies are used:

- Number of very heavy precipitation days (R20mm): days with ≥20 mm in a day.
- Number of extremely heavy precipitation days (R50mm): days with ≥50 mm in a day.

The most conservative among the available indicators is used to determine the frequency class. Low frequency when R20mm = 0–2 per year or R50mm = 0–1 per season; Moderate frequency when R20mm = 3–5 or R50mm = 2–3; High frequency when R20mm ≥ 6 or R50mm ≥ 4.

We assign the storm hazard level by combining intensity and frequency in a 3 by 3 matrix:

- **When intensity is low**, the hazard is low under low frequency, moderate under moderate frequency, and high under high frequency.
- **When intensity is moderate**, the hazard is moderate under low frequency, high under moderate frequency, and very high under high frequency.
- **When intensity is high**, the hazard is high under low frequency, very high under moderate frequency, and extreme under high frequency.

Justification. Percentile-based Rx1day/Rx5day are standard ETCCDI proxies for short-duration convective severity, and the ≥50 mm/day threshold is widely used in impact studies; storm triggers and response protocols are compatible with ISO 24518 emergency procedures for water utilities. [12,7]

All metrics are calculated for each location and each future horizon. The ensemble median is reported as the central estimate, and the interquartile range (IQR) quantifies the associated uncertainty. Storm hazard levels are reported for each grid cell area and scenario.

Table 6. Hazard level matrix to assess Storms.

Hazard intensity	Hazard Frequency		
	Low R20=0-2 / R50=0-1	Moderate R20=3-5 / R50=2-3	High R20≥6 / R50≥4
High Rx >P95	High	Very High	Extreme
Moderate Rx >P75-P95	Moderate	High	Very High
Low Rx ≤P75	Low	Moderate	High

1.2.3.1 Wildfires

Wildfire is treated as a complementary climate hazard for WASH assets exposed (especially plastic HDPE/PVC pipelines, GRP/PE tanks, remote solar PV arrays and cabling, kiosks, meter boxes and telemetry masts). Prolonged heat and dryness raise ignition and spread potential, leading to melting or deformation of plastics, loss of power and control at remote pumps, smoke and dust contamination of panels and cabinets, and blocked access routes that lengthen repair times.

The indicators used to measure intensity are as follows:

- Number of days with maximum temperature $\geq 35\text{ }^{\circ}\text{C}$ (TX35): captures thermal stress on fuels and installations.
- Standardized Precipitation–Evapotranspiration Index (SPEI-12): integrates rainfall and evaporative demand over 12 months, signaling seasonal fuel aridity and moisture stress.
- Consecutive Dry Days (CDD) anomaly: measures prolonged rain-free spells versus the baseline, indicating fuel curing and easier ignition/spread.
- Number of tropical nights (minimum temperature $> 20\text{ }^{\circ}\text{C}$): persistent warm nights dry fuels continuously and raise operator fatigue and safety concerns.
- Monthly precipitation minus potential evapotranspiration (P-PET): water-balance signal; large negatives mark sustained dryness.

Intensity (any primary active signal qualifies):

- **Low intensity:** no active thermal or dryness signal (routine wayleave, vegetation management sufficient).
- **Moderate intensity:** TX35 \geq P75, or SPEI-12 \leq -1.0, or CDD anomaly +6–15 indicates elevated ignition and spread potential of fire.
- **High intensity:** TX35 \geq P90, or SPEI-12 \leq -1.5, or CDD anomaly \geq +16 reflects sustained fuel aridity with credible risk of pipe deformation, PV damage, and access restrictions.

Complementary cues (support escalation when multiple cues co-occur): Tropical nights \geq P90.

Frequency (5-year window): define an “active season” when at least one cue reaches its threshold; then classify the 5-year window by the number of active seasons:

- Thermal load: TX35 days \geq P75 (Moderate) or \geq P90 (High).
- Short-term dryness: SPEI-12 \leq -1.0 (Moderate) or \leq -1.5 (High).
- Persistence of dryness: CDD anomaly +6–15 (Moderate) or \geq +16 (High).

Frequency classes:

- Low frequency: 0 active seasons within 5 years.
- Moderate frequency: 1 active season within 5 years.
- High frequency: ≥ 2 active seasons within 5 years.

We assign the wildfire hazard level by combining intensity and frequency in a 3 by 3 matrix:

- **When intensity is low**, the hazard is low under low frequency, moderate under moderate frequency, and high under high frequency.

- **When intensity is moderate**, the hazard is moderate under low frequency, high under moderate frequency, and very high under high frequency.
- **When intensity is high**, the hazard is high under low frequency, very high under moderate frequency, and extreme under high frequency.

All metrics are calculated for each location and each future horizon. The ensemble median is reported as the central estimate, and the interquartile range (IQR) quantifies the associated uncertainty. Wildfire hazard levels are reported for each grid cell area and scenario.

Table 7. Hazard level matrix to assess Wildfires.

Hazard intensity	Hazard Frequency		
	Low 0/5 yrs	Moderate 1/5 yrs	High ≥2/5 yrs
High ≥1 primary signal	High	Very High	Extreme
Moderate ≥1 primary signal	Moderate	High	Very High
Low No active signal	Low	Moderate	High

1.3 Multi-Hazard Hotspots methodology

This chapter describes how multi-hazard hotspots were derived for the Kunene and Okavango basins. The approach is consistent with a climate-risk screening logic that highlights the locations where multiple hazards co-occur at high intensity so that robust design measures and adaptive pathways can be prioritised.

A hotspot is any grid cell where all assessed hazards, in the overlay, reach at least high levels in the same scenario and time slice. Five climate hazards were assessed with consistent data and methods: (i) heat stress, (ii) drought, (iii) pluvial flash floods, (iv) fluvial floods and (v) wildfires. All hazard layers are built from multi-model ensemble projections against the historical reference period 1995–2014. Two emissions pathways are analysed (SSP2-4.5 and SSP5-8.5) and three time slices are reported: 2020–2039, 2040–2059 and 2060–2079. Each hazard raster is classified into ordered categories: Very Low, Low, Medium, High, Very High and Extreme.

In multi-hazard maps specific hotspot areas are defined as grid cells that fall within the High, Very High or Extreme hazard classes (hereafter “High+”). These High+ bands are used to derive the multi-hazard hotspot maps for the Kunene and Okavango basins and for the 100-km Rundu rural water-supply corridor. Multi-Hazard Hotspot maps support prioritisation and the choice of robust design options but should be read in a broader context together with assets exposure, criticality of services and feasibility constraints.

Heat stress and wildfires are projected to be spatially pervasive and intense across both basins in all future horizons. Therefore those have been treated as baseline, basin-wide constraints rather than discriminators of where risk concentrates. To reveal meaningful spatial differentiation, the hotspot analysis has combined only the remaining three hazards: pluvial flash floods, fluvial floods and drought.

Hotspots do not replace single-hazard maps. They identify where multiple hazards are simultaneously high. In the hotspot analysis the areas out of the hotspots are not necessarily low risk or safe: the background hazards of heat stress and wildfires remain active basin-wide and should be addressed by universal design measures.

1.4 Climate exposure assessment methodology

The exposure analysis determines whether each hazard can physically affect WASH assets and potentially cause damage. Geocoded assets—pipelines, reservoirs, boreholes, pump stations, treatment units, and distribution networks—are overlaid on hazard-class rasters for each scenario (SSP2-4.5, SSP5-8.5) and time slice (2020–2039, 2040–2059, 2060–2079). Each asset is assigned the hazard class of its underlying grid cell. Results are reported by constituency and asset type as the proportion of assets in the High, Very High, and Extreme exposure bands (collectively, “High+”), with critical nodes (e.g., pump stations, borehole and dams) explicitly flagged. In the inventory tables, “NA” denotes that a given asset type is not present in a constituency.

For Kunene North, Kunene South, Kavango West, and Kavango East, maps depict the spatial evolution of exposure from the near term to the long term, while companion tables quantify the share of assets falling in High+ bands. These outputs enable synthesis of spatial patterns and translation into implications for WASH design and operations.

Where suitable data exist, exposure results are corroborated with historical damage-and-loss records by hazard to relate modelled exposure to observed consequences, refine prioritization, and ground recommended measures in documented impact levels.

1.5 Climate vulnerability assessment methodology

1.5.1 Vulnerability assessment of WASH assets in Kunene and Okavango regions

The methodology for vulnerability assessment of WASH assets in Kunene and Okavango regions by constituency defines how vulnerability will be quantified for water, sanitation and hygiene assets under climate hazards in both basins. The objective is to estimate how each asset type is likely to perform when exposed to climate hazard conditions in each scenario and time slice, and to aggregate results to constituencies and regions by basin for design and planning. The approach is aligned with international good practice for climate risk assessment and with African Development Bank guidance, and it is designed to operate under both data rich and data limited conditions.

Vulnerability is treated as the propensity of an exposed system to suffer adverse effects when a hazard occurs. In operational terms it combines two ideas. *Sensitivity* reflects the degree to which the physical asset and its service functions react to stress because of siting, materials and process design. *Adaptive capacity* reflects the ability of the operator and the institutional context to anticipate, absorb, accommodate and recover through redundancy, procedures, standby power and access to spares. *Hazards* considered are heat stress, drought, pluvial flooding driven by intense rainfall, fluvial flooding driven by river levels and wildfires. Hazard fields are taken from the climate ensemble used in the hazard chapter, and model spread is acknowledged through ensemble statistics.

Assessment units are individual geocoded WASH assets in the inventory of water supply points (NSA 2022) from the Ministry of Agriculture, Fisheries, Water & Land Reform. Those for urban areas are from the Ministry of Urban and Rural Development (2022), including boreholes and wells, public taps and kiosks, tanker filling points, pump stations, small dams and assets listed as “other”.

Spatial roll ups are provided at constituency, region and basin level. Given information constraints the assessment is prioritised on multi hazard hotspots, which are areas where the discriminating hazards co-occur at high, very high or extreme levels. Heat stress and wildfire remain basin wide constraints and are handled through design notes that apply universally.

Vulnerability is resolved into four engineering dimensions that together reflect both infrastructure fragility and service performance:

- Physical Damage (PD): describes structural or material harm to works and equipment such as scour, inundation of electrical components or heat damage.

- Operability (OP): describes the ability to run and be accessed during and after the event including loss of access, power interruptions, intake clogging and tanker queuing.
- Service Life (SL): describes long term degradation and maintenance burden such as heat ageing of elastomers, siltation and abrasion or corrosion from wet dry cycling.
- Functionality or Productivity (FL): describes the capacity to deliver the required output and quality such as yield or pressure shortfalls and raw water quality.

Each dimension is scored on a continuous scale between zero and one for each asset type and hazard. A score of zero indicates negligible effect and a score of one indicates severe effect.

Scores are combined in a single **Vulnerability Index** using fixed weights that are consistent with typical WASH impact pathways. The Vulnerability Index is the weighted sum of the four-dimension scores:

- Physical damage weight is 0.30
- Operability weight is 0.35
- Service life weight is 0.15; and
- Functionality weight is 0.20.

For reporting the index is classified into four bands so that results can be compared across hazards and locations:

- Low: corresponds to values below zero point two five,
- Moderate: corresponds to values from zero point two five to below zero point five zero,
- High: corresponds to values from zero point five zero to below zero point seven five, and
- Very high: corresponds to values of zero point seven five and above.

Two parameterisation modes are supported so that results remain traceable as new information becomes available. In the data rich mode, the four-dimension scores are derived from measured attributes at the site such as plinth or threshold elevations relative to mapped flood depths, pump intake margins relative to projected drawdown, motor control centre elevations and enclosure ratings, storage autonomy and access vulnerability.

In the data limited mode which applies when site attributes are missing, scores are set by typology-based defaults per asset type and hazard. These defaults are derived from engineering judgement, prior operations and service guidance and are applied uniformly to assets of that type within a constituency. All defaults are recorded in an annex table and can be updated when field information arrives.

To maintain a link with the vocabulary used in standards, the four dimensions can be mapped to sensitivity and adaptive capacity. Sensitivity is represented by a sub-index that emphasises physical damage and service life together with the intrinsic part of the productivity dimension driven by design and yield limits. Adaptive capacity is represented by a sub-index that emphasises operability together with the managerial part of the productivity dimension driven by procedures, standby power and redundancy. Where required, a qualitative three by three combination of sensitivity and adaptive capacity can be reported alongside the Vulnerability Index to maintain compatibility with guidance.

Hazard specific interpretation rules ensure that dimension scores are assigned consistently.

- For drought, the dominant effects are on operability and productivity through yield and pressure losses and increased reliance on tanker service, while direct physical damage is typically limited.
- For pluvial flooding, physical damage is influenced by inundation and debris impact at low plinths and operability is affected by access loss and electrical submergence, while productivity is reduced by turbidity spikes and short outages.
- For fluvial flooding, longer saturation and hydraulic loads affect crossings and embankments, overbank flows and isolation affect operability and raw water interruptions and sediment pulses derate productivity.
- For heat stress, materials and electrical systems experience derating and thermal trips, longer term ageing accelerates and output falls through lower pump efficiency at higher temperatures.
- For wildfire, radiant heat and combustion threaten kiosks and cables, safety shutdowns and smoke limit operations and water quality can be affected by ash.

The workflow to implement the methodology is structured as a sequence of transparent steps.



1. First, inputs are imported which include the asset inventory, the hazard layers and the hotspot polygons for the selected scenario and time slice.
2. Second, the dimension scores are assigned for each asset type and hazard either from measured attributes where available or from typology-based defaults where site attributes are missing.
3. Third, the Vulnerability Index is computed per asset and hazard using the fixed weights and the results are stored together with a confidence flag that reflects the richness of the underlying data.
4. Fourth, results are aggregated to constituency, sub-region and basin level.
 - a. Asset type summaries report average values and the share of assets in the higher classes.
 - b. Constituency summaries report the average index across present asset types and identify the asset types that contribute most to vulnerability.
 - c. Basin summaries present the distribution of classes and maps.
5. Finally, quality assurance and traceability checks are applied to outliers, and all assumptions, weights and thresholds are documented for review.

The methodology is consistent with principles for climate risk assessment and with sector guidance for drinking water and wastewater services and provides a practical and transparent basis to update results as field data become available.

1.6 Climate risk assessment methodology

1.6.1 Climate Risk Calculation Method for screening with asset-specific limited data

The Climate Risk and Vulnerability Assessment (CRVA) apply a structured, engineering-based method that converts limited but spatially explicit information (spatial exposure, typology-based vulnerability and systemic criticality) into a transparent, formula-based Climate Risk Index. The process is robust under limited data conditions, replicable across basins, and suitable for decision-making in infrastructure planning and climate adaptation

The process is intentionally formula-driven, enabling defensible screening even when detailed asset-specific data are unavailable.

Step 1. Establish Exposure. Exposure is quantified as the percentage of assets, by typology and constituency, that fall within the High, Very High, or Extreme hazard hotspot classes (High +). This is computed directly overlying GIS asset coordinates with hazard hotspot rasters.

$$\% \text{ Exposed Assets in High+} = (\text{Assets in High+ hotspots} / \text{Total assets}) \times 100$$

Step 2. Compute the Vulnerability Index (VI). Vulnerability is evaluated at typology-level, not per individual asset, to reflect structural sensitivity under limited-data conditions. Each asset-hazard combination is scored across four engineering criteria: (i) Physical Damage (PD); (ii) Operability (OP); (iii) Service Life degradation (SL); and (iv) Productivity loss (or functionality) (PR). The resulting Vulnerability Index represents the intrinsic susceptibility of each asset type to each hazard, independently of its location.

The weighted formula is:

$$\text{Vulnerability Index (VI)} = 0.35 \text{ PD} + 0.30 \text{ OP} + 0.15 \text{ SL} + 0.20 \text{ PR}$$

Step 3. Assign Criticality (C). Criticality adjusts the vulnerability score to reflect the systemic importance of an asset type. Fixed multipliers are used due to limited performance data. Thus: C = Criticality multiplier per typology: (i) Pump stations, intakes, treatment units (C=1.30); (ii) Motorised boreholes, dams (C=1.20); (iii) Tanker filling points (C= 1.10); Public taps, wells, other small assets (C=1)

Step 4. Compute Hazard-Specific Risk per Asset Type. For each hazard, constituency, scenario and time slice, the risk per asset type is computed. This step transforms exposure and engineering susceptibility into a quantified hazard-specific risk value:

$$\text{Risk (asset, hazard)} = \% \text{ High+} \times \text{VI} \times \text{C}$$

Step 5. Aggregate Risks Across Asset Types. The constituency-level risk for each hazard is obtained by summing the contributions of all asset typologies. This produces a continuous index useful for comparing hazard impacts across locations:

$$\text{Risk hazard Constituency} = \Sigma (\% \text{High+} \times \text{VI} \times \text{C})$$

Step 7 – Multi-Hazard Aggregation (Optional). A composite climate risk score is obtained by summing hazard-specific risks. This identifies constituencies facing cumulative impacts across hazards.

Step 8. Interpretation and Prioritisation. The resulting scores allow ranking and categorisation of constituencies as Low, Moderate, High or Very High risk. They guide: (i) Design upgrades; (ii) preparedness planning; (iii) investment prioritisation; (iv) Integration into long-term WASH planning.

1.6.2 Climate Risk assessment method when asset-specific data is available (Kavango-Link water project).

The climate risk assessment for the CAN–Okavango Link follows the standard risk framing used by the IPCC and climate-resilient infrastructure guidelines. In this framing, climate risk is understood as the combined effect of: (i) climate-related hazards, (ii) the exposure of the infrastructure to those hazards, and (iii) the vulnerability of the system.

The objective of the assessment is to identify and compare climate risk levels along the Okavango Link – including the intake, pump stations and transmission pipeline – and to support the design of robust adaptation measures. This is achieved by: (i) segmenting the project into homogeneous stretches of infrastructure, (ii) characterising present and future climate hazards for each stretch, (iii) assessing vulnerability in four dimensions of infrastructure performance, and (iv) combining hazard and vulnerability into a segment-level climate risk index.

Climate data, scenarios and hazard indicators

Climate hazards are derived from regional climate model projections and hydrological simulations used for the project. The analysis is performed for standard future time horizons (near-, mid- and late-century) and for at least two emissions scenarios.

From these datasets, a focused set of hazard indicators is derived for the project area, including:

- Changes in mean, minimum and maximum air temperature.
- Changes in total annual and seasonal precipitation.
- Changes in drought characteristics, especially the longest dry spell.
- Changes in river regime at and around the intake and along the conveyance system.

All indicators are expressed as changes (absolute or percentage) relative to a historical baseline period. This allows direct comparison between present and future conditions.

Segmentation of infrastructure and exposure analysis

Because the CAN–Okavango Link is a linear system, the analysis is carried out by infrastructure segments. The alignment is subdivided into stretches that are homogeneous in terms of:

- Asset type (intake, pump station, buried pipeline, above-ground pipeline).
- Topographic, geotechnical and land-use context.
- Climate-hazard patterns, according to the gridded hazard maps.

Break points are placed at all major nodes (intake and pump stations), at crossings with significant hydrological features, and wherever hazard classes change along the alignment. This segmentation creates a set of stretches that each have a coherent exposure profile.

For each segment, the geometry of the stretch is overlaid with the climate and hydrological rasters within a GIS. For each hazard indicator and time horizon, representative values are extracted (e.g. median or upper-quantile values within or near the segment). These values define the exposure of that segment to each hazard. Where several grid cells intersect a segment, the dominant or worst-case class is retained to avoid underestimating risk.

Vulnerability assessment in four dimensions

Vulnerability is assessed for each segment in four complementary dimensions of infrastructure performance:

1. **Structural robustness:** resistance of physical components to climate stresses, considering pipe material and pressure class, burial depth, corrosion protection, structural design of pump stations and freeboard at the intake.
2. **Operational vulnerability:** sensitivity of operations to climate extremes, considering dependence on continuous power supply, availability of backup systems, operational flexibility, access for maintenance and availability of spare parts.
3. **Service life:** susceptibility of the local environment to erosion, gulying or instability, considering slope, soil characteristics, proximity to floodplains and riverbanks, and the presence or absence of protecting vegetation.
4. **Service criticality:** the criticality of each segment for the continuity of water supply, considering the share of demand it serves, the presence of redundancy or alternative routes, and the consequences of temporary failure.

Each dimension is scored on a simple ordinal scale from 1 (very low vulnerability / high robustness) to 5 (very high vulnerability). Scores are based on design documentation, geotechnical and environmental information, planned operational strategies and expert judgement from engineers and climate specialists.

A composite vulnerability score is then calculated for each segment as a weighted average of the four dimensions.

Hazard classification and thresholds

The continuous hazard indicators are converted into a common hazard index on a 1–5 scale, where 1 indicates very low hazard and 5 very high hazard. This step enables a transparent and comparable representation of hazard across indicators and segments.

The procedure to evaluate climate risk combines: (i) how often a hazardous condition is expected to occur (Likelihood); with (ii) how severe its effects would be on the asset or service (Consequence).

Likelihood (L) measures frequency on a five-point scale for the selected time horizon. Scores are interpreted as follows:

1. Rare: means an annual probability up to five percent (5%).
2. Unlikely: means five to twenty percent (20%).
3. Possible means twenty to fifty percent (20-50%).
4. Likely: means fifty to eighty percent (50-80%).
5. Almost certain means above eighty percent (>80%), thus every year.

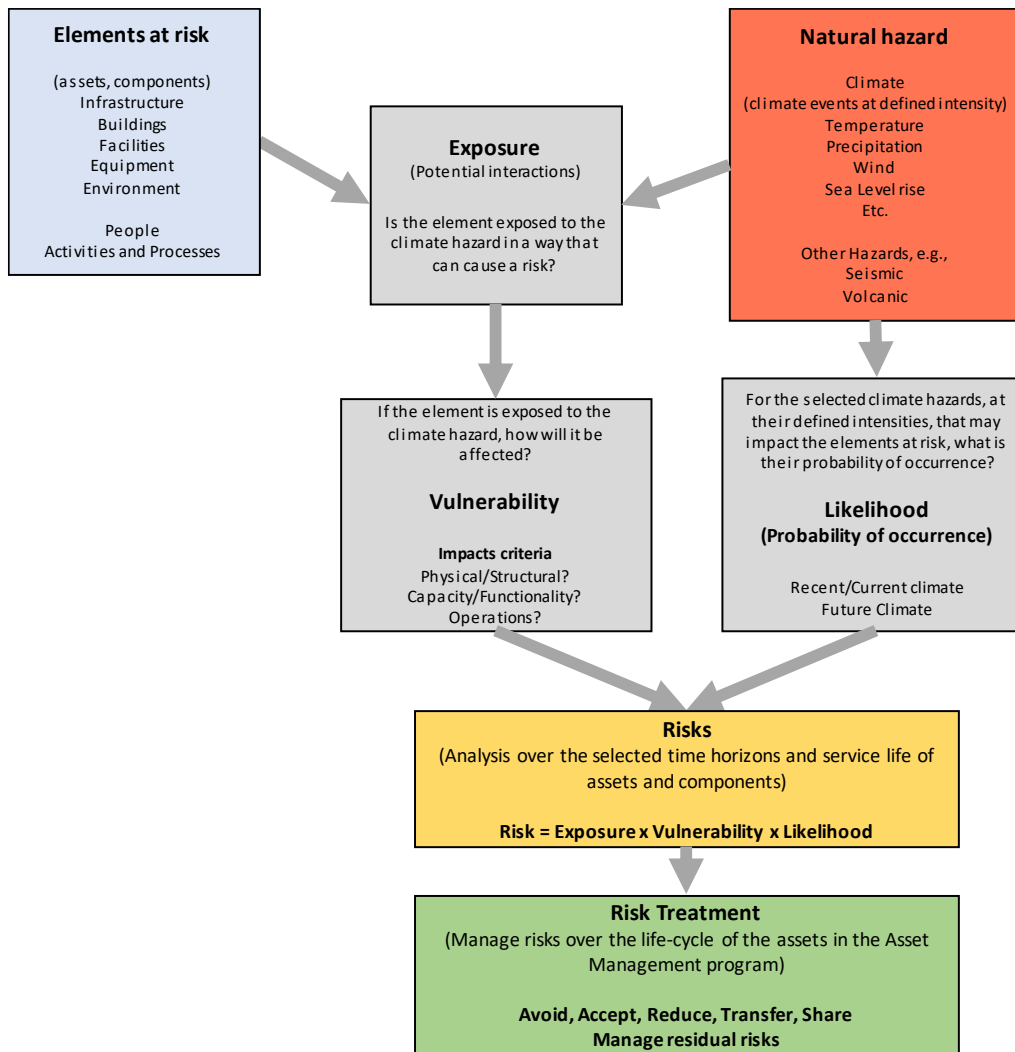
To assign Likelihood, climate metrics such as the number of days above the P90 temperature threshold, the frequency of heavy rainfall days, river stage exceedance, among other indicators are translated into an annual probability for each asset or segment under the chosen scenario.

Consequence (C) measures severity on a five-point scale that reflects functional impact, repair needs, service disruption, and potential health, safety or environmental effects:

1. Insignificant indicates negligible damage and no service interruption and routine O&M only. No asset damage.
2. Minor indicates very short service interruption, minor O&M, superficial asset damage and minor repairs.

3. Moderate indicates service interruption up to two days, component replacement, limited local public-health or environmental effects with localized effects.
4. Major indicates multi-day service interruption with significant asset damage and repairs or partial reconstruction, risk of non-compliance with water or effluent standards.
5. Catastrophic indicates major asset failure or a prolonged loss of service or production capacity; widespread environmental or public-health impact and major cost.

Figure 1. Illustration of Climate risk assessment process. Source: the author.



The **Risk Index** is calculated as the product **Likelihood (L) x Consequence (C)** and ranges from 1 to 25. For each segment we converted climate metrics into a Likelihood score from 1 to 5, for example days above the P90 temperature threshold, heavy rainfall frequency, river stage exceedance at Rundu, drought indices, and storm frequency. We then assigned a Consequence score from 1 to 5 based on service impact, operations and maintenance implications, asset damage, and compliance risk for water and sanitation services.

Multiplying Likelihood by Consequence produced a Risk Index from 1 to 25, which we mapped to Low, Moderate, High, or Extreme using fixed bands. For every case we will document the chosen mitigations and the residual risk in next stages of the assessment. The same procedure has been applied consistently across all segments, enabling comparison and easy updates as new climate data become available.

Two short examples illustrate the method:

- If fluvial flooding at the river intake is almost certain during high water years, so “L” equals five (5), and would cause major disruption unless mitigated, so “C” equals four (4), the risk index is twenty (20) and the rank is Extreme.
- If extreme heat at the Base Pump Station is likely in the 2050s, so “L” equals four (4), and would have a moderate effect on performance without additional cooling, so “C” equals three (3), the risk index is twelve (12) and the rank is High.

Risk treatment follows the rank:

- Extreme requires redesign or relocation and immediate engineered controls.
- High requires engineered mitigations and operational controls with monitoring.
- Moderate calls for low-cost measures and procedures with periodic review.
- Low may be accepted and documented with routine monitoring.

The method is deliberately simple. It relies on the best available climate information to score frequency, anchors severity in asset performance and service continuity, and produces a single index that enables clear, auditable decisions. As new data become available, the scores can be refreshed and the register updated without changing the underlying logic.

Table 8. Risk Assessment Criteria Tables.

LIKELIHOOD		CONSEQUENCE				
		1	2	3	4	5
		Insignificant	Minor	Moderate	Major	Catastrophic
5	Almost Certain	Low	High	Extreme	Extreme	Extreme
4	Likely	Low	Moderate	High	Extreme	Extreme
3	Possible	Low	Moderate	Moderate	High	Extreme
2	Unlikely	Low	Low	Moderate	Moderate	High
1	Rare	Low	Low	Low	Low	Low

LIKELIHOOD	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
		1	2	3	4	5
		CONSEQUENCE				

Risk index	Risk Rank
15 – 25	Extreme
10 – 14	High
6 – 9	Moderate
1 - 5	Low

Risk Treatment is the step where each asset/system gets a lifecycle plan that turns risk scores into concrete action: for every prioritized risk, decide whether to avoid, reduce, transfer, share, or accept the risk. The criteria used to treat risk are clear and related risk levels, cost-effectiveness, feasibility, co-benefits, and socioenvironmental safeguards. For selected options an implementation plan will be defined, including measure, responsible entity, timeline, Key performance indicators (KPIs) showing the impacts reduction. Additionally, the required Standard Operation Procedures (SOP) and Supervisory Control and Data Acquisition (SCADA) monitoring systems to operate and verify performance will be defined where feasible. Finally, state the residual risk, set alerts and review cycles, and commit to updating measures as climate conditions, assets, or service demands change.

2 PART II. CLIMATE CHANGE ANALYSIS RESULTS

This chapter describes Namibia's physical setting and dominant climate drivers, and presents a climatological analysis based on portal-derived CMIP6 information. The objective is to provide a clear reference frame for interpreting projected changes and for linking climate signals to hazard classes used in the CRVA for the Kunene and Okavango basins. This chapter presents a focused assessment of current and projected climate conditions in Namibia, with emphasis on temperature and precipitation related extremes. Unlike studies that rely on bespoke downscaling, this analysis uses authoritative, pre-processed multi-model information from the World Bank Climate Change Knowledge Portal (CCKP). This portal provides CMIP6 ensemble outputs and standardized indicators that have undergone quality control and bias adjustment within their pipelines. All results are harmonized to a 1995–2014 reference period for mapping and comparison and are reported for the Kunene and Okavango basin areas in Namibia.

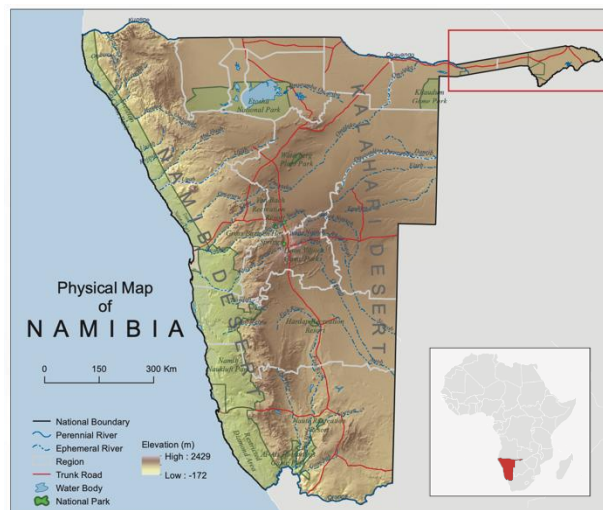
The emerging picture is consistent across ensembles: continued warming in all seasons with an increase in both the frequency and duration of hot conditions, particularly inland; high interannual variability of rainfall persists, while short, intense rainfall events during the wet season are expected to become more consequential for pluvial and small-catchment flooding in the north and northeast. Longer dry spells and episodic meteorological drought remain a defining feature of the climate, with implications for water-supply reliability and ecosystem stress. Portal indicators for wind are less uniform; where available, they do not indicate a robust country-wide shift in mean winds, so wind-related risk is discussed cautiously and in conjunction with heat and aridity signals.

Overall, the report is designed to feed directly into CRVA hazard grading and NWSSIP II decision windows. By using transparent, reproducible CMIP6 information and standardized indices, the analysis supports proactive adaptation planning -from heat-ready operations and occupational safety to drainage design for intense rainfall, to drought-resilient water resources management.

2.1 Topographic and geographic analysis

Namibia spans about 825,000 km² between 17 to 29°S and 11 to 26°E, with roughly 1,500 km of Atlantic coastline. The terrain organises into three north-south belts: the hyper arid Namib coastal plain, the abrupt Great Escarpment, and an elevated interior plateau that grades east into the Kalahari Sandveld. In the north lie the Etosha Pan and the Cuvelai–Etosha ephemeral network. Perennial boundary rivers govern surface-water availability and flood risk (the Kunene to the northwest and the Okavango/Zambezi systems to the northeast) while most interior channels are seasonal; settlement and infrastructure concentrate on the plateau and northern regions.

Figure 2: Topography, perennial and ephemeral rivers and water bodies in Namibia.



2.2 Main drivers of the climate in Namibia

Seasonal rainfall over northern Namibia is tied to the austral-summer migration of the Intertropical Convergence Zone (ITCZ) and the development of a shallow Angola Low, which together support deep convection from roughly October to April, with a peak between December and March. Moisture transport from the tropical Atlantic and the Congo air mass feeds convective systems that organize along mesoscale boundaries and topographic contrasts. Along the southwest African margin, the cold Benguela Current maintains a cool, stable marine boundary layer that suppresses convection near the coast and reinforces the hyper-arid regime of the Namib Desert. Interannual variability is modulated by large-scale modes, particularly ENSO: El Niño events generally reduce summer rainfall over much of Namibia, while La Niña increases wet-season activity in the north and northeast. Anomalies in South Atlantic Sea-surface temperatures and the Southern Hemisphere subtropical circulation further modulate moisture fluxes, pressure gradients and the frequency of convective outbreaks.

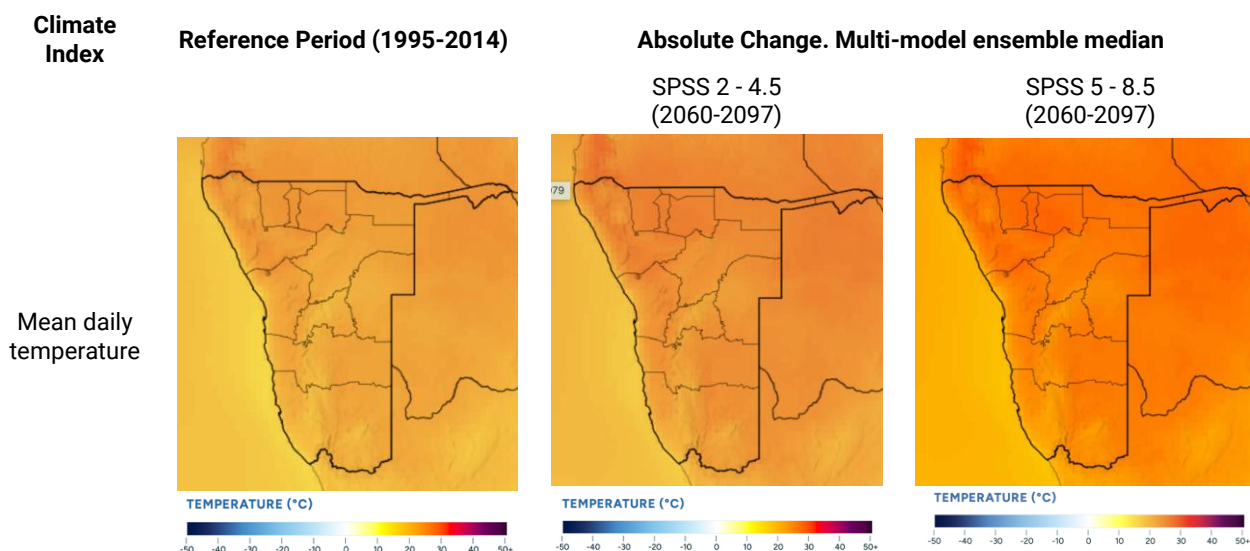
2.3 Climate change in Namibia

2.3.1. Temperature

Projected mean daily temperature (Tmean)

The reference-period (1995–2014) multi-model ensemble median shows Namibia’s typical thermal gradient: cooler along the Atlantic coast under the Benguela upwelling and warmer over the inland plateau and far north-east. Late-century projections indicate country-wide warming of the mean daily temperature, with the SSP2-4.5 scenario showing a moderate increase that is slightly stronger over the interior and north-eastern regions and weaker near the coast. Under SSP5-8.5, the magnitude of warming is larger and more spatially uniform, extending well inland and further elevating already warm areas. Overall, both scenarios point to higher baseline temperatures, reduced coastal–inland contrast, and increased thermal stress across Namibia by 2060–2097, with SSP5-8.5 representing the upper bound.

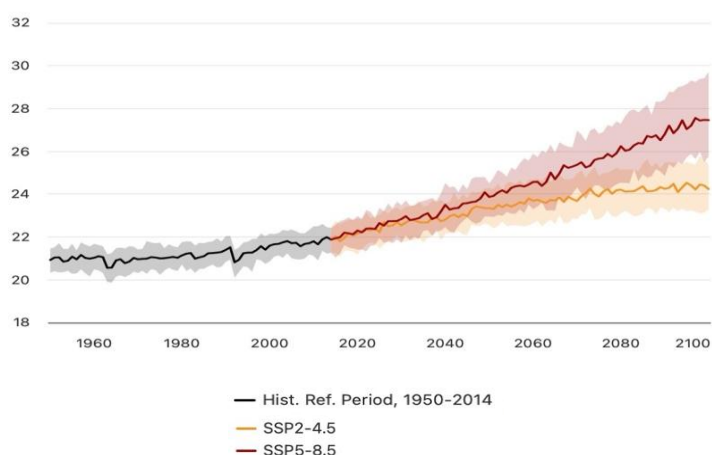
Figure 3. Mean daily temperature for the reference period (on the left) and absolute changes (with respect to the reference period) of the mean daily temperature recorded for the SPSS 2-4.5 and SPSS 5-8.5 future scenarios (2060-2079), central and right side, respectively.



Tmean monthly anomalies relative to 1995–2014

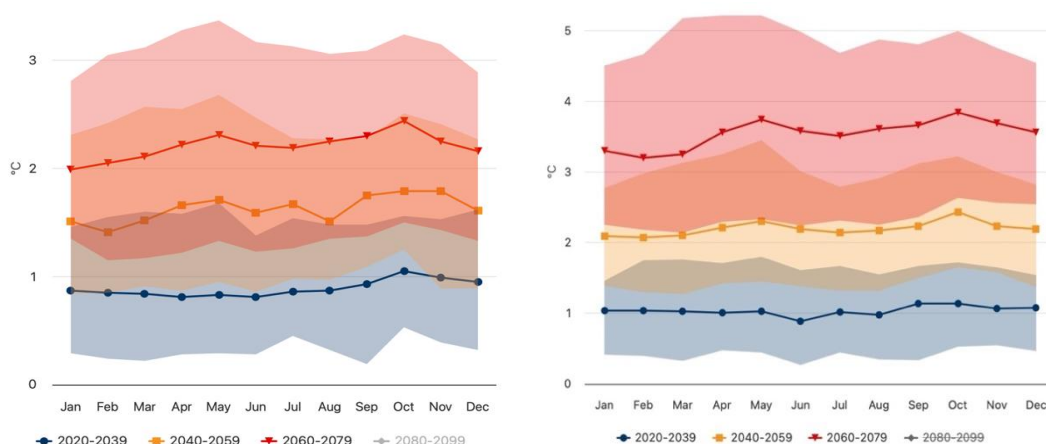
Under SSP2-4.5 (figure 5, left panel) monthly mean temperatures increase consistently across all months relative to 1995–2014: about +0.9 to +1.1 °C in 2020–2039, around +1.8 to +2.2 °C by 2040–2059, and roughly +2.8 to +3.2 °C by 2060–2079, with marginally larger anomalies in late austral autumn and spring (April–May and October–November). Uncertainty bands (10th–90th percentile) widen modestly with time but remain narrower than in the high-emissions case. Under SSP5-8.5 (figure 5, right panel), the seasonal shape is similar, but the amplitudes are larger: +0.9 to +1.1 °C in 2020–2039, +2.0 to +2.5 °C by 2040–2059, and +3.5 to +4.5 °C by 2060–2079, again peaking in late autumn/spring and with a broader uncertainty envelope. These trajectories confirm robust, year-round warming across Namibia, stronger under SSP5-8.5, with implications for cooling demand, evapotranspiration and heat-risk management across sectors.

Figure 4. Projected timeseries of average mean daily temperature from the historical reference period (1950–2014) and SPSS 2-4.5 and SPSS 5-8.5 future scenarios. Dots represent the median values, shaded areas the 10th–90th percentile's range.



Projected timeseries of average mean daily temperature from the historical reference period (1950–2014) in figure 4 below, shows a steady warming of mean daily temperature from the historical baseline (1950–2014), followed by a clear scenario divergence after about 2030: under SSP2-4.5 the median trend rises more gradually and begins to stabilize toward late century, whereas SSP5-8.5 accelerates throughout the second half of the century. In both cases the uncertainty envelope (10–90th percentile) widens with time.

Figure 5. Projected change of average means daily temperature for 2020–2039, 2040–2059 and 2060–2079 time periods. Multi-Model Ensemble (reference period 1995–2014) for SPSS 2-4.5 on the left and for SPSS 5-8.5 on the right.

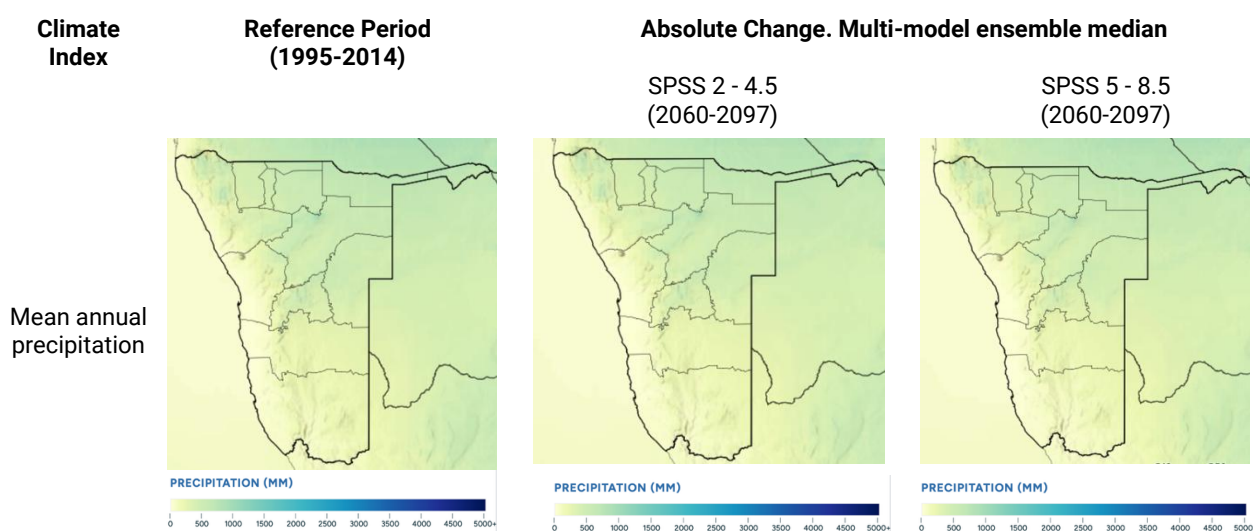


2.3.2. Precipitation

Mean annual total precipitation

Mean annual precipitation maps in figure 6, show Namibia’s well-known west-to-east gradient in mean annual precipitation: very low totals along the Atlantic coast and south-western deserts, increasing over the central plateau and peaking in the far north-east (Kavango/Zambezi corridor), while the south and west remain arid. Late-century projections indicate modest changes in annual totals. Under SSP2-4.5 (2060–2097), the multi-model median suggests small absolute shifts—near-neutral to slightly drier over interior and western domains, with localized slight increases toward the north-east—preserving today’s gradient. Under SSP5-8.5, the spatial pattern is similar but with somewhat larger amplitudes, again without a robust basin-wide wetting signal. Overall, both scenarios imply that temperature-driven aridity (via higher evaporative demand) rather than large gains in annual rainfall is likely to be the dominant pressure on water resources, with interannual variability remaining a key factor for planning.

Figure 6. Mean total annual precipitation for the reference period (on the left) and absolute changes (with respect to the reference period) of the mean total annual precipitation recorded for the SPSS 2-4.5 and SPSS 5-8.5 future scenarios (2060-2079), central and right side, respectively.



The multi-model ensemble (see Figure 7 timeseries). shows large interannual variability in Namibia’s annual precipitation and a wide uncertainty envelope that persists through the century. Median projections under SSP2-4.5 remain close to the historical mean with no robust trend, while SSP5-8.5 exhibits a slight downward drift in the median toward late century. In both scenarios, the 10th–90th percentile range is broad and overlaps the historical distribution for most years, indicating that changes in mean annual totals are not strongly constrained by the models and that variability will continue to dominate planning. In practical terms, this points to the need to manage volatility (dry and wet years) rather than expecting a large, uniform shift in average rainfall.

Monthly changes relative to 1995–2014 (see Figure 8 below) across time horizons, monthly anomalies cluster near zero for much of the year, with small, non-robust deviations that vary by horizon: modest negative anomalies often appear during the core rainy months (January–March) and again in spring (October–November), while some months in the early dry season (May–June) show slight positive departures. Differences are generally larger under SSP5-8.5 than SSP2-4.5, yet the uncertainty bands are wide and encompass zero in most months. Overall, the ensemble suggests no consistent, basin-wide shift in seasonality—reinforcing that water-resource stress is more likely to arise from higher evaporative demand and episodic variability than from substantial changes in mean monthly rainfall.

Figure 7. Projected timeseries of precipitation from the historical reference period (1950-2014) and SPSS 2-4.5 and SPSS 5-8.5 future scenarios. Dots represent the median values, shaded areas the 10th-90th percentile's range.

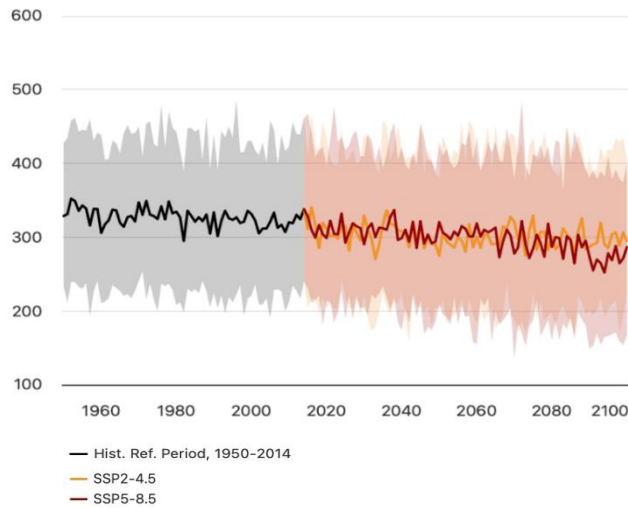
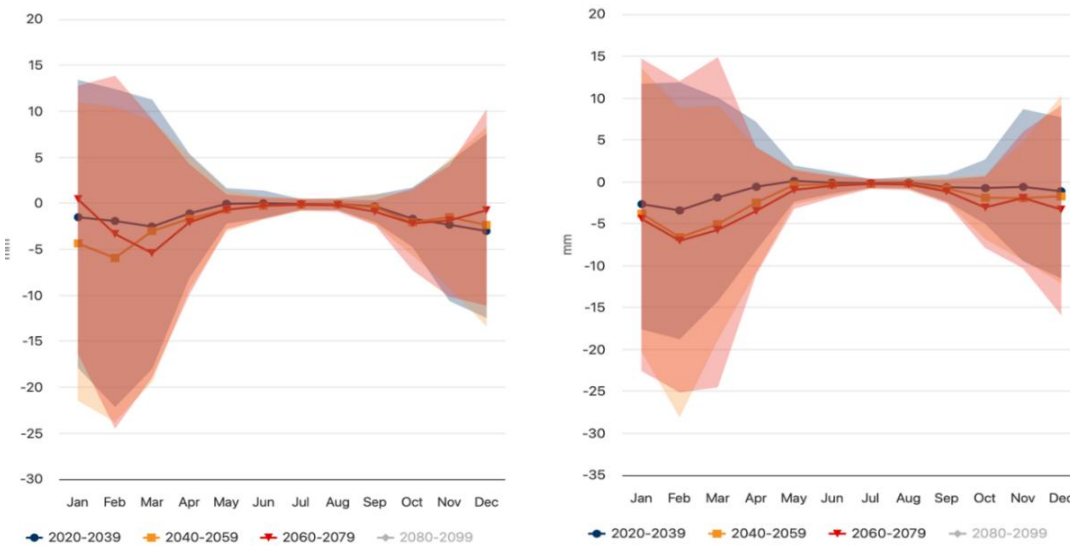


Figure 8. Change in the mean total annual precipitation from the reference period (1995-2014) to the historical period (1991-2020, in black) and SPSS 2-4.5 and SPSS 5-8.5 future scenarios (left side). Dots represent the median values, shaded areas the 10th-90th percentile's range.



2.4 Climatological analysis by river basin

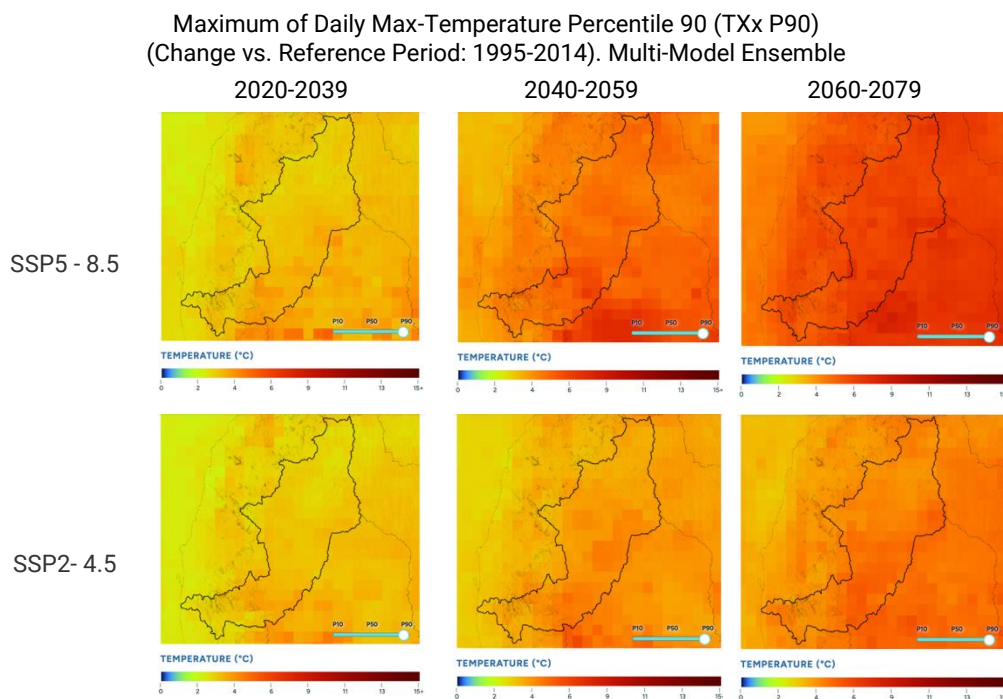
2.4.1. Climatological analysis in Kunene River basin

2.4.1.1. Temperature variability

Annual maximum of the 90th percentile of daily maximum temperature (TXx P90)

The multi-model ensemble indicates a steady, basin-wide intensification of peak daytime heat relative to 1995–2014. Under SSP2-4.5, the spatial pattern of warming is like the high-emissions case, but its magnitude and pace are smaller—showing moderate increases through 2020–2039 and 2040–2059, with lower end-century extremes by 2060–2079. By contrast, SSP5-8.5 shows an earlier and stronger signal: warming is already evident in 2020–2039, becomes pronounced and spatially uniform by 2040–2059, and is strongest by 2060–2079, with large increases across both interior lowlands and headwater areas. Overall, this index points to substantially higher extreme-temperature ceilings later in the century, heightening thermal stress on assets and operations during heat events.

Figure 9. Kunene river basin. Change in Maximum of Daily Max-Temperature Percentile 90 (TXx P90) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

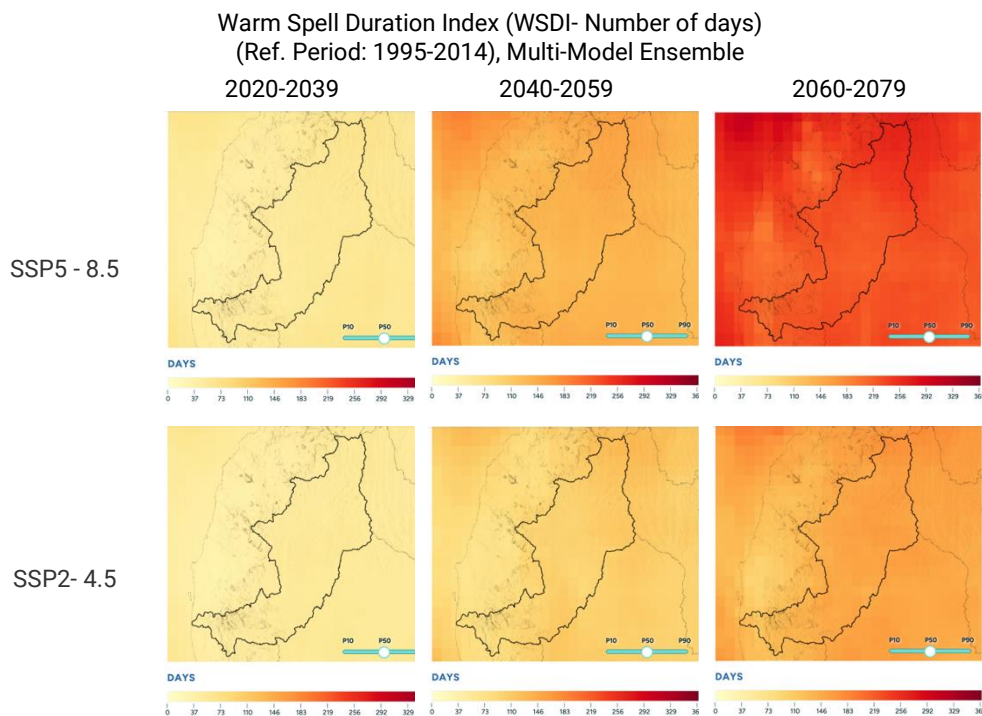


Heat Waves

WSDI (Warm Spell Duration Index, days in warm spells above the historical threshold).

Projected changes point to a clear increase in the duration of warm spells across the Kunene Basin. Under SSP2-4.5, warm-spell days rise gradually—from modest near-term changes to broader, basin-wide extensions by 2040–2059, reaching sustained but comparatively smaller totals by 2060–2079. By contrast, SSP5-8.5 follows a steeper trajectory: modest early changes evolve into widespread multi-month conditions by 2040–2059 and intensify further by 2060–2079. The lengthening of warm spells implies longer periods of sustained heat stress, with implications for worker safety, cooling/ventilation requirements, and process stability in heat-sensitive components.

Figure 10. Kunene river basin. Change in the warm spell duration index from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.



2.4.1.2. Precipitation

Maximum daily precipitation

Mean maximum 1-day accumulated precipitation (Rx1day)

Under SSP2-4.5, projected changes in Rx1day are modest, largely following today's spatial gradient: a weak signal in 2020–2039, a gradual uptick by 2040–2059 focused on the upper/northeastern escarpment and headwaters, and incremental increases by 2060–2079—implying only a limited rise in design-storm intensity, mainly relevant for small catchments, culverts, and compound/urban drainage in the highlands. By contrast, SSP5-8.5 shows the same pattern with stronger amplitudes—from modest near-term changes to more pronounced increases by 2040–2059, and noticeably higher, more spatially uniform peaks by 2060–2079, especially across the headwaters and escarpment—indicating a greater likelihood of short-duration pluvial/fluvial responses, network surcharging, and overtopping at road crossings compared with SSP2-4.5.

Maximum 5-day accumulated precipitation (Rx5day)

Under SSP2-4.5, the multi-model ensemble for Rx5day indicates modest to moderate increases, concentrated mainly along the upper basin and escarpment where orographic effects dominate. The near-term (2020–2039) signal is small, strengthens by 2040–2059, and then stabilizes by 2060–2079 at levels below those expected under high emissions; the arid western lowlands show little change. This suggests a limited but noticeable rise in multi-day storm runoff and local overtopping at culverts and small crossings in headwater catchments. By contrast, SSP5-8.5 retains the same spatial pattern but with earlier onset and larger amplitudes: increases are more pronounced by 2040–2059 and become higher and more spatially coherent by 2060–2079, especially across the headwaters and escarpment belt—implying a greater likelihood of short- to multi-day fluvial responses, drainage network surcharging, and more frequent overtopping at road and canal crossings compared with SSP2-4.5.

Figure 11. Kunene river basin. Change in Mean Maximum 1-day precipitation (Rx1day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

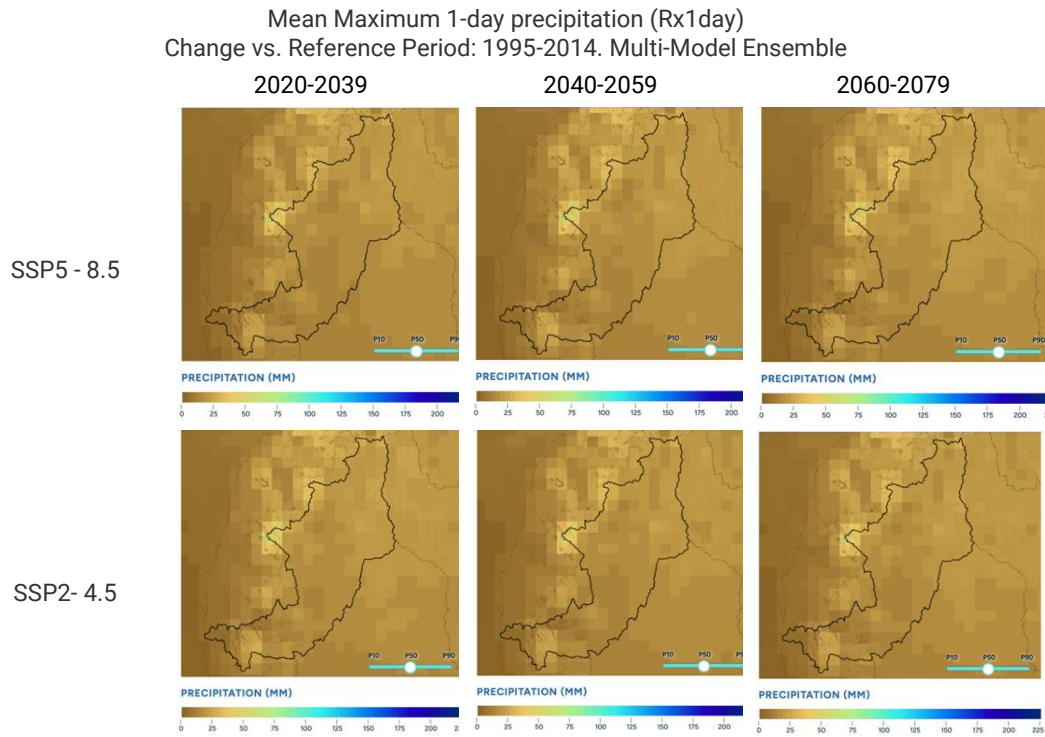
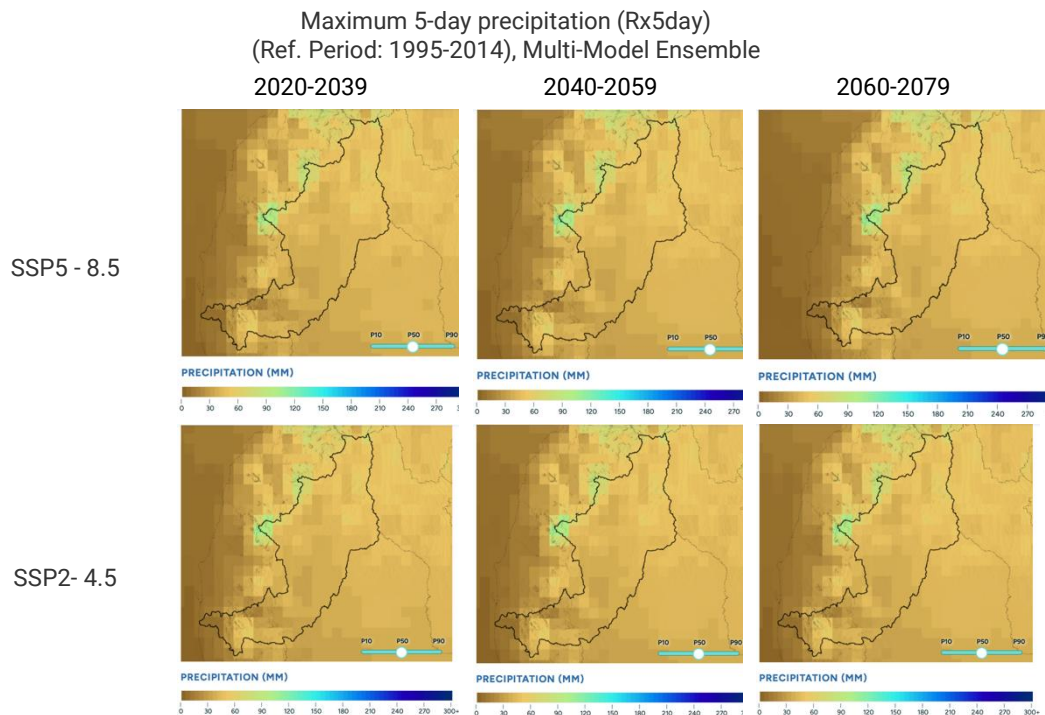


Figure 12. Kunene river basin. Change in Mean Maximum 5-day precipitation (Rx5 day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.



Heavy precipitation events

Days with precipitation ≥ 20 mm (R20mm)

Under SSP2-4.5, the heavy-precipitation indices show a restrained signal focused on the orographic belt. For R20mm (days with ≥ 20 mm), the near-term (2020–2039) change is small and largely confined to the headwaters/escarpment; by 2040–2059 a modest increase spreads along this upper-basin corridor, with the arid western lowlands showing little to no change, and by 2060–2079 the pattern stabilizes without a basin-wide jump. By contrast, under SSP5-8.5 the same spatial pattern emerges earlier and with larger amplitudes. R20mm days become more frequent by mid-century and more spatially coherent by 2060–2079.

Days with precipitation ≥ 50 mm (R50mm)

Under SSP2-4.5, R50mm increases are limited and remain localized to the same high-relief zones, indicating only a slight rise in very heavy-event frequency; under this pathway, design implications concentrate on spot upgrades to drainage crossings and erosion control in headwater catchments. Under SSP5-8.5 the same spatial pattern emerges earlier and with larger amplitudes. R20mm days become more frequent by mid-century and more spatially coherent by 2060–2079, while R50mm also shows clearer hot spots in the upper basin and along the escarpment. The high-emissions pathway therefore points to a greater likelihood of short-lived but intense runoff, compound drainage surcharging, and more frequent overtopping at road and canal crossings, especially in the headwaters, compared with SSP2-4.5.

2.4.1.3. Drought

Drought Index (SPEI)

Across the Kunene Basin, the multi-model ensemble SPEI show a clear, progressive drying signal relative to 1995–2014. Under SSP5-8.5, conditions remain near-neutral in 2020–2039, shift to widespread mild drought by 2040–2059, and intensify to moderate drought by 2060–2079, with the strongest negative anomalies concentrating over the western and central basin (downstream Namibian reaches) while the headwaters to the northeast also trend drier. The lower-emissions pathway (SSP2-4.5) displays the same spatial pattern but a smaller magnitude: mostly weak drying through mid-century, strengthening to mild-to-moderate drying by 2060–2079. The temporal progression and the divergence between pathways indicate that drought risk is both time- and scenario-dependent, with materially higher hazard under SSP5-8.5. Practically, this implies increasing pressure on baseflows, reservoir inflows, and groundwater recharge—raising the likelihood of supply deficits and the need for demand management and drought-ready operations in the basin's WASH systems.

Consecutive Dry Days (CDD)

The multi-model maps indicate a basin-wide lengthening of the longest seasonal dry spells in the Kunene Basin relative to 1995–2014. Under SSP5-8.5, increases are modest in 2020–2039, become widespread by 2040–2059, and are pronounced by 2060–2079, with the central and western reaches showing the largest extensions of dry sequences. Under SSP2-4.5, the spatial pattern is similar, but the signal is weaker and emerges more gradually. A longer maximum CDD implies extended intervals without effective rainfall, raising the risk of soil-moisture depletion, higher irrigation and storage drawdowns, and greater pressure on small surface sources and shallow groundwater. In operational terms, lengthier dry spells can increase the need for demand management, trucking or conjunctive use, and heighten wildfire risk in the dry season.

Figure 13. Kunene river basin. Change in the Number of days with precipitation ≥ 20 mm (R20mm) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

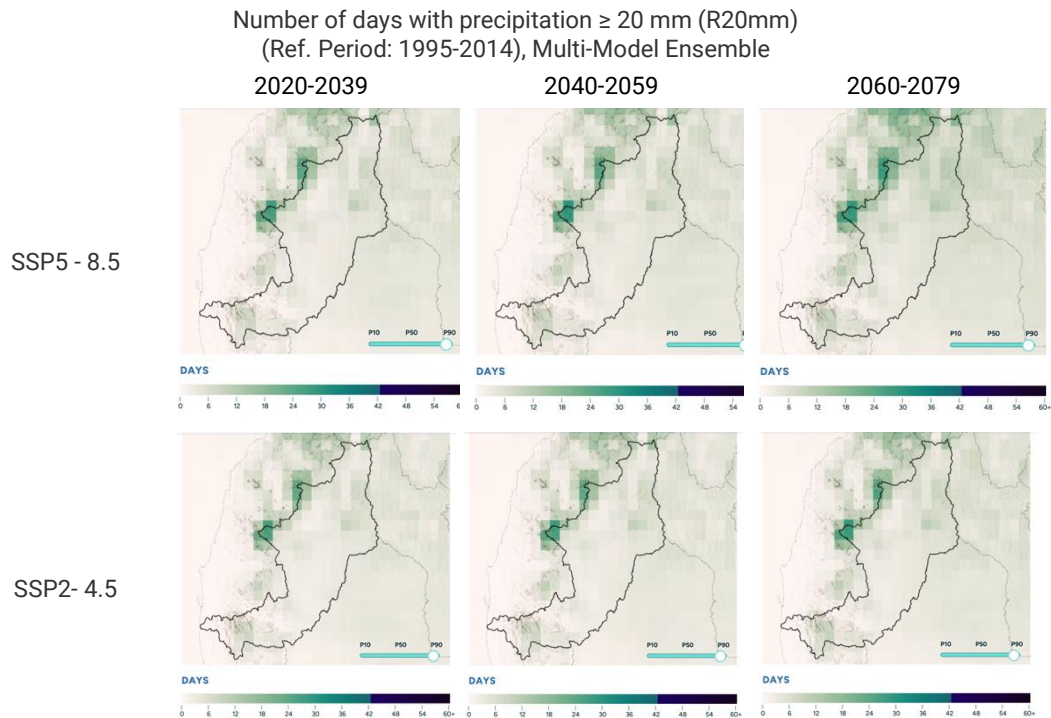


Figure 14. Kunene river basin. Change in the Number of days with precipitation ≥ 50 mm (R50mm) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

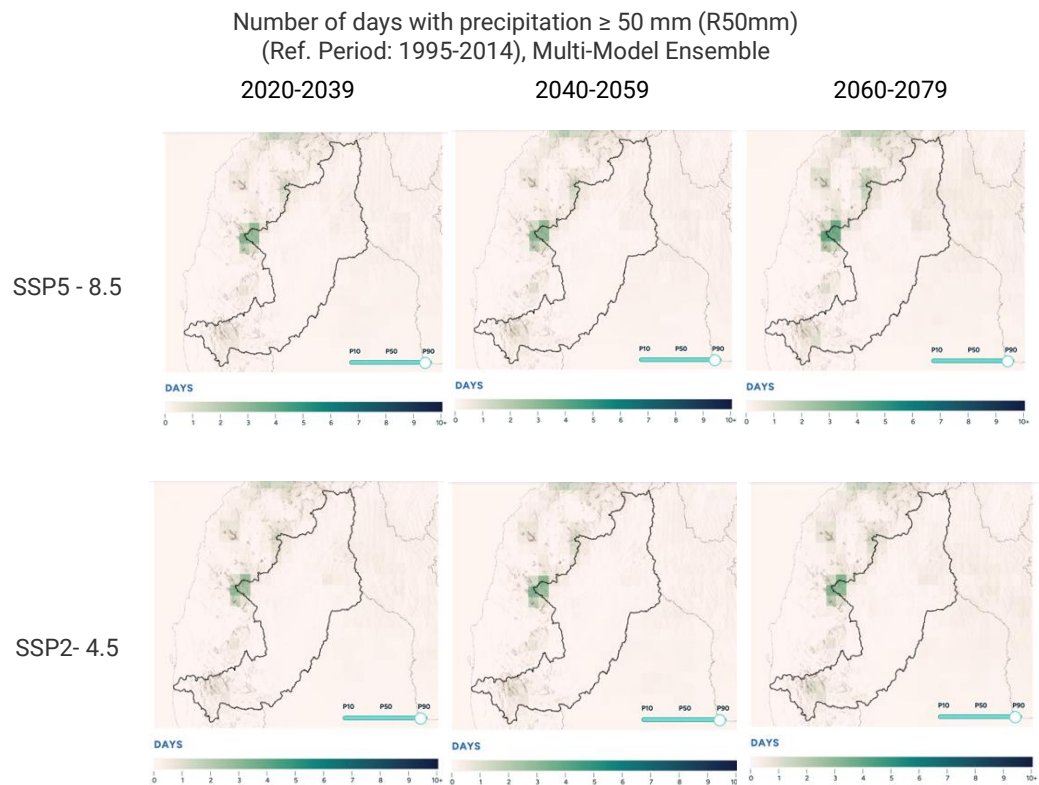


Figure 15. Kunene river basin. Change of the Drought index (SPEI) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

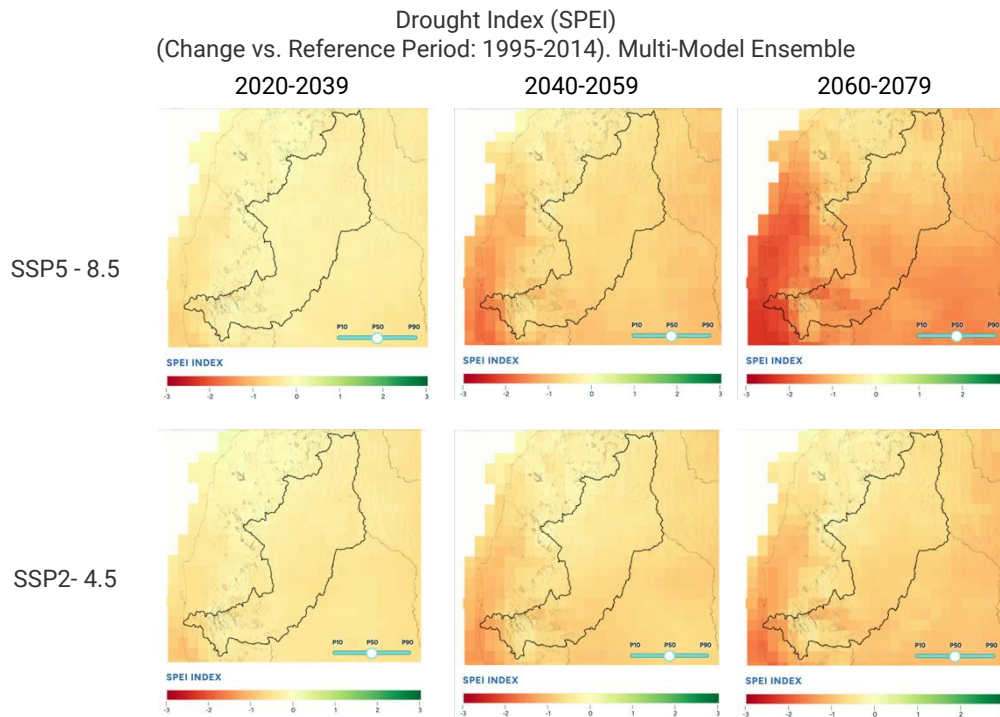
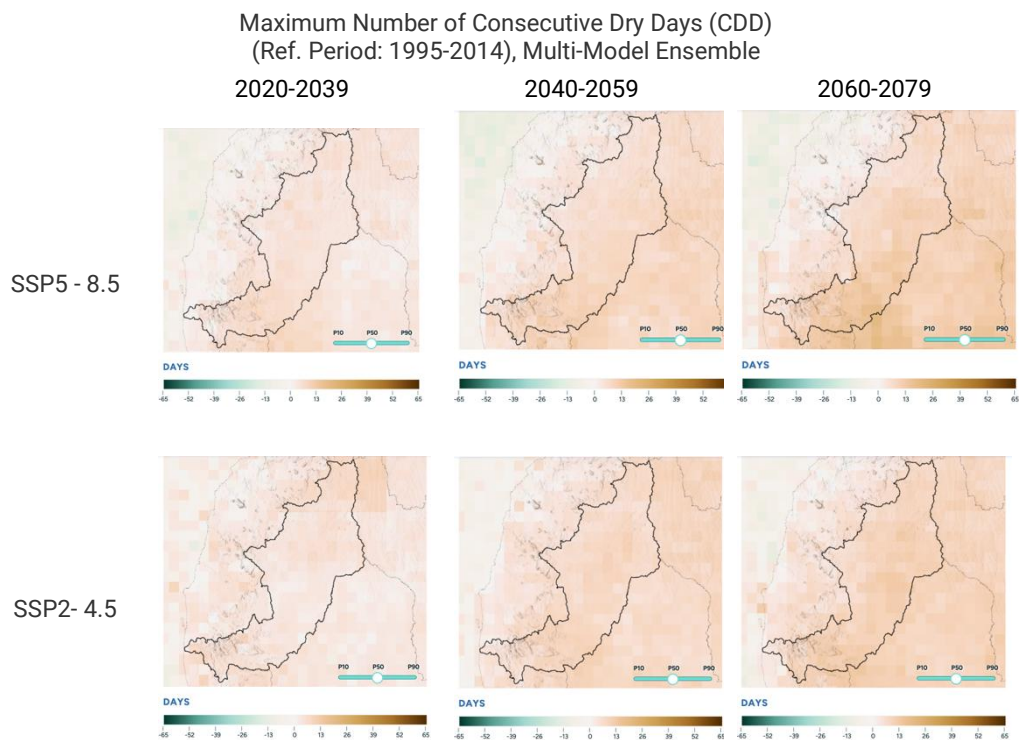


Figure 16. Kunene river basin. Change in Maximum number of Consecutive Dry Days (CDD) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.



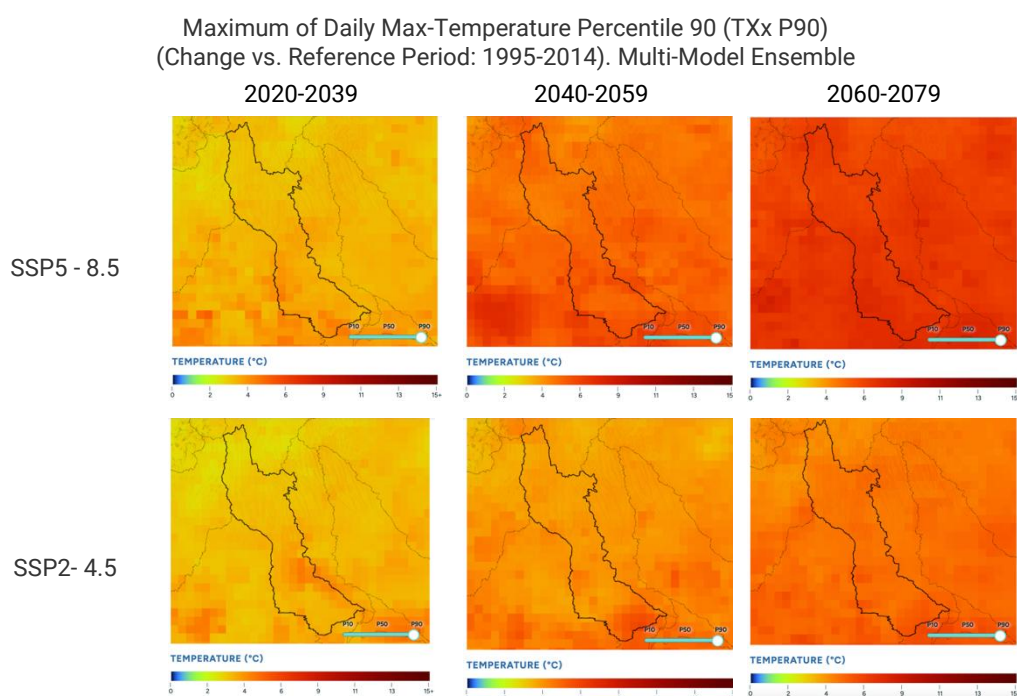
2.4.2. Climatological analysis in Okavango river basin

2.4.2.1. Temperature variability

Annual maximum of the 90th percentile of daily maximum temperature (TXx P90)

Under SSP2-4.5, the multi-model ensemble shows a steady, basin-wide rise relative to 1995–2014: warming is modest in 2020–2039, becomes more pronounced by 2040–2059, and continues to intensify into 2060–2079/2080–2099 with a broadly uniform spatial pattern across the Okavango headwaters and downstream reaches. By contrast, SSP5-8.5 follows the same spatial progression but with an earlier onset and much larger amplitudes—already prominent warming by 2040–2059 and widespread, strong heat intensification by 2060–2079/2080–2099. Overall, the maps indicate progressively higher extreme-temperature ceilings, implying greater heat-stress risk for communities and operations, higher evaporative losses, and tighter thermal margins for heat-sensitive assets.

Figure 17. Okavango river basin. Change in Maximum of Daily Max-Temperature Percentile 90 (TXx P90) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

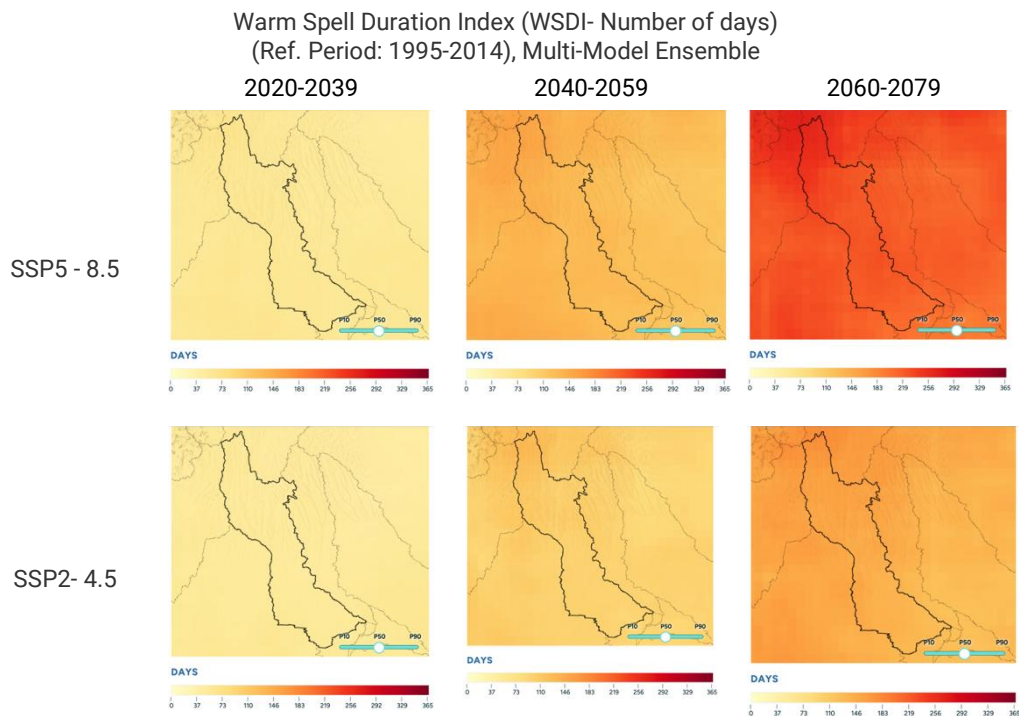


Heat Waves

WSDI (Warm Spell Duration Index, days in warm spells above the historical threshold).

Under SSP2-4.5, the duration of warm spells in the Okavango Basin increases gradually—from modest near-term changes in 2020–2039 to broader, basin-wide extensions by 2040–2059, reaching sustained but comparatively smaller totals by 2060–2079/2080–2099. The spatial pattern is fairly uniform, with early strengthening in the northern/headwater sectors and a slower response downstream. By contrast, SSP5-8.5 exhibits an earlier onset and larger amplitudes: near-term increases grow into widespread multi-month warm spells by mid-century and intensify further toward late-century. The lengthening of warm spells implies longer periods of sustained heat stress, with implications for worker safety, cooling/ventilation requirements, and process stability in heat-sensitive components.

Figure 18. Okavango river basin. Change in the warm spell duration index from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.



2.4.2.2. Precipitation

Mean maximum 1-day accumulated precipitation (Rx1day)

Under SSP2-4.5, the multi-model ensemble for Rx1day in the Okavango Basin indicates minimal to modest change relative to 1995–2014. The near term (2020–2039) signal is weak across most of the basin, with slight increases confined to the orographic headwaters and escarpment; by 2040–2059 a gradual uptick appears in these upper-basin corridors while the drier southwestern lowlands show little to no change. By 2060–2079 the pattern persists with incremental increases rather than sharp jumps, implying only a limited rise in design-storm intensity—most relevant for small catchments, culverts and compound/urban drainage in headwater towns. By contrast, SSP5-8.5 retains the same spatial pattern but with earlier onset and somewhat larger amplitudes: modest near-term changes become more pronounced by mid-century and somewhat higher by late-century, particularly over the headwaters and escarpment. The high-emissions pathway therefore points to a greater likelihood of short-duration pluvial surges and localized overtopping at road and canal crossings in the upper basin, while a basin-wide step change is not indicated.

Maximum 5-day accumulated precipitation (Rx5day)

Under SSP2-4.5, changes in the mean of the annual maximum 5-day precipitation (Rx5day) relative to 1995–2014 are small and spatially muted across the Okavango Basin through 2020–2039, with near-neutral anomalies over most sub-basins. By mid-century (2040–2059) the ensemble median suggests slight increases—at most on the order of a few tens of millimetres—confined mainly to the northern headwaters and upper mainstem, with little signal elsewhere; by 2060–2079 this pattern persists, indicating no robust basin-wide intensification of multi-day rainfall totals. Under SSP5-8.5, the spatial pattern is similar, but amplitudes are marginally larger in the same northern sectors by mid- to late-century, while much of the basin remains close to reference conditions. Overall, both pathways show limited and heterogeneous changes in Rx5day compared with 1995–2014, implying that flood-risk planning should continue to account primarily for variability and local controls rather than a uniform increase in multi-day extremes.

Figure 19. Okavango river basin. Change in Mean Maximum 1-day precipitation (Rx1day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

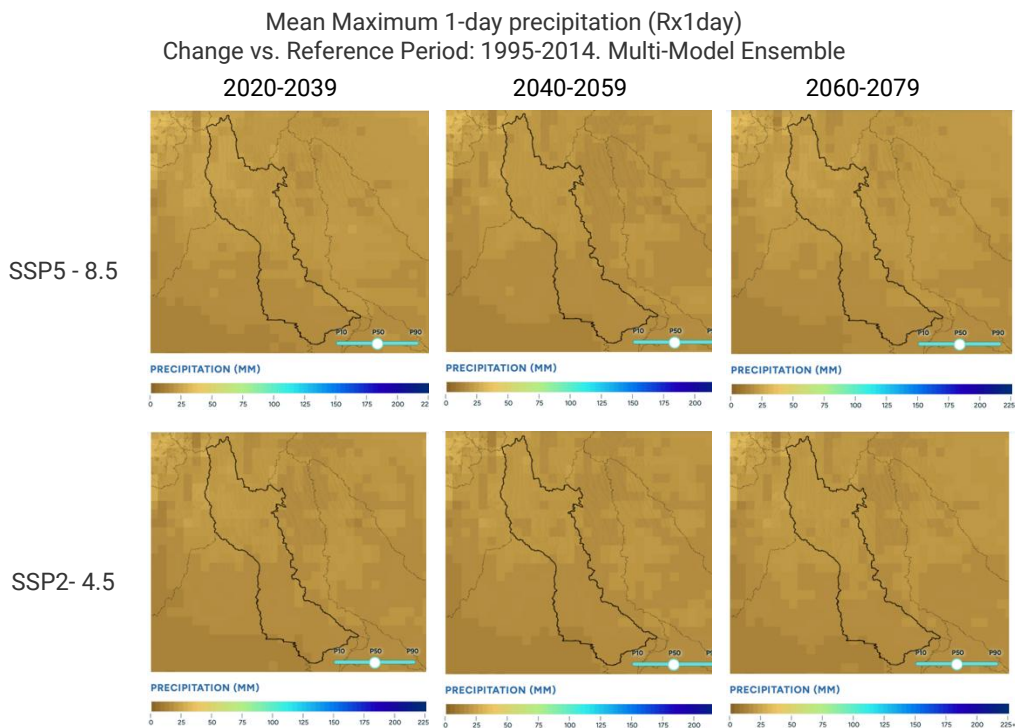
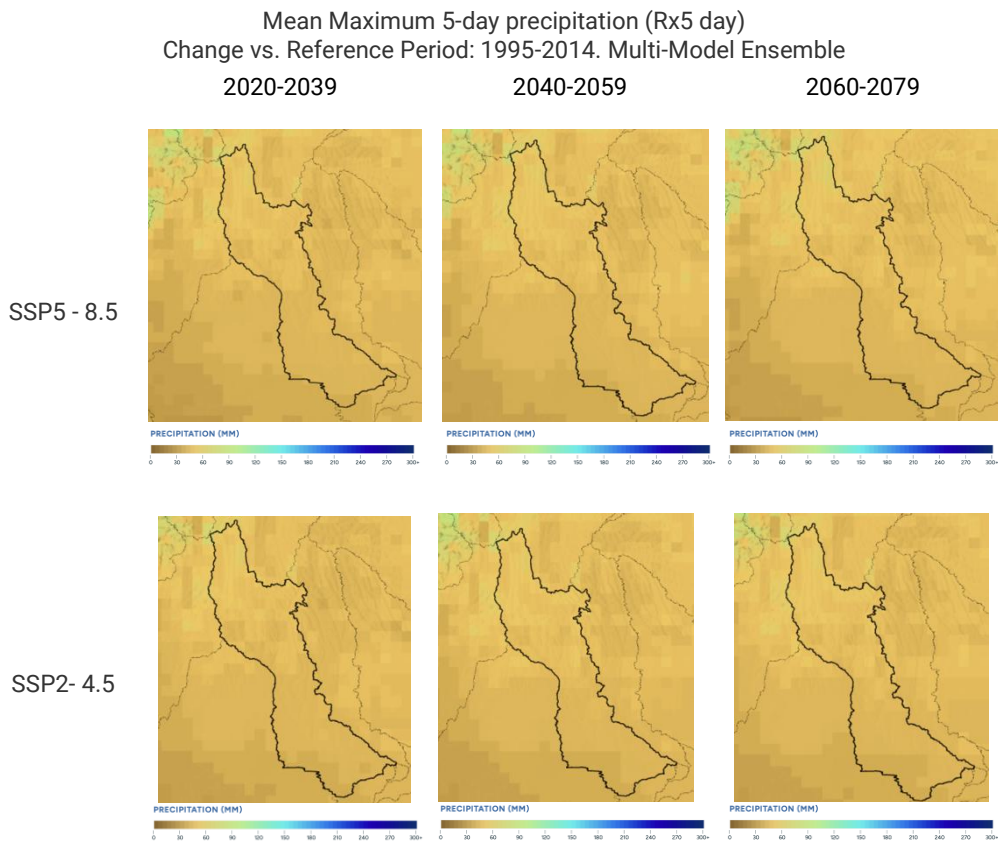


Figure 20. Okavango river basin. Change in Mean Maximum 5-day precipitation (Rx5 day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

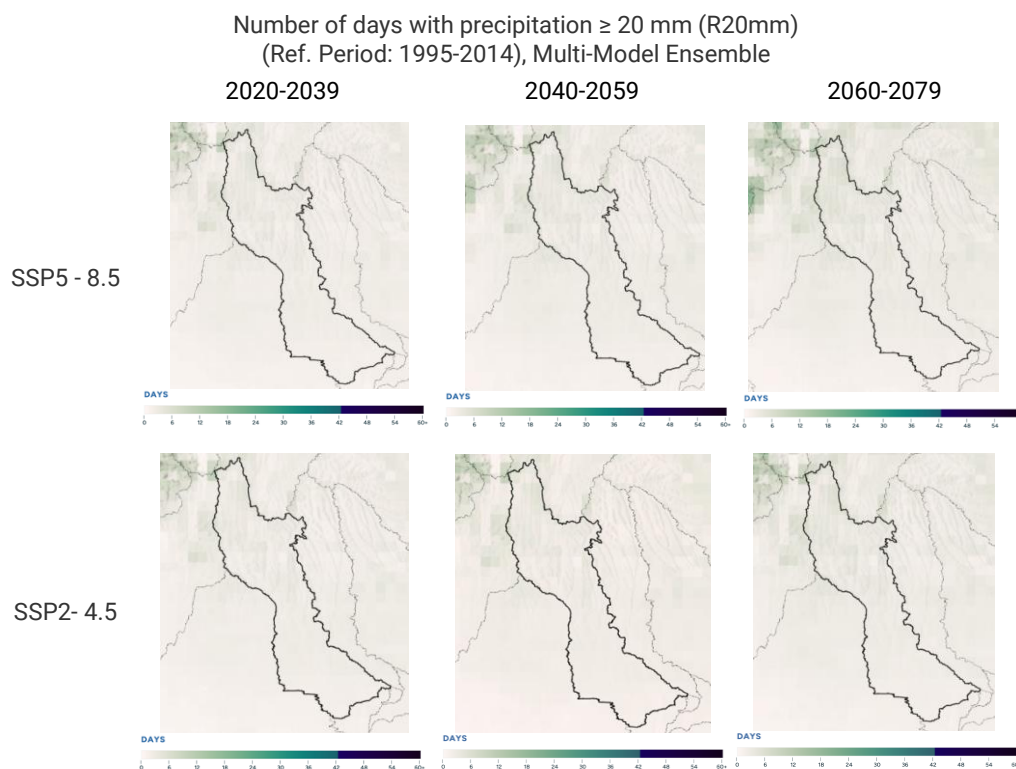


Heavy precipitation events

Days with precipitation ≥ 20 mm (R20mm)

Under SSP2-4.5, the multi-model ensemble median indicates small, spatially patchy changes in the number of ≥ 20 -mm days relative to 1995–2014. During 2020–2039, most of the basin remains near neutral, with only modest increases emerging along the northern headwaters. By 2040–2059 and 2060–2079, that pattern persists: slight increases (at most a few days per season) appear in the same upstream belts, while large areas of the middle and lower basin show weak or indistinguishable signals. Under SSP5-8.5, the spatial pattern is similar, but amplitudes are marginally larger by mid- to late-century in the northern sectors, whereas the remainder of the basin stays close to the reference climatology. Overall, neither scenario shows a robust, basin-wide escalation in R20mm frequency; planning for heavy-rain risks should therefore continue to emphasize interannual variability and local convective controls rather than a uniform shift in the number of ≥ 20 -mm days.

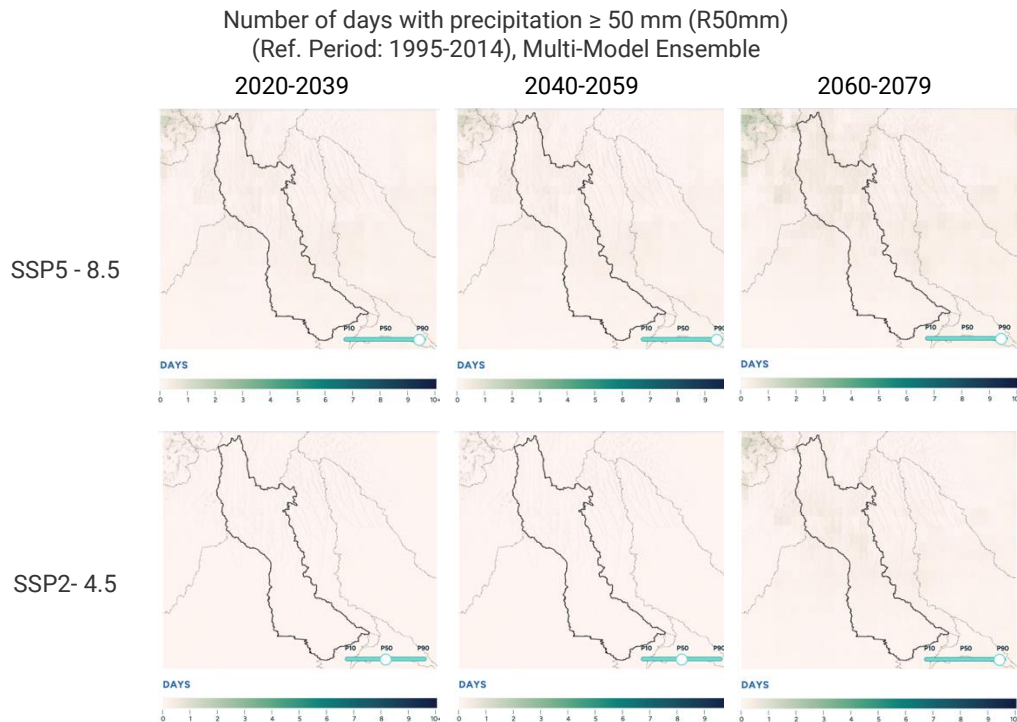
Figure 21. Okavango river basin. Change in the Number of days with precipitation ≥ 20 mm (R20mm) from the reference period (1994–2014) to near future (2020–2039), mid-term future (2040–2059) and long-term future (2060–2079). Source: CCKP, World Bank.



Days with precipitation ≥ 50 mm (R50mm)

Under SSP2-4.5, the multi-model ensemble for R50mm in the Okavango Basin shows little change relative to 1995–2014. The near-term (2020–2039) signal is weak across most areas with very few days with precipitation over 50mm. By 2040–2059 slight increases appear locally in the orographic headwaters and escarpment, while the drier southwestern lowlands remain largely unchanged. By 2060–2079 the pattern stabilizes with only slight additional growth in these upper-basin corridors—indicating a limited rise in very-heavy event frequency under this pathway. SSP5-8.5 retains the same spatial pattern but with an earlier onset and larger amplitudes: localized hot spots in the headwaters become more evident by mid-century and somewhat more coherent by late-century, though precipitation events ≥ 50 mm remain relatively infrequent basin-wide. Operationally, the main implications are targeted upgrades for culverts, small bridges, and erosion control in the orographic belt, rather than a basin-wide shift in design standards.

Figure 22. Okavango river basin. Change in the Number of days with precipitation ≥ 50 mm (R50mm) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.



2.4.2.3. Drought

Drought Index (SPEI)

Under SSP2-4.5, the multi-model ensemble for SPEI indicates a gradual shift toward drier hydro-climatic conditions relative to 1995–2014. The near term (2020–2039) remains close to neutral with only localized mild drying, but by mid-century (2040–2059) a basin-wide negative anomaly emerges and by 2060–2079 mild-to-moderate drying is widespread—though magnitudes remain notably smaller than under the high-emissions pathway. By contrast, SSP5-8.5 shows an earlier and stronger drying signal: mild drying appears already near term, becomes moderate and spatially coherent by 2040–2059, and intensifies further by 2060–2079 with pronounced deficits across northern and central sectors. Because SPEI integrates both precipitation and evaporative demand, these patterns imply that warming-driven PET increases will compound any rainfall shortfalls, increasing the persistence of hydrologic deficits, reducing baseflows and recharge, and raising the likelihood of multi-season drought stress for surface- and groundwater-fed WASH systems in the Okavango Basin.

Maximum number of Consecutive Dry Days (CDD)

Under SSP2-4.5, the multi-model ensemble for CDD in the Okavango Basin shows a gradual, basin-wide lengthening of the longest seasonal dry spell relative to 1995–2014. The near-term (2020–2039) signal is weak across most areas; by 2040–2059 a modest extension becomes apparent—most consistently over the interior and headwater corridors—while the driest southwestern lowlands change little. By 2060–2079 the increase is more evident yet remains moderate, indicating longer intervals without effective rainfall but not a step-change in aridity under this pathway. SSP5-8.5 exhibits the same spatial pattern with an earlier onset and larger amplitudes: weak changes in 2020–2039 give way to broader, more coherent extensions by mid-century and clearer lengthening by 2060–2079. Operationally, longer maximum dry spells raise the risk of soil-moisture depletion, storage drawdowns and higher demand on conjunctive-use strategies, especially for small surface sources and shallow groundwater.

Figure 23. Okavango river basin. Change of the Okavango River (SPEI) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.

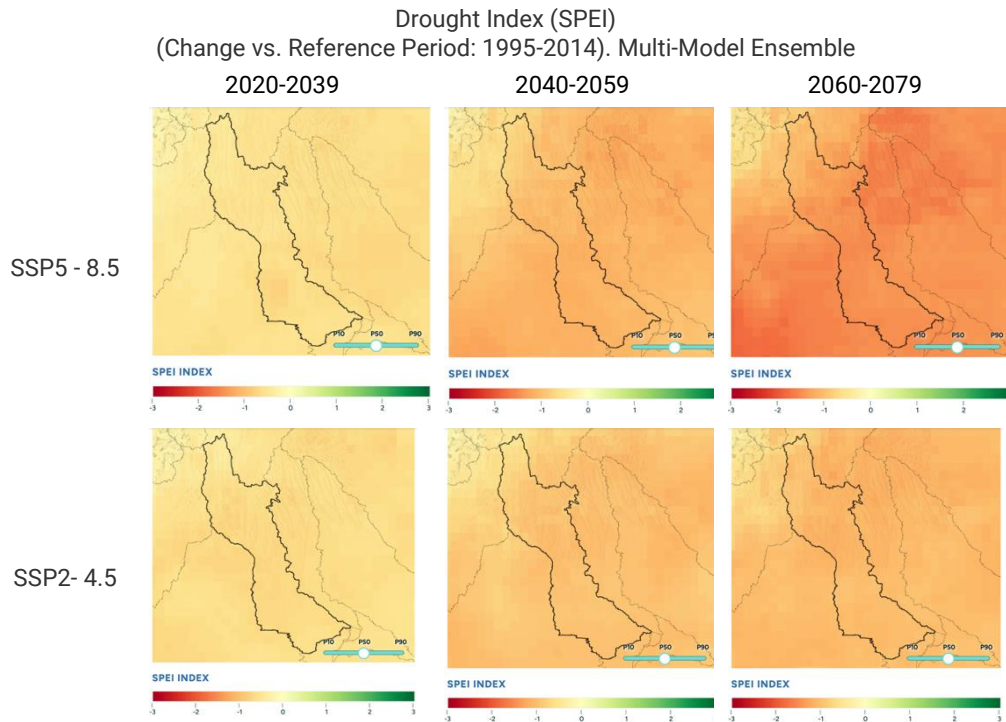
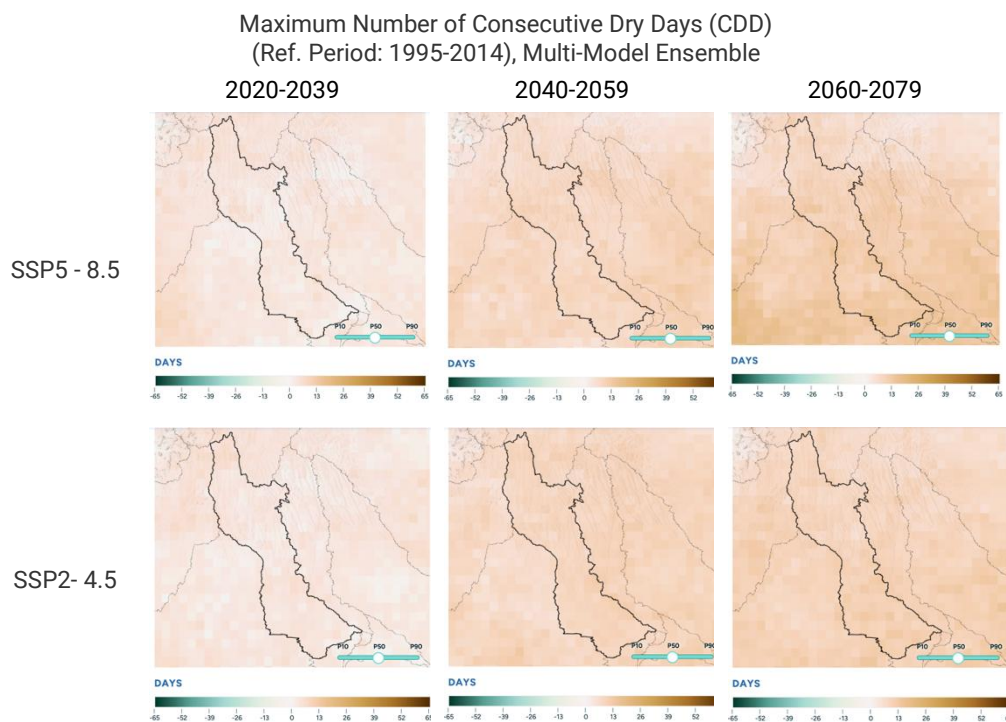


Figure 24. Okavango river basin. Change in Maximum number of Consecutive Dry Days (CDD) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.





3 PART III. CLIMATE HAZARDS ASSESSMENT: KUNENE AND OKAVANGO RIVER BASINS

3.1 Introduction

Climate change is expected to significantly impact Northern Namibia—particularly the Kunene and Okavango River basins—through intensified drought conditions, increased water scarcity, and reduced agricultural productivity. Projections indicate that rainfall could decline by up to 7% by mid-century and 14% by the end of the century, while average annual temperatures may rise between 2°C and 4°C under worst-case scenarios. These changes are likely to exacerbate evaporation rates, groundwater stress, and the risk of wildfires, particularly in semi-arid regions where vegetation is already sparse.

The Kunene and Okavango cross-border regions are historically interconnected through hydrological, ecological, and socio-economic dynamics. Communities across these basins share water resources, engage in subsistence agriculture and livestock rearing, and depend heavily on the availability and quality of water. However, climate stress is making their livelihoods increasingly precarious. Droughts have become more frequent and intense, significantly reducing pasture availability and water for livestock, which are essential assets for rural households. In addition, rainfed crops such as millet, maize, and sorghum have shown decreasing yields due to erratic rainfall and shorter growing seasons.

As of 2024, food and water insecurity remain key concerns. Most households in rural Northern Namibia rely on shallow boreholes and seasonal rivers for their domestic and agricultural water needs. When these sources dry up or become contaminated—especially during prolonged droughts—access to safe water becomes severely restricted, increasing vulnerability to malnutrition and water-borne diseases. Moreover, women and girls are disproportionately affected, often bearing the burden of walking longer distances to fetch water, which limits their time for education and economic activities.

Infrastructure in the region is also at high risk from climate hazards. Key systems such as the Calueque-Oshakati Canal, rural boreholes, pumping stations, and sanitation facilities are exposed to high temperatures, evaporation losses, flash floods, and windstorms. For example, high evaporation rates compromise the efficiency of open canals and storage reservoirs, while intense rainfall events can overwhelm drainage systems, damage embankments, and disrupt service delivery. Limited road access to remote areas exacerbates the situation, impeding maintenance efforts and emergency responses.

The combination of damaged infrastructure, declining water availability, and agricultural losses create a cycle of vulnerability that disproportionately affect poor and rural populations. Interruptions in bulk water supply systems, such as those connected to the Calueque-Oshakati Canal or the Abenab borehole scheme, have direct consequences on both urban centers and outlying villages. Moreover, institutional capacity to manage these systems under pressure from climate change remains limited.

3.2 Kunene and Okavango River basins

The Kunene and Okavango basins are Namibia's two perennial river systems of strategic importance, sustaining life and development in otherwise arid and water-scarce regions. As lifelines in a predominantly dry landscape, they support communities, ecosystems, and economies that could not survive without them. Their transboundary nature makes cooperative management indispensable: in the Kunene, through the Permanent Joint Technical Commission (PJTC) established with Angola, and in the Okavango, through the Permanent Okavango River Basin Water Commission (OKACOM), which also includes Botswana as a key partner. In both cases, governance is therefore not only a technical requirement for managing water resources, but also a political and diplomatic priority essential to ensure long-term resilience and shared benefits.

The Kunene, flowing from the Angolan highlands to the Atlantic, anchors Namibia's north-west through critical assets such as the Ruacana Hydropower Plant and the proposed Baynes Hydropower Project, while also supporting irrigation schemes at Epupa and Ruacana, smallholder agriculture, and livestock watering in the hyper-arid Kunene Region. Its ephemeral tributaries, including the Hoarusib and Hoanib, rarely provide sustained flows, making the main river corridor and its riparian vegetation a vital ecological refuge and a buffer for communities along the Skeleton Coast.

The Okavango, by contrast, traverses Namibia's north-east through the Kavango regions, providing reliable water for domestic supply in Rundu and surrounding settlements, small-scale irrigation, and a growing tourism sector linked to its floodplains and forests. It underpins long-term water security strategies such as the Okavango–Central Namibia water transfer scheme, designed to augment supplies to the Central Area of Namibia (CAN) where Windhoek and other major towns face chronic deficits.

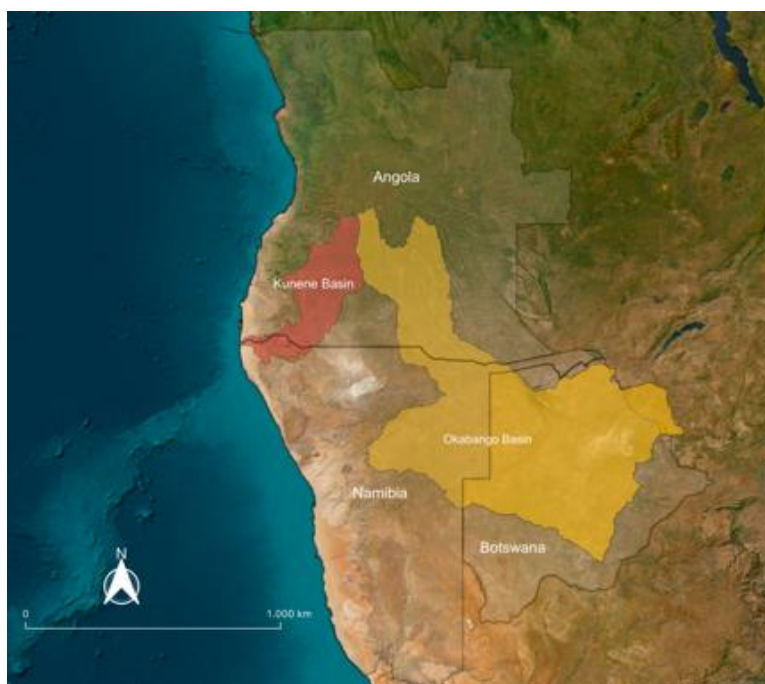
In both basins, water abstraction, pumping stations, cross-border regulation, and potential transfer schemes highlight their dual role as lifelines for local livelihoods and as cornerstones of Namibia's national water and energy infrastructure, while their transboundary nature with Angola and Botswana underscores the importance of cooperative governance and careful balancing of ecological flows with development needs.

The Kunene Basin is distinguished by its capacity to generate hydropower, anchored by the Ruacana Plant and the proposed Baynes project, which together are central to Namibia's energy security. In contrast, the Okavango Basin's development potential is constrained by its ecological sensitivity, particularly the UNESCO-listed Delta downstream, but it nonetheless holds strategic importance as a potential supplier of bulk water to the Central Area of Namibia through long-considered transfer schemes. In both cases, infrastructure opportunities are inseparably linked to ecological considerations: while the Kunene must balance power generation and irrigation with maintaining downstream flows into the Skeleton Coast ecosystems, the Okavango faces the challenge of reconciling national water demand with the imperative to safeguard one of Africa's most iconic wetland systems.

Both basins are profoundly climate-sensitive, as their flows depend on rainfall in Angola. Shifts in precipitation patterns upstream translate directly into Namibia's water security, increasing the stakes of climate change. In the Kunene, where the surrounding Kaokoveld Desert receives less than 50 mm of annual rainfall, the river represents an ecological and socio-economic artery in an otherwise hyper-arid landscape. By contrast, the Okavango lies in Namibia's most sub-humid zone, with rainfall reaching up to 600 mm/year – a relative abundance that supports more intensive land use, small-scale irrigation, and denser settlement patterns around Rundu.

The physical and ecological contrasts are equally striking. The Kunene's lower reaches form narrows but biologically rich corridors of riparian vegetation, critical for wildlife and pastoralist communities in the Skeleton Coast hinterlands. The Okavango's broad floodplains and riparian forests, buffered by protected areas such as Bwabwata National Park, sustain agriculture, fisheries, and a thriving tourism economy. These protected landscapes, including the Skeleton Coast National Park in the west, serve as buffers against overexploitation while highlighting the dual value of the rivers as both development engines and biodiversity reservoirs. Together, the Kunene and Okavango embody Namibia's most strategic hydrological assets. Their interplay lies in a shared dependency on transboundary cooperation, their contrasting yet complementary roles in energy and water supply, and their joint vulnerability to climatic shifts. They are at once opportunities for sustainable growth and sources of potential tension if governance and ecological safeguards fail to keep pace with rising demand and mounting climate risks.

Figure 25. Kunene and Kavango transboundary river Basins. Source: the author.



3.3 Climate Hazard identification

This section outlines the identification of key climate hazards that threaten the integrity, functionality, and reliability of water and sanitation infrastructure across the Kunene and Okavango River basins. The objective is to generate a comprehensive inventory of climate-related threats that will inform the vulnerability, exposure, and risk assessment phases of the Climate Risk Assessment by river basin (Kunene and Okavango) and at project level.

Primary hazards include extreme heat, drought, pluvial flash floods, fluvial floods, strong winds and storms (including dust), and wildfires. Secondary/compound hazards include erosion/sedimentation, groundwater contamination from sanitation overflows, and rapid stage rises associated with upstream dam operations. Hazards are identified from historical records, downscaled projections and expert judgement, and are validated with national stakeholders where feasible.

The hazards directly induced by climatic variability and change are:

- **Heat stress:** Intensifies evaporation from open reservoirs and canals (e.g., Eastern National Water Carrier-ENWC canal), leads to accelerated degradation of infrastructure materials (e.g., PVC pipes, tank linings), and increases stress on pumping equipment.
- **Droughts:** Recurring across the region, droughts reduce groundwater recharge and surface water availability, affecting water abstraction points, storage capacity, and continuity of supply—especially in rural and peri-urban systems.
- **Rainfall Extremes and Pluvial Flash floods:** Irregular rainfall patterns undermine water harvesting systems and complicate the planning of sanitation infrastructure reliant on seasonal drainage. Short-duration, high-intensity rainfall events can overwhelm drainage systems, erode canal embankments, and cause contamination or overflow in sanitation facilities.
- **Riverine flooding:** Particularly relevant along the Okavango River, this hazard may threaten borehole infrastructure, latrines near floodplains, and informal settlements in low-lying zones.

- **Windstorms:** Increasingly reported in northern Namibia, high winds can damage elevated tanks, latrine superstructures, and water kiosks.
- **Wildfires:** Aggravated by high temperatures and dry vegetation, wildfires threaten critical assets such as exposed piping networks, solar pumps, and protective vegetative buffers around boreholes.

The **table 9** below outlines the key climate hazards and their expected impacts on water and sanitation infrastructure components in the target areas.

There are also secondary and compound hazards that emerge because of primary events or that involve multiple interacting stressors:

- **Erosion and sedimentation:** Triggered by intense rainfall or uncontrolled runoff, leading to blockages in canals and degradation of water intakes.
- **Groundwater contamination:** Arising from flooding of pit latrines or poorly designed sanitation systems, particularly in areas with high water tables or limited separation distances.
- **Dam operation and transboundary releases.** Sudden releases from upstream dams in Angola (e.g., Gove/Calueque) can trigger rapid stage rises into Namibia, overtopping low banks and damaging intakes, crossings, and access.

Table 9. Overview on relevant climate hazards in the water and sanitation sector.

Climate Hazard	Asset / Components Potentially Affected	Example of Impacts in the area (Kunene and Okavango)
Heat Stress (Heatwaves and extreme heat)	<ul style="list-style-type: none"> • Water treatment plants (process units, chemical dosing, chlorination rooms). • Open reservoirs and canals. • Pumping stations, motors and electrical panels (incl. SCADA cabinets). • Boreholes (submersible pumps, controllers). • Solar PV arrays, inverters, batteries. • Plastic pipelines (HDPE/PVC), operator facilities. 	<ul style="list-style-type: none"> • Higher evaporation from canals/reservoirs giving reduced yields. • Overheating/derating of pumps and electrical gear; faster battery degradation. • Lower PV output at high temperatures. • Softening/deformation of plastic pipes and joints. • Reservoir stratification, algal blooms, reduced chlorine residuals. • Higher water demand (cooling/household); reduced worker productivity and more H&S incidents during O&M.
Droughts (multi-season rainfall deficits)	<ul style="list-style-type: none"> • Raw-water sources low flows. • River intakes (insufficient submergence). • Groundwater/boreholes (well screens, pumps). • Irrigation and livestock points. • Service reservoirs. 	<ul style="list-style-type: none"> • Water scarcity for domestic, agricultural and industrial uses. • Intakes stranded, higher intake outage frequency. • Declining groundwater levels, dry boreholes, increased pumping lifts. • Rising TDS/salinity and source temperature. • Competition/conflict between users; emergency rationing/water trucking; ecological stress downstream.
Pluvial Flash Floods (short-duration, high-intensity rainfall)	<ul style="list-style-type: none"> • Surface water schemes and canal embankments. • Sediment basins and raw-water inlets. • Rural latrines/on-site sanitation systems. • Access roads/culverts to assets. 	<ul style="list-style-type: none"> • Localized flooding and scouring of embankments. • Sediment and debris load clogging. • Intakes/canals; turbidity spikes at WTPs (chemical over-run). • Latrine overflow/collapse contaminating shallow groundwater and river margins. • Road washouts blocking O&M and emergency repairs.
Fluvial Floods	<ul style="list-style-type: none"> • Boreholes near floodplain (wellhead seals) 	<ul style="list-style-type: none"> • Inundation of intakes/electrical rooms; prolonged downtime

Climate Hazard	Asset / Components Potentially Affected	Example of Impacts in the area (Kunene and Okavango)
	<ul style="list-style-type: none"> • River intakes and pumphouses • Transmission mains at river crossings/supports. • Elevated tanks foundations; kiosks near banks 	<ul style="list-style-type: none"> • Bank erosion undermining pipelines and supports • Fecal/chemical contamination of sources • Service interruptions for floodplain settlements; structural damage to tank pedestals
Strong winds and storms (including dust storms)	<ul style="list-style-type: none"> • Elevated tanks (roofing, ladders, fall protection). • Exposed pipelines and fittings. • Water kiosks and latrine structures • Overhead power to sites; PV arrays and mounting. • SCADA/telemetry masts and antennas. 	<ul style="list-style-type: none"> • Physical damage to lightweight structures. • Debris/treefall on mains and service lines. • Dust fouling PV modules, reducing pump output; sand abrasion on gates and valves. • Lightning/surge damage to PLC/RTU; communication outages; unplanned downtime.
Wildfires	<ul style="list-style-type: none"> • HDPE/PVC pipelines; GRP/PE tanks. • Remote solar equipment and cabling; meter boxes. • Vegetation around assets; wooden kiosks. 	<ul style="list-style-type: none"> • Melting/burning of plastic components; tank/pipe failure. • Loss of power/control at remote pumps. • Access routes blocked; longer repair times; need for firebreaks and cleared asset perimeters.

3.4 Hazards in Kunene River Basin

The Kunene River Basin, shared between Angola and Namibia, represents one of the most strategic yet climate-sensitive freshwater resources in southern Africa. In Namibia, the basin sustains critical bulk water infrastructure such as the Calueque-Oshakati Canal, the Ruacana Hydropower Plant, and multiple rural borehole schemes, which collectively provide water to urban centers, smallholder irrigation schemes, and dispersed pastoralist communities in the hyper-arid northwest [22].

Despite this strategic importance, the basin is highly exposed to climate hazards that threaten water security, infrastructure reliability, and public health. Projections indicate an increase in mean annual temperature between 2 °C and 4 °C by the end of the century under high-emission scenarios, coupled with a potential rainfall decline of up to 7 % by mid-century and 14 % by 2100, leading to higher evaporation losses, reduced river discharge, and recurrent multi-season droughts [23]. These conditions exacerbate the already limited sanitation coverage - particularly in rural areas where most households depend on shallow boreholes, latrines, and seasonal streams - leaving populations vulnerable to both water scarcity and contamination risks [24].

The combined effects of extreme heat, prolonged droughts, pluvial flash floods, and strong windstorms increasingly disrupt water abstraction, pumping, storage, and sanitation systems across the basin, while wildfires and sedimentation pose secondary risks to conveyance structures and solar-powered equipment [25]. Given the basin’s transboundary dependence on Angolan rainfall, the fragility of aging Namibian infrastructure, and the socio-economic reliance on subsistence farming and livestock, the Kunene Basin exemplifies the systemic vulnerability of Namibia’s water and sanitation sector to climate hazards [26].

The Namibian reach of the Kunene—an arid, infrastructure-critical corridor that supports bulk transfers (e.g., Calueque–Oshakati), hydropower at Ruacana, rural boreholes and smallholder uses—faces a compound hazard profile dominated by recurrent drought, intensifying heat stress, and episodic pluvial/fluvial flooding, with strong winds/dust and wildfire as aggravating risks [22–26]. Projections for Namibia show continued warming (+2 to +4 °C by late century under high emissions) and rainfall variability/declines that elevate evaporative losses, depress low flows and groundwater recharge, and increase multi-season water stress on intakes, canals, storages and treatment performance [23, 26].

National policy instruments (Updated NDC, adaptation actions; National Drought Policy & Strategy) recognize northern basins—including the Kunene—as hotspots where climate hazards directly threaten water security, livestock and rain-fed production, with cascading effects on food security and rural livelihoods [27–28].

Service coverage disparities magnify vulnerability: rural WASH access lags behind urban and safely managed services remain limited in many settlements, raising contamination and service-continuity risks during droughts and floods [24, 29]. Operational evidence from utilities confirms high inter-annual flow variability at Ruacana and climate-sensitive supply constraints that necessitate resilience measures in bulk transfer, treatment, and energy support systems [25, 30]. In combination, these drivers mean the Kunene Basin’s water and sanitation services—and the livestock/crop systems that depend on them - are systemically exposed to climate shocks, with risk reduction hinging on drought-robust supply, flood-safe siting/design, heat-tolerant O&M, and strengthened institutional capacity across the basin [22–28, 30].

3.4.1. Heat stress hazard

The ensemble-based hazard classification indicates a strong and spatially uniform escalation of heat-stress across the basin. Under SSP2-4.5, the near term (2020–2039) is already High to Very High over most cells, with only small western pockets below Very High. By 2040–2059, Very High becomes the basin-wide standard; by 2060–2079 the basin reaches Very High to Extreme almost everywhere. Under SSP5-8.5, the near term already exhibits Very High–Extreme conditions across nearly all grid cells; mid-century and late-century maps are effectively uniformly Extreme, signaling persistent exceedance of heat-stress thresholds.

Figure 26 and **Table 10** jointly indicate Kunene basin High to Extreme heat-stress hazard in all futures, with SSP5-8.5 reaching Extreme earlier and more uniformly than SSP2-4.5. All investments in the basin should be appraised and designed assuming Very High/Extreme heat conditions over asset lifetimes.

Table 10. Heat Stress Indicators - Anomalies vs. Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
TXx (°C) Mean	0.97	1.72	2.34	1.09	2.35	3.68
TXx P90 (°C)	1.17	1.99	2.79	1.24	2.74	4.41
WSDI Mean (days)	44.29	97.63	146.84	45.34	135.44	229.87
Tmax ≥ 35°C (days/year)	11.41	22.55	34.29	12.64	33.00	62.87
Tmax ≥ 40°C (days/year)	0.01	0.10	0.35	0.02	0.45	3.20

3.4.2. Drought hazard

Drought hazard shows a progressive increase across the Kunene Basin. As shown in **figure 27** under SSP2-4.5, in the near term (2020–2039) drought hazard is largely *Low* over the interior and north, with *Moderate* pockets along the southwest fringe. By 2040–2059, *Moderate* conditions expand over much of the basin, and by 2060–2079 a clearer *High* gradient emerges and consolidates along the western and southern sectors while *Moderate* levels persisting elsewhere. Under SSP5-8.5, the Near-Term pattern remains *Low–Moderate* for most cells, but by mid-century *Moderate* is widespread with *High* cells appearing on the western boundary. By late-century, *High to Very High* dominates the western/southern half of the basin, with *Moderate* lingering in parts of the northeast. These spatial patterns indicate a west- and south-weighted intensification as warming and drying accumulate.

Table 10 corroborates the maps with indicator anomalies. For SSP2-4.5, basin-median SPEI becomes more negative over time (–0.61 to –0.74 to –0.93), and CDD remains high and slightly increasing (173 to 175 days), with CDD exceedance frequency rising to 6 and 4 events in Mid- and Late-century, respectively. Under SSP5-8.5 the signal is stronger: SPEI deepens from –0.39 to –1.29 by 2060–2079, while CDD climbs from 172 to 176 days and the frequency of SPEI and CDD exceedances rises (up to 4 and 6, respectively). Together, these metrics explain the transition to High/Very High hazard in the western and southern basin by late century.

Figure 26. Kunene river basin. Heat Stress Hazard) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

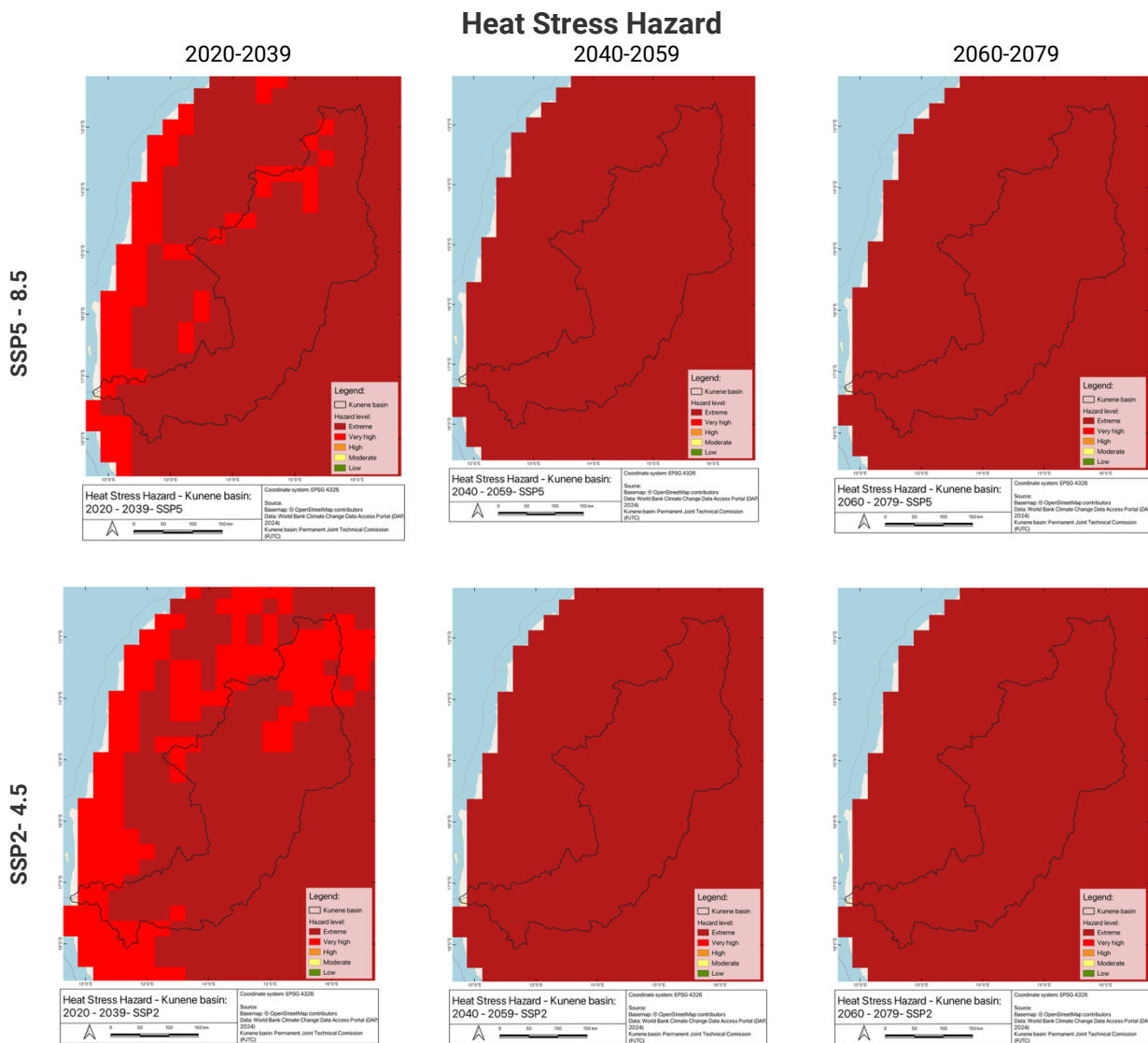


Figure 27 and Table 11 jointly indicate strengthening drought hazard for all futures, with a pronounced west-south hotspot by late-century under SSP5-8.5. All WASH investments in the basin should assume at least Moderate-High drought conditions over asset lifetimes and integrate storage, conjunctive use, and demand-side controls accordingly.

3.4.3. Pluvial Flash Floods

Pluvial flash-flood hazard in the Kunene Basin appears mostly localized. The maps in figure 28 show a broadly stable background class across time and scenarios, with small hotspots rather than a basin-wide escalation.

Under SSP2-4.5, the near-term and mid-century views display isolated higher-hazard cells in the southwest and along a central corridor; by 2060-2079 similar pockets persist without forming extensive zones. Under SSP5-8.5, small upland cells are visible near the central axis in the near term, and a few grid cells move to higher classes by mid to late century, yet the pattern remains spatially constrained. This profile points to asset-level management at kiosks, pump stations, access roads, culverts and canal or river crossings.

The indicator in **table 12** supports this interpretation. Under SSP2-4.5 the multi-model median of maximum one-day precipitation (Rx1day) rises modestly from about 35.4 mm in 2020–2039 to about 37.1 mm in 2040–2059 and about 38.6 mm in 2060–2079. The number of days with at least 50 mm (R50mm) remains very low, about 0.07, 0.10 and 0.11 days per year. Under SSP5-8.5 the Rx1day values are about 40.6, 38.0 and 40.0 mm for the three periods, with R50mm of about 0.16, 0.11 and 0.13 days per year. Values that represent fractions of a day per year explain why the mapped hazard does not expand widely.

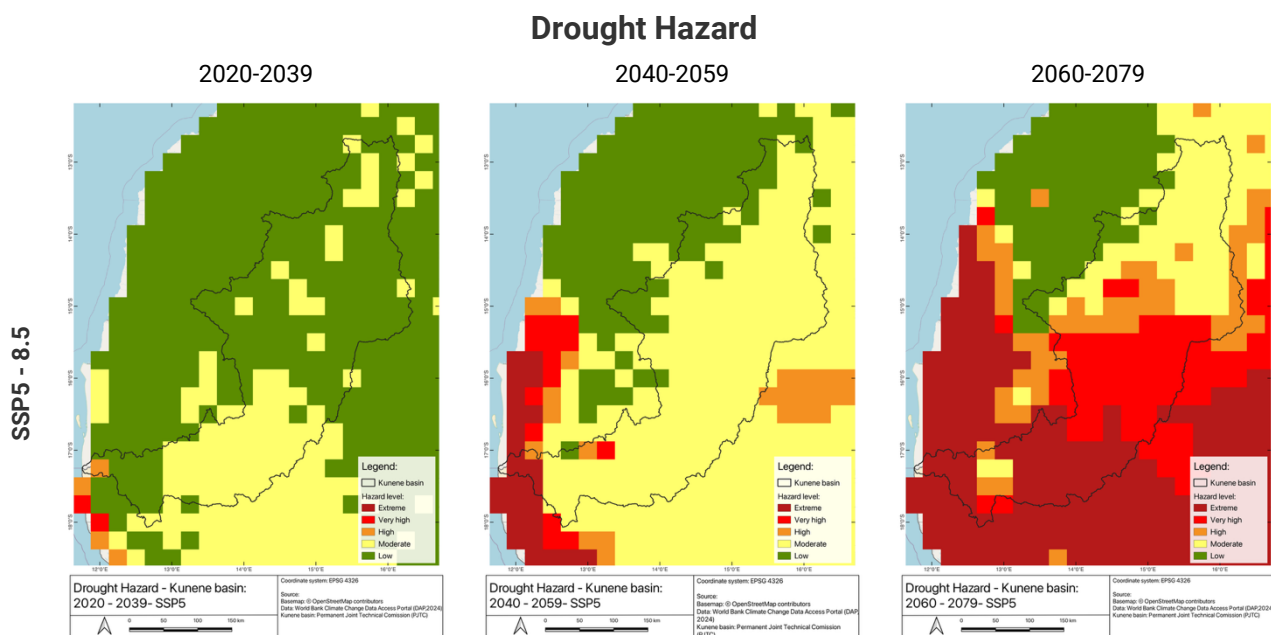
For water and sanitation investments the recommended approach is: (i) to apply site-specific drainage and access protection at the hotspots highlighted in the maps; (ii) to size culverts and yard drainage to the Rx1day design storm with allowances for blockage; (iii) to harden embankments and crossings that concentrate rapid runoff; (iv) to schedule pre-season and post-storm maintenance of inlets and grates; and (v) to link operational triggers to daily rainfall thresholds such as R20 mm and R50 mm. Crisis and asset management procedures should be consistent with ISO 24518 and ISO 24516.

Overall, pluvial flash-flood hazard is localized but material for asset design and operations under both SSP2-4.5 and SSP5-8.5. Targeted site protection, drainage performance and rapid maintenance are measures that offers strong response for both time horizons.

Table 11. Drought Indicators - CDD vs. Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
SPEI	-0,61	-0,74	-0,93	-0,39	-0,8	-1,29
CDD	173,25	175,18	175,35	172,35	174,08	175,78
SPEI frequency	0	0	0	0	0	4
CDD frequency	0	6	4	0	1	6

Figure 27. Kunene river basin. Drought Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.



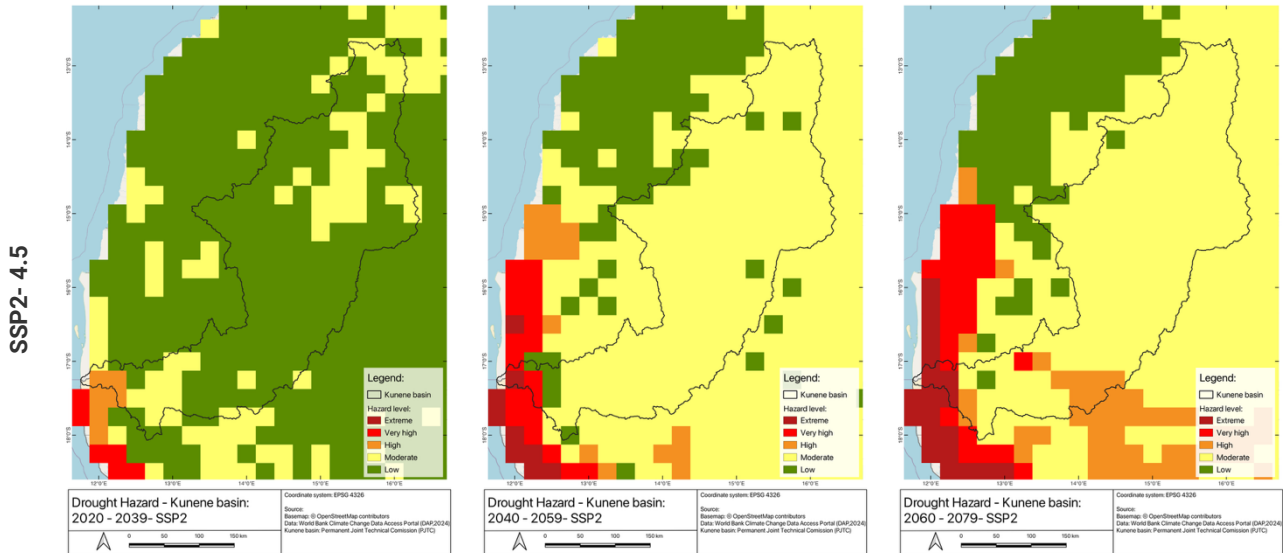
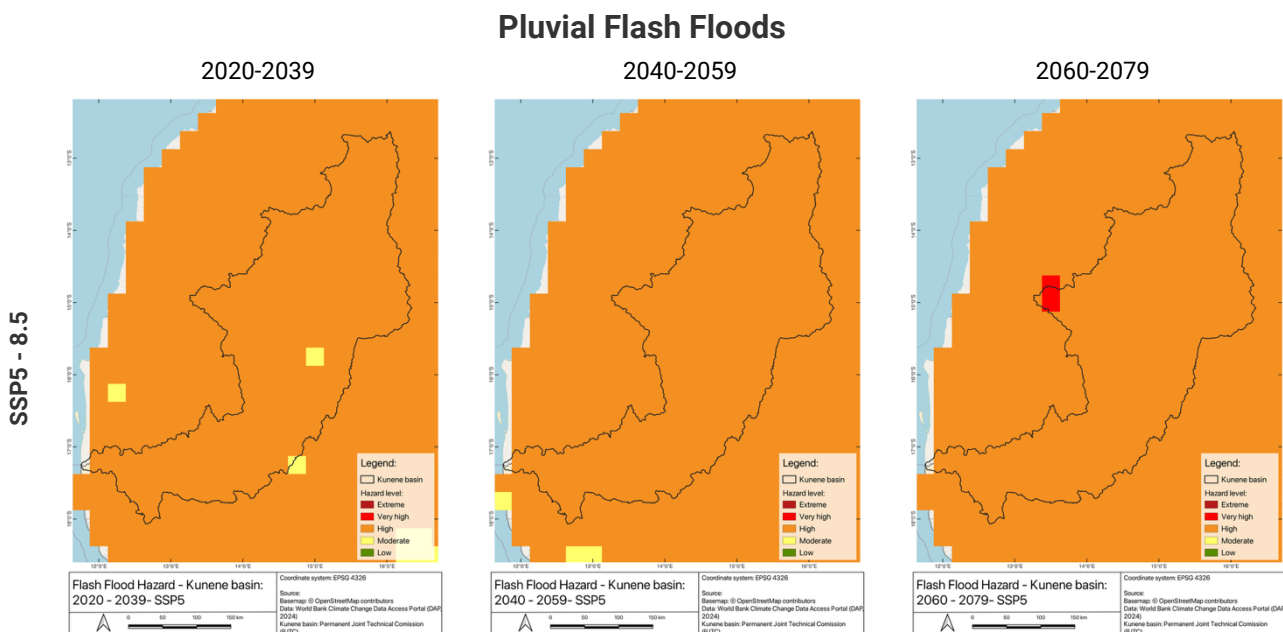
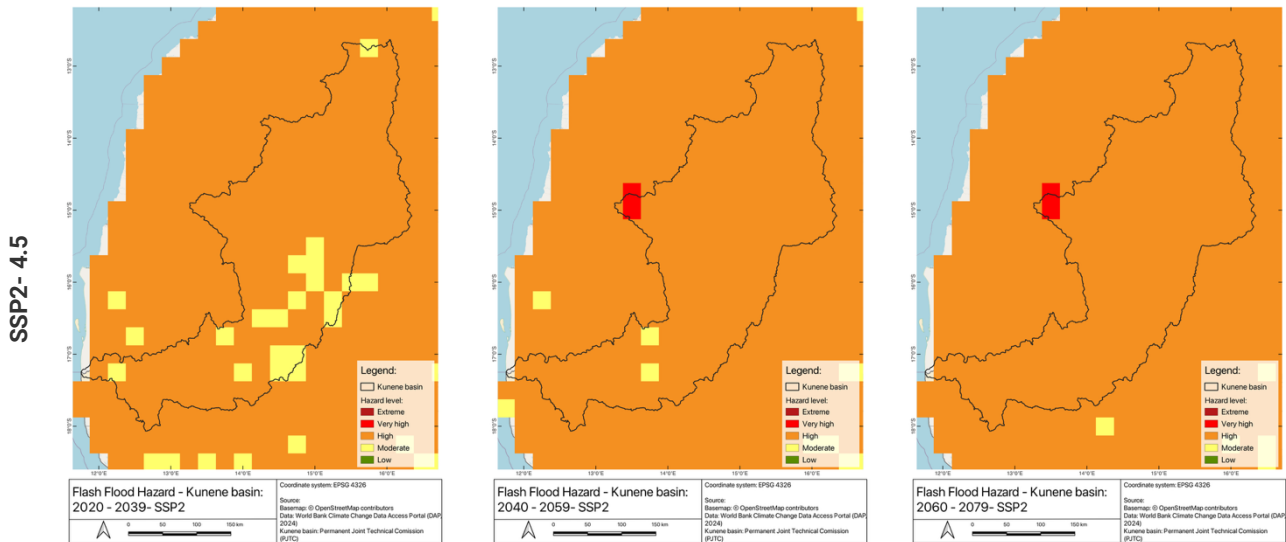


Table 12. Pluvial Flash Floods - Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
Maximum 1-day precipitation (Rx1 day)	35,38	37,06	38,62	40,62	38,02	40
Number of days with ≥ 50 mm (R50mm)	0,07	0,1	0,11	0,16	0,11	0,13

Figure 28. Kunene river basin. Pluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.





3.4.4. Fluvial Floods

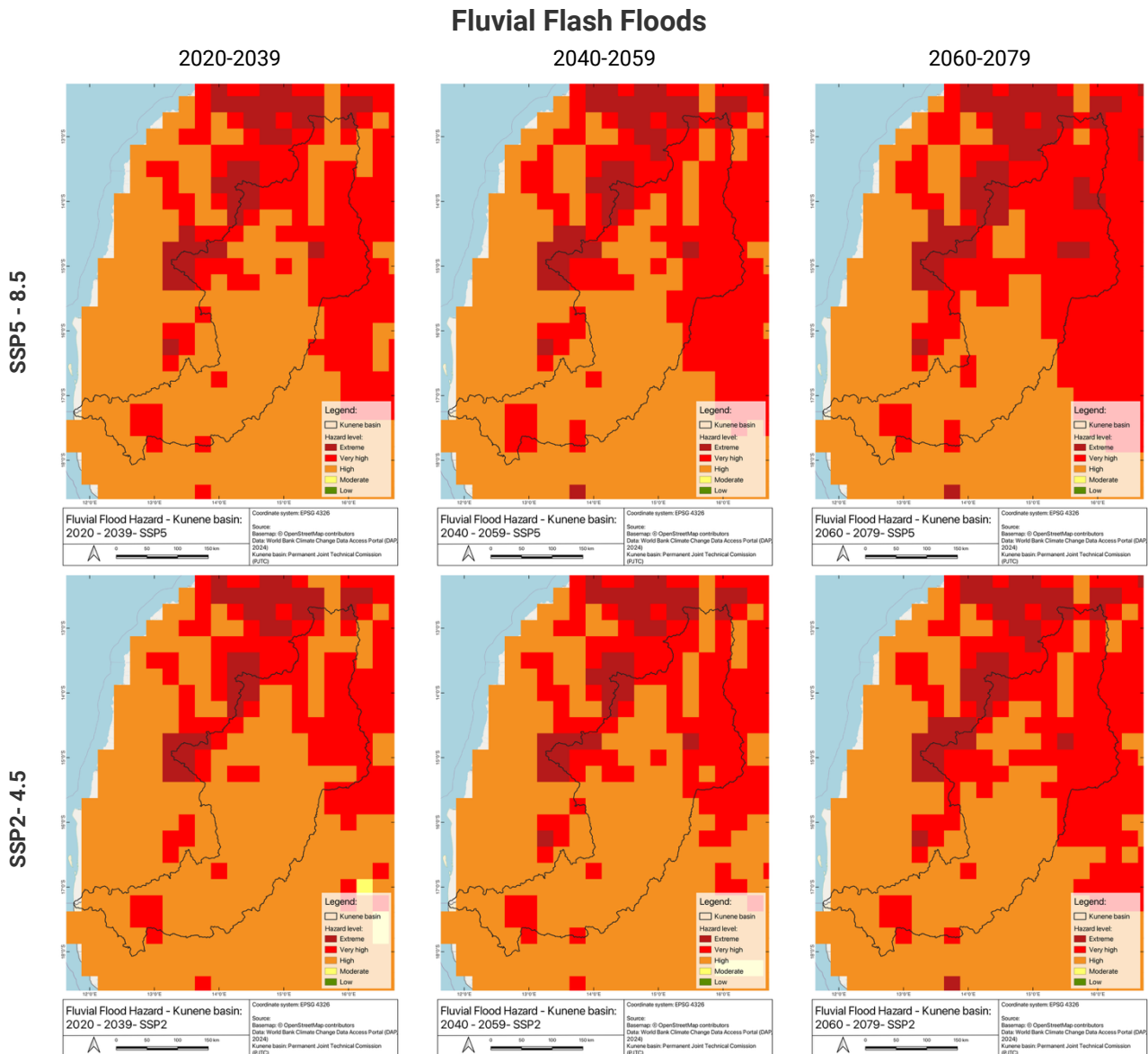
Fluvial flood hazard presents a river-aligned pattern, with higher classes concentrated along the northern main stem and eastern tributaries. Under SSP2-4.5, the maps show a largely moderate background in 2020–2039 with localized high values near the channel and at tributary fans; by 2040–2059 the high-hazard footprint widens along the same corridors and remains focused on the river belt through 2060–2079, without a basin-wide escalation far from channels. Under SSP5-8.5, the same structure appears earlier and more strongly—high classes become more contiguous from mid-century and persist into the long term across the northern reach and selected eastern tributaries—while interior southern sectors stay comparatively lower. The mapping in **figure 29** therefore points to a corridor-type riverine risk driven by multi-day rainfall and local hydraulics.

The indicators in **table 13** supports this reading. Maximum five-day precipitation (Rx5day) under SSP2-4.5 rises from about 35.4 mm in 2020–2039 to about 37.1 mm in 2040–2059 and about 38.6 mm in 2060–2079, while the number of days with at least 20 mm (R20mm) increases from about 4.42 to about 4.71 and about 4.89 days per year. Under SSP5-8.5, Rx5day remains near about 40.6, 38.0 and 40.0 mm for the three horizons, with R20mm around about 5.73, 5.08 and 5.45 days per year. These changes are consistent with the enhanced river-response corridors in the maps. For water and sanitation investments, design and O&M should prioritize intake siting outside flood conveyance zones, freeboard and scour protection for canals and embankments, bridge and culvert sizing that reflects Rx5day-scale events and debris allowance, access-road resilience and safe egress, and rainy-season maintenance to keep channels and inlets clear.

Table 13. Fluvial Floods - Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
Maximum 5-day precipitation (Rx5day)	35,38	37,06	38,62	40,62	38,02	40
Number of days with ≥ 20 mm (R20mm)	4,42	4,71	4,89	5,73	5,08	5,45

Figure 29. Kunene river basin. Fluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.



3.4.5. Wildfire

Wildfire hazard displays a consistently high baseline across most of the basin, with the highest classes clustered along the northern rim and eastern margins where dry vegetation and wind exposure are likely to concentrate ignition and spread. Under SSP2-4.5, the maps in **figure 30** for 2020–2039 is already dominated by high hazard with pockets of moderate conditions near some northern uplands; by 2040–2059 the moderate pockets contract and high hazard become the modal class across the interior; by 2060–2079 only small border areas retain moderate levels. Under SSP5-8.5, the same spatial structure intensifies earlier and remains widespread through all horizons, with contiguous high hazard across the north and east and only isolated moderate cells persisting. The map evidence therefore points to a pervasive, landscape-scale fire environment in which ignition potential and rapid spread are credible through much of the warm season.

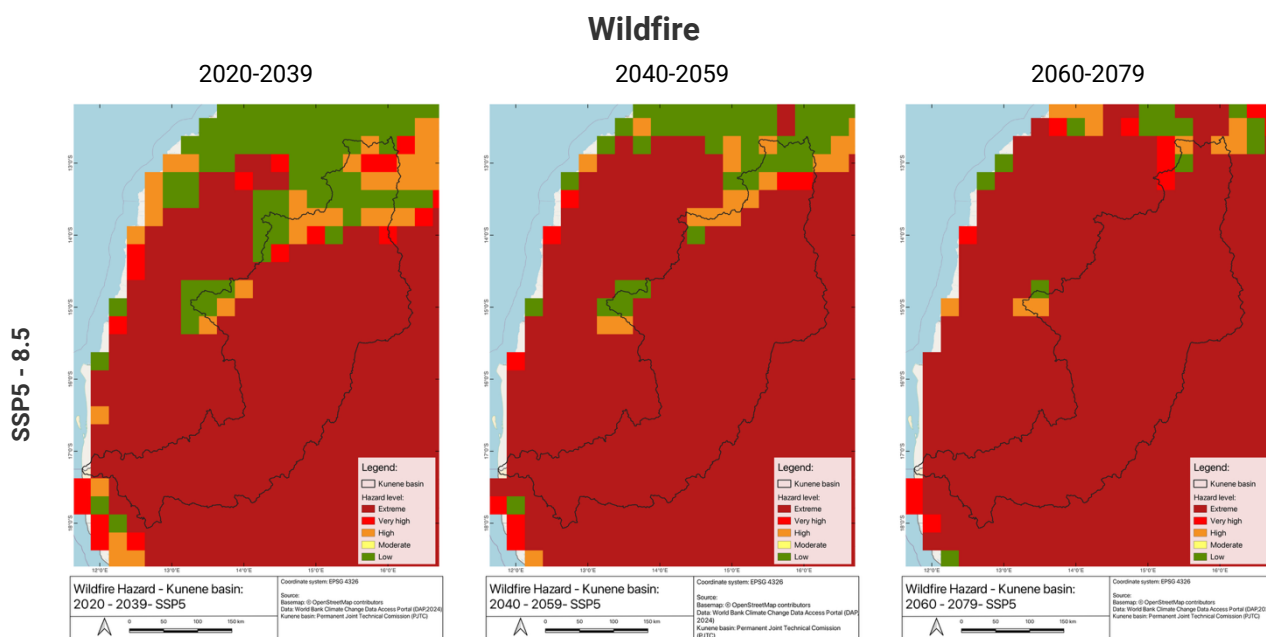
The indicator context reported in the **table 14** shows the number of days with maximum temperature at or above 35 °C (TX35) under SSP2-4.5 increasing from about 35 in 2020–2039 to about 37 in 2040–2059 and

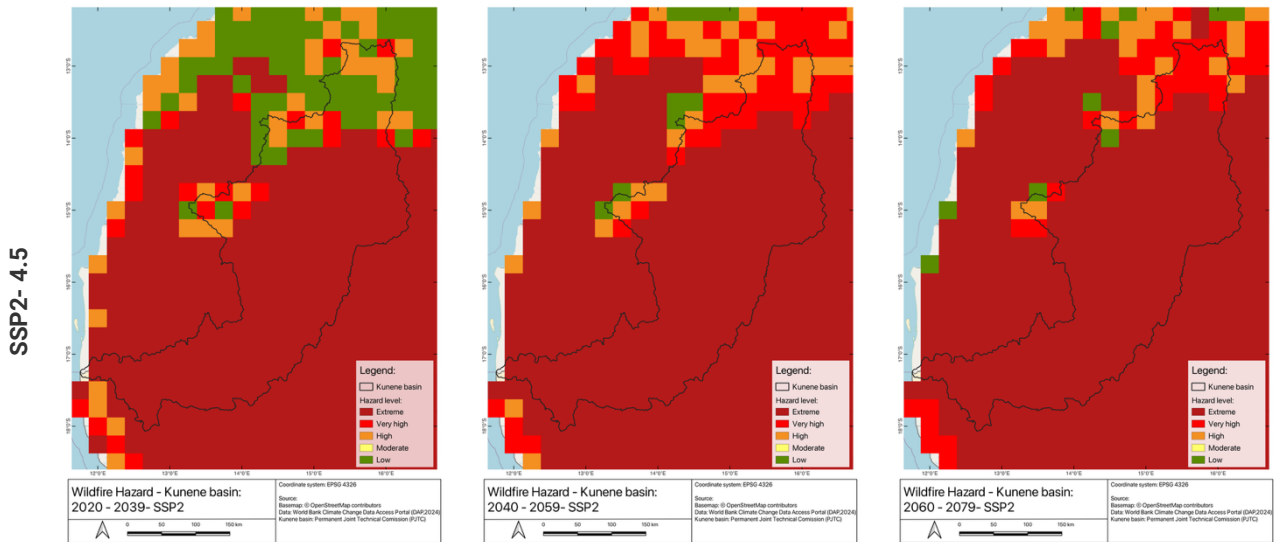
about 39 days in 2060–2079, while the consecutive dry-day anomaly (CDD) rises from about 4.4 to about 4.7 and about 4.9 days, respectively. Under SSP5-8.5, TX35 is higher for all horizons (around 41, 38, and 40 days), with CDD anomalies near about 5.7, about 5.1, and about 5.5 days. More frequent very hot days combined with longer dry spells align with the extensive high-hazard footprint in the maps and indicate elevated ignition pressure, faster rates of spread and greater intensity. For water and sanitation assets, engineering and O&M should therefore: (i) include defensible-space management around kiosks, borehole heads, pump stations and PV arrays; (ii) heat- and flame-resistant cable routing and conduit protection; backup power and ventilation strategies to manage heat-related shutdowns; (iii) access-road control with clear egress; and (iv) pre-season fuel reduction and spark-control protocols with community engagement. Asset stewardship and emergency procedures should be aligned with ISO 24516 for asset management and ISO 24518 for crisis readiness, and service-level communication and recovery actions should follow good-practice guidance in ISO 24510/24512.

Table 14. Wildfires - Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
Number of days with maximum temperature $\geq 35^\circ\text{C}$ (TX35)	35,38	37,06	38,62	40,62	38,02	40
Consecutive Dry Days anomaly (CDD anomaly)	4,42	4,71	4,89	5,73	5,08	5,45

Figure 30. Kunene river basin. Wildfire Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.





3.5 Hazards in Okavango River Basin

3.5.1. Heat Stress

Heat stress is already a basin-wide concern in the Okavango system and intensifies over time under both emissions pathways. Under SSP2-4.5, the hazard maps for 2020–2039 in **figure 31**, show high classes dominating the interior with limited moderate pockets along the south-western fringe; by 2040–2059 very high hazard becomes spatially continuous across most zones; by 2060–2079 the basin is largely covered by very high levels with only small edges below that class. Under SSP5-8.5, the spatial progression is faster and stronger: high–very high classes are widespread already in 2020–2039, and a near-uniform, basin-wide very high hazard is established by mid-century and persists through the long-term horizon. The heat-stress hazard maps (**Figure 31**) point to sustained, multi-month operational heat pressure for field crews and heat-sensitive components from intake sites to pump stations, kiosks, PV frames and telemetric systems.

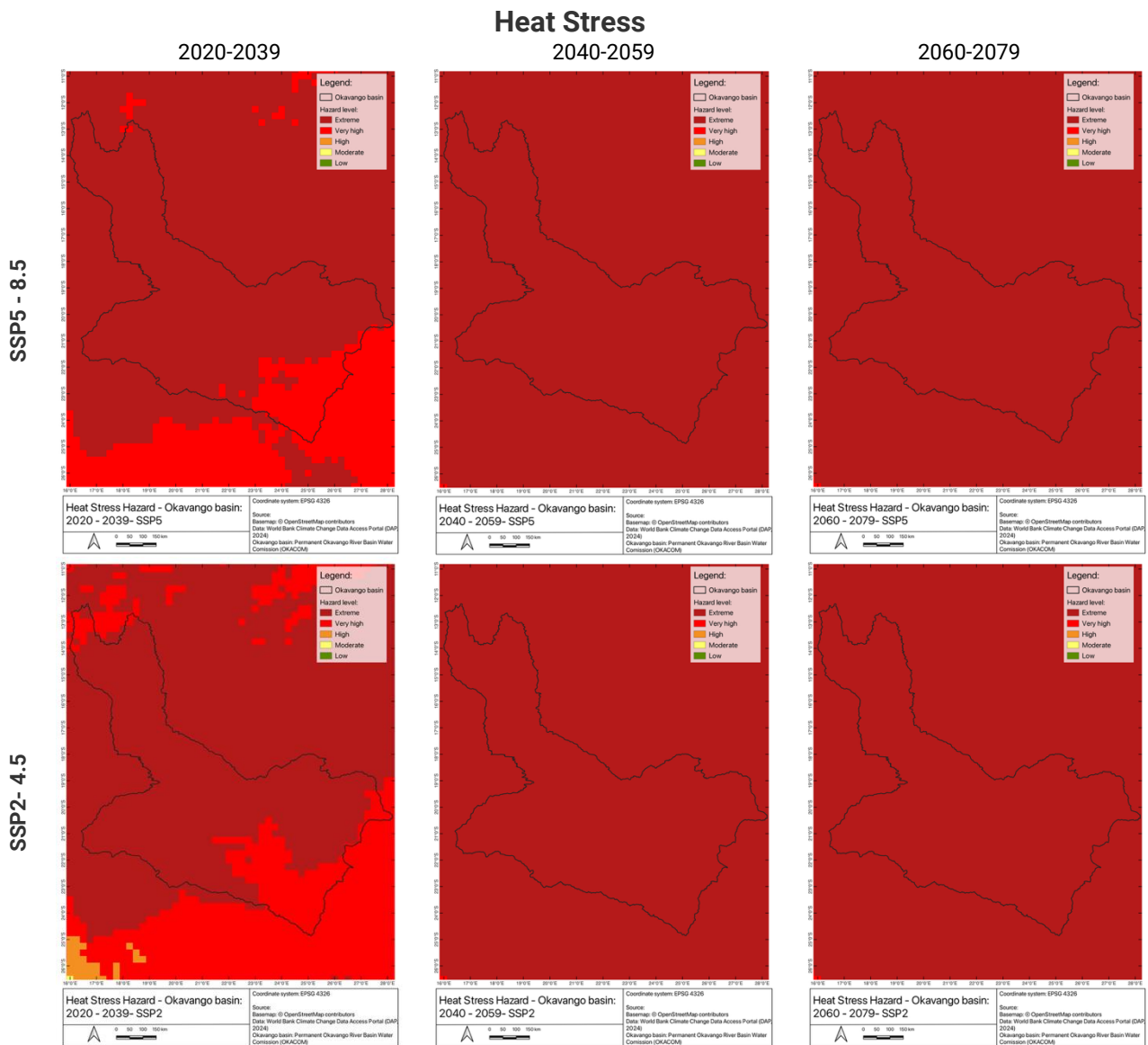
Indicator values in **Table 16** align with the maps. Under SSP2-4.5, peak heat (TXx) rises roughly +1–3 °C through mid-century and to about +3.2 °C by 2080–2099; warm-spell duration (WSDI) doubles from 0.7 to 1.4 days mid-century and approaches 2.4 days by late century; hot days (≥ 35 °C) expand from 10 to 40 days/year while ≥ 40 °C remains rare (≤ 2 days/year). Under SSP5-8.5, the signal is much stronger: TXx nears +6 °C by late century, WSDI climbs toward 5 days, and very hot days (≥ 35 °C) exceed 100 days/year with 25 days ≥ 40 °C. These shifts explain the basin-wide very-high hazard classes by mid- to late-century, and imply longer and hotter work periods, elevated derating and thermal fatigue of electro-mechanical equipment, and higher ventilation/cooling demand and water-quality risks due to accelerated disinfectant decay.

For WASH project operations, design and O&M should anticipate persistent heat conditions through the asset life. Priority measures include heat-safe work procedures, shading and ventilation retrofits at pump houses, derating-aware equipment selection (motors/VSDs), thermal protection of control cabinets and battery enclosures, reservoir/canal evaporation management, materials and linings selected for high-temperature performance, and contingency protocols for power outages and wild-heat days.

Table 15. Heat Stress indicators anomalies. Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5				SSP5-8.5			
	2020–2039	2040–2059	2060–2079	2080–2099	2020–2039	2040–2059	2060–2079	2080–2099
TXx (°C) Mean	1.20	2.02	2.74	3.22	1.33	2.66	4.17	6.05
TXx P90 (°C)	22.68	23.39	23.98	24.40	22.79	23.93	25.29	26.97
WSDI Mean (days)	0.68	1.39	1.98	2.40	0.79	1.93	3.29	4.97
Tmax ≥ 35°C (days/year)	9.85	21.72	32.56	40.66	10.46	31.60	58.71	103.16
Tmax ≥ 40°C (days/year)	0.00	0.08	0.66	1.88	0.00	0.68	6.84	24.73

Figure 31. Okavango river basin. Heat Stress Hazard) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.



3.5.2. Drought

Drought conditions in the Okavango basin intensify and expand over time. Under SSP2-4.5, SPEI-based deficits and CDD increases remain modest in 2020–2039 and then spread by 2040–2059, with CDD anomalies roughly doubling from near-term values to around one hundred days and recurring in several seasons per decade in southern and central areas (Table 17). By 2060–2079 the maps show predominantly Moderate to High drought hazard in the interior while the northern headwaters retain lower levels.

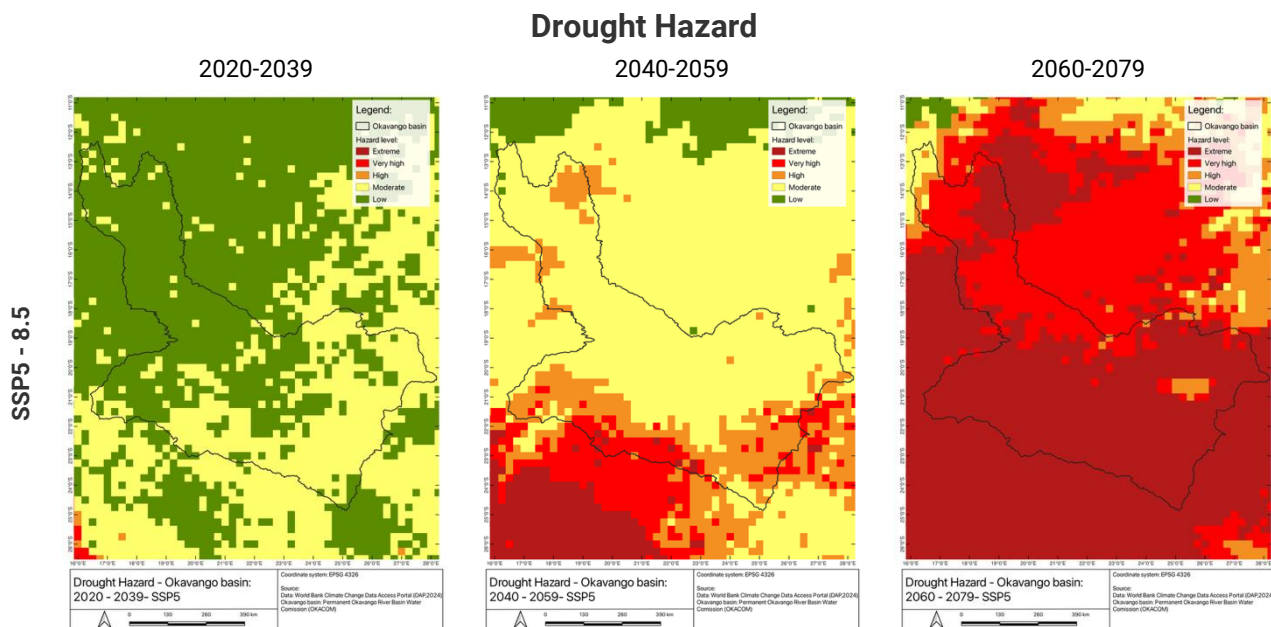
Under SSP5-8.5 the signal is stronger and earlier: by mid-century large swathes shift to High/Very High hazard and, by 2060–2079, extreme classes dominate the interior and south-west, with CDD anomalies approaching or exceeding two hundred days and SPEI-triggered events appearing in multiple years per decade (Table 17), fully consistent with the spatial saturation of high hazard in Figure 32.

Operationally, this points to longer dry spells, more sustained stress on surface and shallow-groundwater sources, and more frequent years breaching design and O&M thresholds, especially under SSP5-8.5.

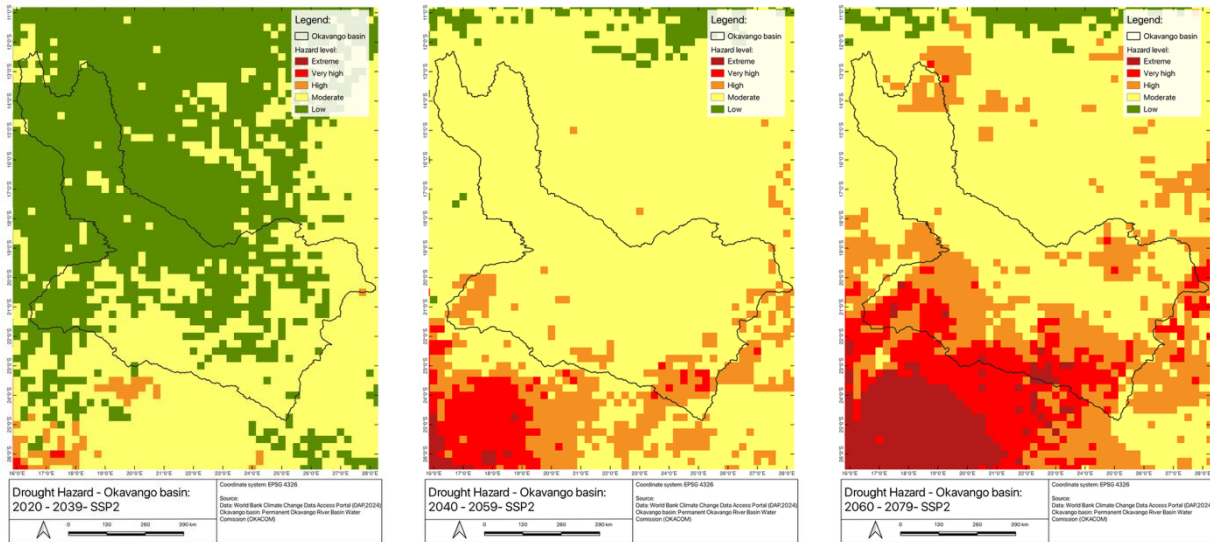
Table 16. Drought indicators. Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
SPEI	28,63	59,69	111,51	23,09	88,29	173,41
CDD	49,3	100,8	143,6	52,9	133,9	222,5
SPEI frequency	0	0	0	0	0	2
CDD frequency	0	3	2	0	0.50	3

Figure 32. Okavango river basin. Drought Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.



SSP2 - 4.5



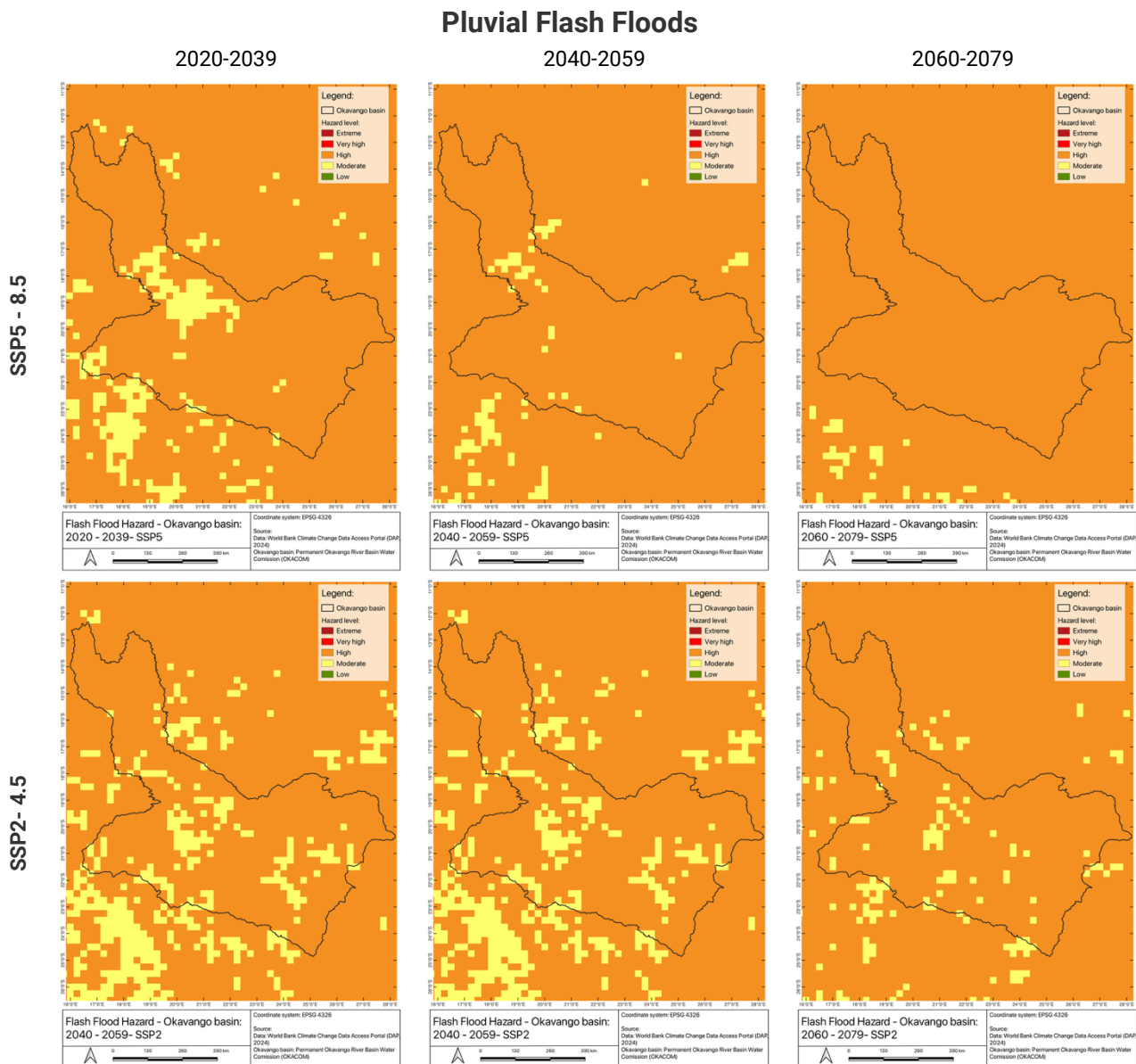
3.5.3. Pluvial Flash Floods

Under the intermediate pathway (SSP2-4.5), the ensemble shows a gradual intensification of short-duration rainfall ceilings, with Rx1day rising from about 49 mm in 2020–2039 to 101 mm by mid-century and 144 mm by 2060–2079 (see table 18). Despite this increase in intensity, days exceeding 50 mm remain infrequent (0 days per year across horizons), which is consistent with the hazard maps that portray a basin largely in moderate classes, punctuated by small, spatially scattered high cells in the western and northern sectors in the near term and fewer hotspots later on. In practical terms, this points to localized pluvial-ponding problems around low-standard drainage and road embankments rather than a uniform, basin-wide step-change in flash-flood severity. Under SSP5-8.5 the signal is stronger—Rx1day increases from 53 mm in the near term to 134 mm mid-century and 223 mm later in the century—yet the frequency of ≥ 50 -mm days still remains near zero in the multi-model median (table 18). The hazard maps in figure 33 mirror this behavior: most grid cells stay in moderate hazard levels across horizons, with only isolated high-hazard areas emerging in the central corridor by mid- to late-century. The combined evidence suggests that pluvial-flash-flood hazard in the Okavango basin is governed by occasional, high-intensity downpours rather than sustained increases in storm-day counts; therefore, risk management should emphasize conveyance at known points, stormwater inlet capacity, and maintenance of urban/settlement drainage where exposure is highest, while monitoring IDF curves for design updates.

Table 17. Pluvial Flash Floods indicators. Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
Maximum 1-day precipitation (Rx1day)	49,3	100,84	143,6	52,89	133,93	222,51
Number of days with ≥ 50 mm (R50mm)	0,0	0,0	0,0	0,0	0,0	0,0

Figure 33. Okavango river basin. Pluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.



3.5.4. Fluvial Floods

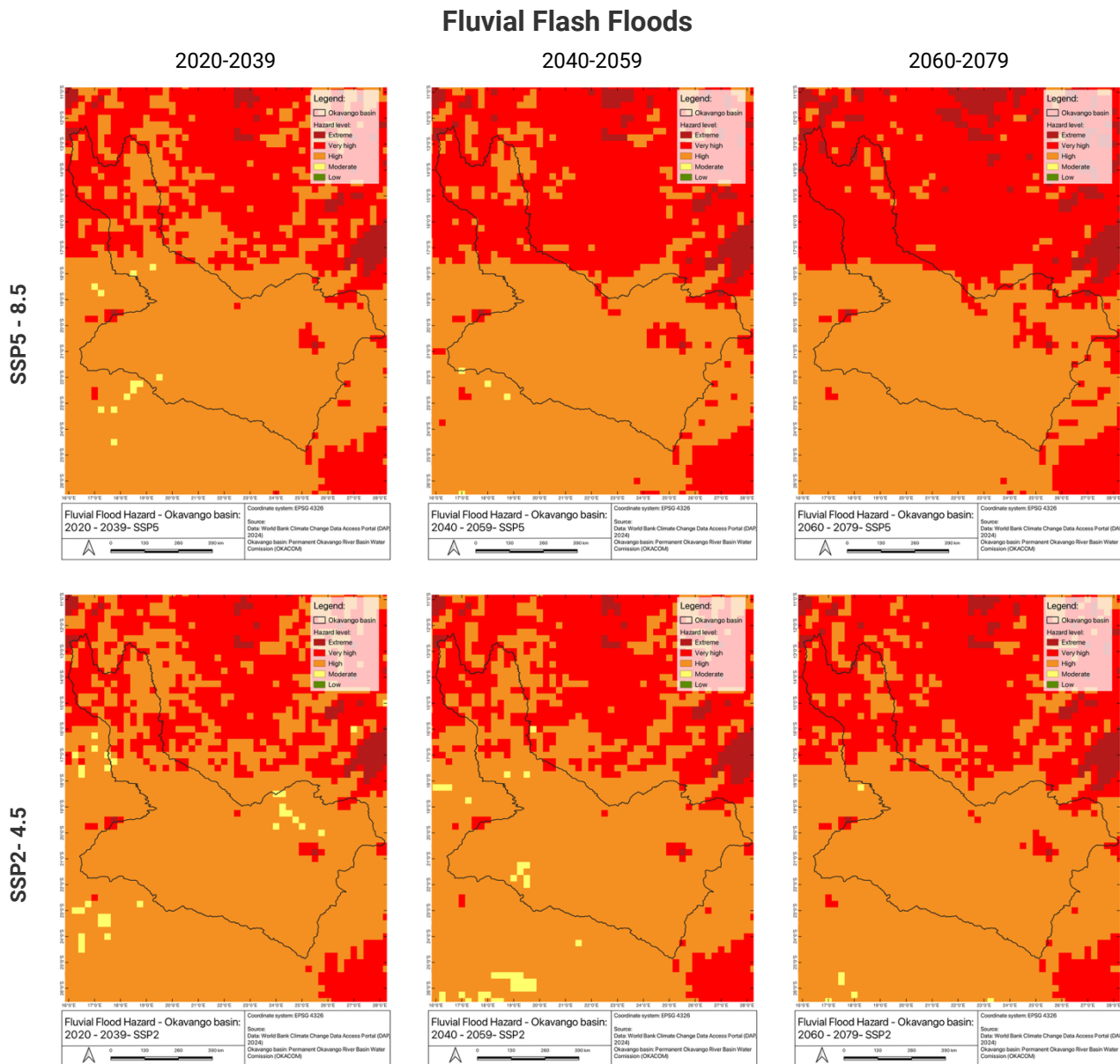
Fluvial flood hazard is expected to increase across the Okavango basin as multi-day rainfall extremes strengthen. Under SSP2-4.5, the multi-model median of the maximum 5-day precipitation (Rx5day) rises from about 49 in 2020-2039 to roughly 101 in 2040-2059 and 144 by 2060-2079; the number of days with at least 20 mm (R20mm) moves from about 2.0 to 2.2 and 2.46 days per year. Under SSP5-8.5, the signal is stronger: Rx5day increases from about 53 in the near term to around 134 mid-century and about 223 late-century, while R20mm grows from about 2.26 to 2.74 days per year. These values (**Table 19**) imply greater potential for bankfull exceedance and backwater effects even where annual rainfall totals change modestly.

The spatial patterns in the hazard maps in **figure 34** show that higher flood susceptibility consolidates along the northern and eastern corridors and progressively expands downstream floodplains through mid- and late-century, with more extensive high to very high classes under SSP5-8.5 than under SSP2-4.5. For planning, this points to the need for: (i) channel conveyance checks; (ii) culvert and bridge capacity reviews; and (iii) drainage maintenance programs prioritized in the hotspots.

Table 18. Fluvial Floods indicators. Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
Maximum 5-day precipitation (Rx5day)	49,3	100,84	143,6	52,89	1333,93	222,51
Number of days with ≥ 20 mm (R20mm)	2	2,2	2,46	2,26	2,43	2,74

Figure 34. Okavango river basin. Fluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.



3.5.5. Wildfires

Wildfire drivers in the Okavango basin strengthen through the century under both emissions pathways. As shown in **table 20**, the number of very hot days and the persistence of dry spells rise markedly: under SSP2-4.5, days with maximum temperature above 35 C increase from about 12 in 2020–2039 to roughly 27 by 2060–2079, while the consecutive dry days anomaly grows from near 10 to about 51. Under SSP5-8.5 the signal is stronger, with hot days rising from about 12 to around 40 and the dry-spell anomaly more than doubling to over 100 by late century. These trends indicate a longer, hotter and drier fire season, higher ignition likelihood, and faster spread potential.

As shown in **figure 35** wildfire hazard expanding from scattered pockets in the near term to basin-wide high levels by mid-century, with the late-century maps dominated by high to very high classes. Hotspots concentrate along the northern and eastern fringes and around settlement and transport corridors, where fine fuels and human activity coincide. Even under the moderate pathway, most of the basin shifts from moderate to high hazard.

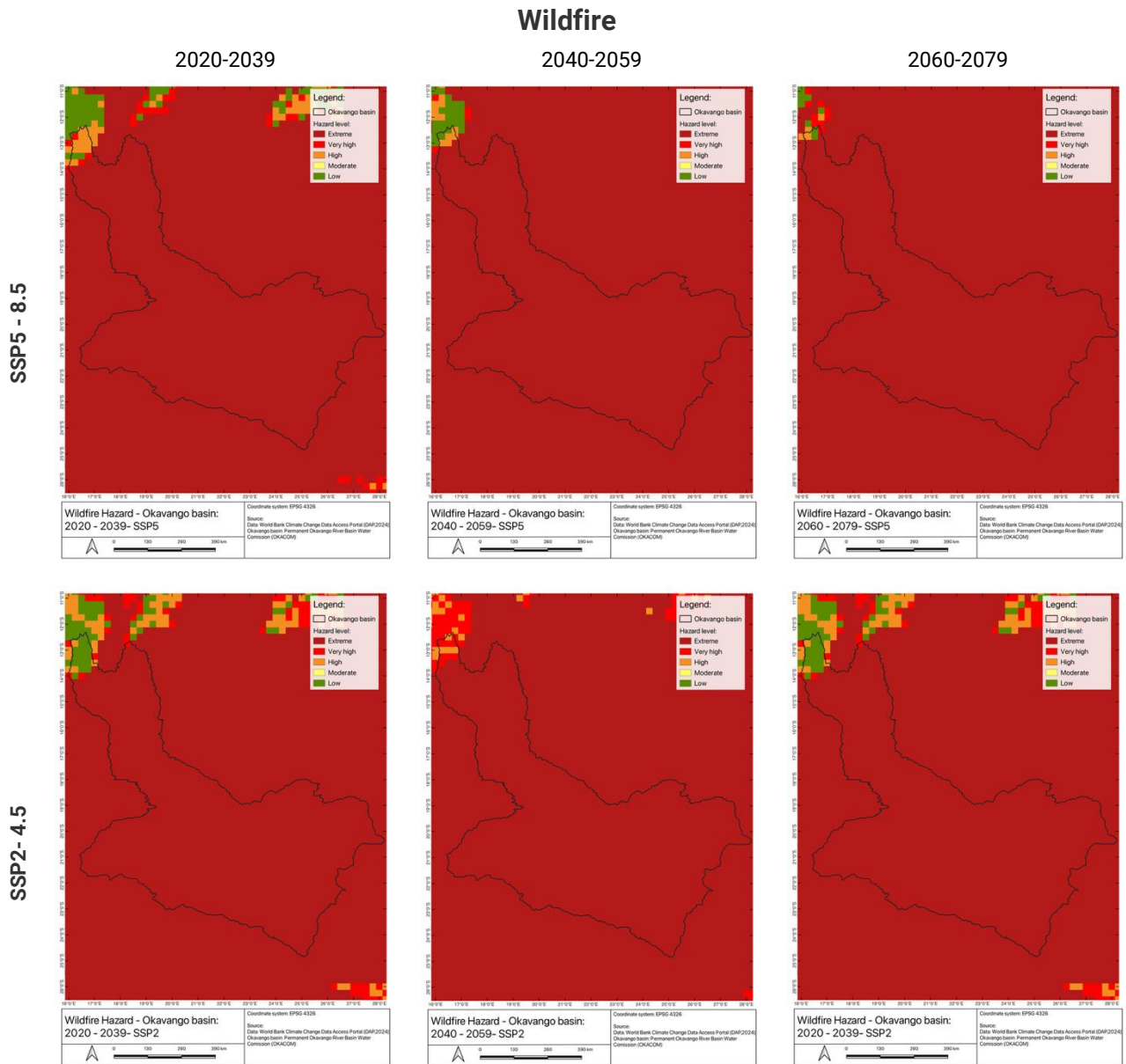
The implications for WASH projects are: (i) raw-water intakes, pump-station compounds, treatment plants and telemetry power lines are exposed to ignition, radiant heat and access disruption; (ii) smoke and ash can cause short-term turbidity spikes, taste-and-odor episodes and accelerated filter loading; and (iii) high temperatures can reduce strength in polymer pipelines and gaskets.

Design and O&M should therefore consider: (i) defensible space and vegetation management around assets and non-combustible enclosures; (ii) buried or shielded critical conduits, backup power and redundancy for key pumps; (iii) upgraded HVAC and particulate filtration for control rooms; (iv) fire-weather triggers in operating procedures, seasonal scheduling of high-risk works and contingency water supply agreements to maintain service continuity during fire events.

Table 19. Wildfires proxy indicators. Reference Period (1995–2014). Source: CCKP, World Bank.

Time period	SSP2-4.5			SSP5-8.5		
	2020–2039	2040–2059	2060–2079	2020–2039	2040–2059	2060–2079
Number of days with max. T _≥ 35 °C (TX35)	12.52	20.77	26.72	12.00	24.98	40.49
Consecutive Dry Days anomaly (CDD anomaly)	9.92	30.89	51.38	10.10	50.40	104.56

Figure 35. Okavango river basin. Wildfire Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.



3.6 Hotspots in Kunene and Okavango river basins

To better understand where climate hazards are most likely to exert the strongest combined pressure on WASH systems, multi-hazard hotspot maps have been developed for the Kunene and Okavango basins. The hotspot analysis follows a screening logic: it overlays the drought, pluvial flash flood and fluvial-flood hazard rasters for each scenario and time slice and flags those grid cells where all three hazards simultaneously reach at least High levels. These cells are labelled *multi-hazard hotspots* and indicate locations where WASH systems are more likely to experience compound or closely spaced climate shocks over their lifetime.

All hazard layers are built from a common multi-model ensemble referenced to the historical 1995–2014 period, which serves as the baseline climate for both basins. The hotspot overlays themselves are computed only for the three projection horizons 2020–2039, 2040–2059 and 2060–2079 under SSP2-4.5 and SSP5-8.5. In practical terms, the near-term horizon 2020–2039 approximates the current planning horizon for NWSISP II (design, construction and early operation) and is used in this report as a proxy for the “current climate” hotspot configuration, while the mid- and long-term horizons are used to test the robustness of investments under more severe climate futures. The 1995–2014 reference period does not have a separate hotspot map; instead, it provides the baseline against which changes in hazard classes and the emergence or expansion of hotspots in the three projection horizons are interpreted.

It is important to underline that multi-hazard hotspots are a complementary screening tool rather than a substitute for the single-hazard maps. Siting and design decisions for NWSISP II investments should continue to rely primarily on the individual hazard maps and their High / Very High / Extreme bands (“High+”), which provide the most detailed information on the magnitude and spatial extent of each process. The hotspot overlays highlight those sub-areas where several High+ bands for drought, pluvial and fluvial floods overlap, signalling where compound or sequential impacts are more likely and where more conservative design standards, redundancy or alternative locations may be warranted. Areas outside hotspots are not necessarily “safe”: background hazards of extreme heat and wildfires remain pervasive and must be addressed through basin-wide design and operational measures.

In the near-term horizon 2020–2039, which is taken here as the current-climate configuration for planning purposes, hotspot patterns remain limited but already show clear areas of concern. In the Kunene Basin, early hotspots are localised, appearing mainly in the south-western lowlands and along the coastal fringe of the lower valley. In the Okavango Basin, near-term hotspots occur as scattered patches in the southern interior, with smaller clusters south of the mainstem between Nkurenkuru and Rundu and along inland tributaries in Kavango West. The following subsections (3.6.1 and 3.6.2) describe how these initial patterns intensify and expand under mid- and long-term climate futures for both basins and under both emissions pathways.

3.6.1. Hotspots in Kunene River basin

In the near-term horizon 2020–2039, multi-hazard hotspots in the Kunene River Basin are relatively limited in extent and mostly confined to localised cells in the south-western lowlands and the coastal fringe of the lower valley. These early hotspots nevertheless signal areas where drought, pluvial flash floods and fluvial floods are already projected to reach High or higher hazard levels within the current planning horizon of NWSISP II. Under the mid-term and long-term horizons, these clusters expand along the lower valley and selected inland sub-basins, as described in the paragraphs below, indicating a gradual but clear intensification of compound flood-and-drought pressures along key corridors of potential WASH investment.

The hotspots maps for the Kunene basin in **figure 36** show, under the SSP2-4.5 pathway, near-term hotspots (2020–2039) are localised, appearing mainly in the south-western lowlands and at the basin’s coastal fringe near the lower valley. By mid-century (2040–2059) these clusters expand along the south-western corridor and appear intermittently across the interior piedmont and lower plateau. By 2060–2079 the pattern consolidates into larger, contiguous zones in the south-west with additional pockets emerging in the interior, indicating increasing coincidence of drought with flash- and riverine-flood hazards.

Under SSP5-8.5 the intensification is stronger and faster. The near-term still shows mostly coastal and south-western cells, but by mid-century hotspots extend along the lower Kunene corridor and across parts of

the interior plateau. By 2060–2079 much of the central and eastern basin becomes a continuous hotspot field, with only limited breaks near higher-relief headwaters. This trajectory signals a transition from localised multi-hazard stress to basin-wide concurrence of hydrological extremes.

In summary, the Kunene hotspot pattern evolves from localised south-western clusters to broad interior coverage under the high-emissions pathway, indicating growing concurrence of drought and flood hazards. WASH systems that combine multi-source water security, flood-tolerant civil works and operational flexibility will be more likely to meet service targets under this emerging risk regime.

3.6.2. Hotspots Okavango River basin

In the Okavango River Basin, the near-term multi-hazard hotspot configuration (2020–2039) is also limited but more fragmented, with scattered clusters in the southern interior and smaller patches south of the mainstem between Nkurenkuru and Rundu and along inland tributaries in Kavango West. These hotspots mark locations where High+ drought, pluvial and fluvial flood hazard are already expected to interact within the current planning horizon. As climate forcing strengthens towards 2040–2059 and 2060–2079, these initially isolated clusters expand and connect along the lower Okavango corridor and into adjacent sub-catchments, as detailed in the following paragraphs, creating longer stretches of the basin where compound or sequential impacts on WASH infrastructure become more likely.

The hotspots maps for the Okavango basin in **figure 37** show a marked escalation from scattered clusters to basin-wide coalescence.

Under SSP2-4.5, the near term displays isolated hotspot patches primarily in the southern basin, with minor clusters south of the mainstem between Nkurenkuru and Rundu and along inland tributaries in Kavango West. By 2040–2059, hotspots consolidate into a discontinuous band along the southern interior of Kavango East, extending east of Rundu toward the lower Okavango corridor, while smaller pockets persist to the southwest of Nkurenkuru. By 2060–2079, the distribution remains concentrated in the southern half of the basin but expands northward toward the river corridor in eastern districts, indicating greater co-occurrence of drought with both pluvial and fluvial flooding in the floodplain-adjacent settlements.

Under SSP5-8.5 the transition is sharper: the near term shows few hotspots, the mid-term introduces a broad swath of hotspots across the south-central basin, and the long-term horizon exhibits extensive hotspot coverage across Kavango East and much of Kavango West, including around Rundu and Nkurenkuru and along the Okavango River floodplain. This pattern points to progressively stronger compound interactions between low-flow deficits, intense rainfall events and mainstem flood response across the basin.

Figure 36. Kunene river basin. Multi-hazard hotspots combining drought, pluvial flash floods and fluvial floods for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots correspond to grid cells where all three hazards simultaneously fall within the High, Very High or Extreme classes (“High+”). Source: the author.

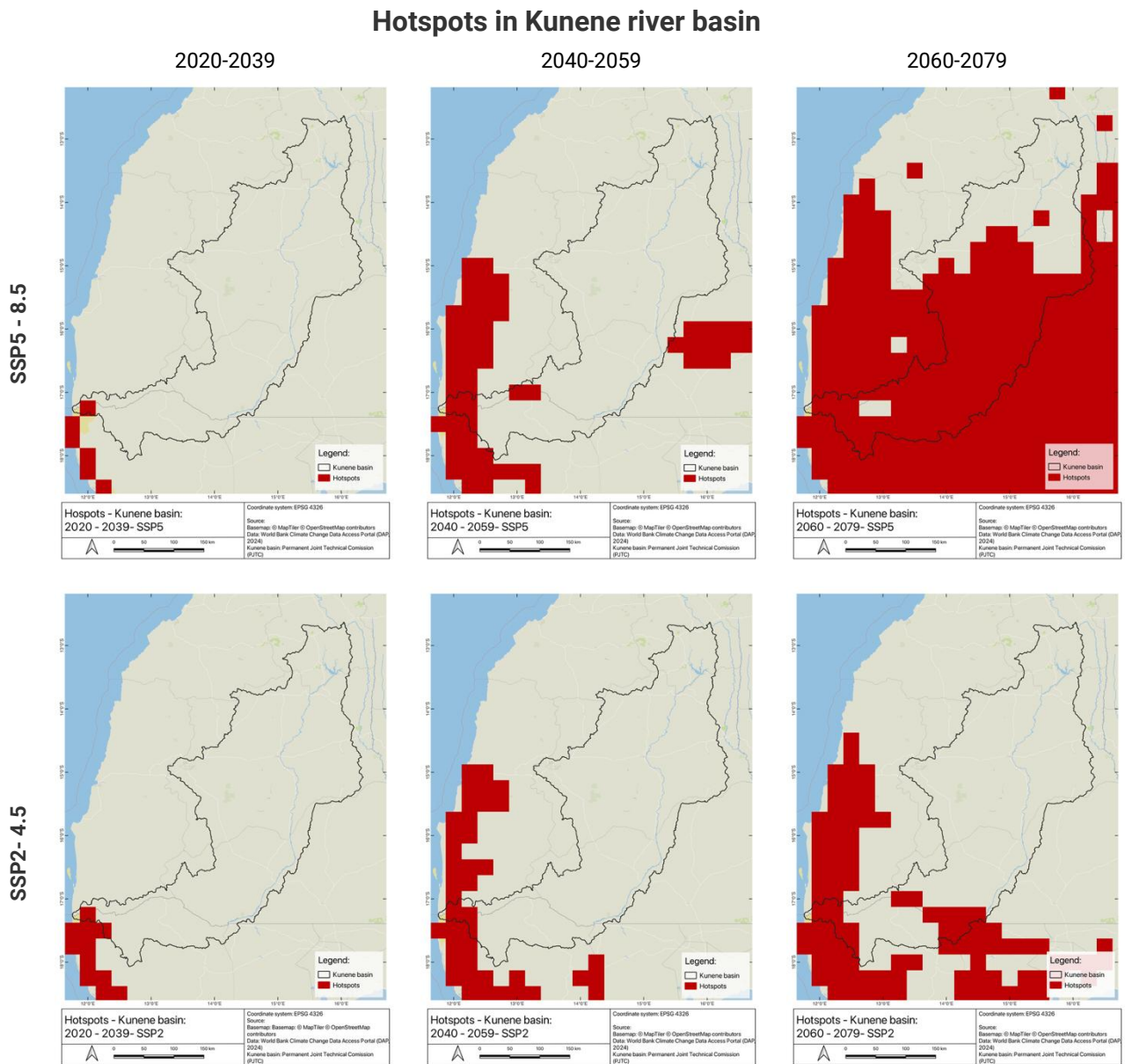
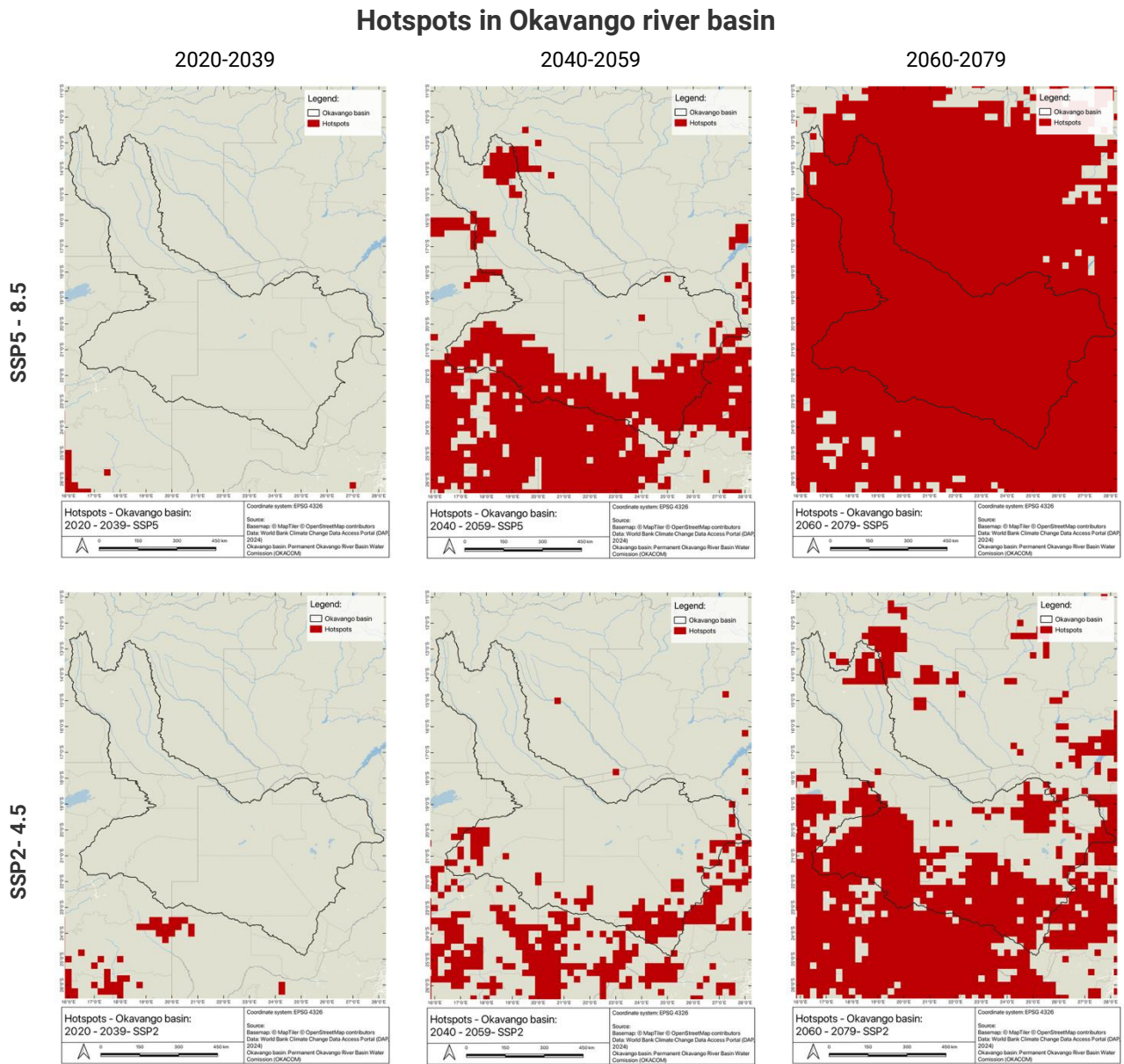


Figure 37. Okavango River Basin. Multi-hazard hotspots combining drought, pluvial flash floods and fluvial floods for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots correspond to grid cells where all three hazards simultaneously fall within the High, Very High or Extreme classes (“High+”). Source: the author.



3.7 Hazard and multi-hazard implications for WASH projects in Kunene and Okavango River basins

The basin-wide hazard assessment for the Kunene and Okavango systems shows coherent multi-hazard patterns that are directly relevant for the siting and design of NWSISP II investments. In both basins, combinations of flood, flash flood, drought, heat-stress and wildfire hazards generate corridors and clusters where bulk-water and sanitation infrastructure would face higher probability of damage, service interruption and accelerated wear if placed without additional protection.

Sections 3.7.1 and 3.7.2 summarise these patterns for each basin and highlight their implications for the location and design of intakes, treatment plants, conveyance corridors and storage. These conclusions provide an early screening layer to guide subsequent scheme-level feasibility work, so that detailed designs for the Kunene investments, the Kavango Link and the Rundu 100-km rural extensions can prioritise safer locations and incorporate appropriate multi-hazard resilience measures where exposure cannot be fully avoided.

3.7.1. Kunene basin hazard conclusions

Heat stress and drought set the structural envelope for Kunene’s WASH services. Heat becomes a dominant constraint by mid-century and remains very high to extreme thereafter, driving evaporation losses, peaking demand and thermal stress on equipment. Drought stays high in SSP2-4.5 and intensifies to very high-extreme in SSP5-8.5 late in the century, lowering dependable yields and increasing the frequency of difficult years. Pluvial flash floods rise from low/moderate to high and should be managed as episodic shocks through siting (above flow paths), robust drainage, silt control, and access protection. Fluvial flooding remains low at basin scale under our meteorological proxies but is site-specific (should be verified against hydrologic extremes before final design). Wildfire stays extreme throughout, warranting defensible space, fire-resistant materials, and rapid-response plans to handle ash and turbidity pulses. These patterns are summarized in **Table 20** below.

Hotspots cluster first along the coastal and south-western belt in the near term, then expand markedly by 2060–2079 under SSP5-8.5, where drought, pluvial flash floods and fluvial floods co-peak.

For water supply projects in **Kunene river basin**, seasonal streamflow intermittency and sediment pulses during flash events will raise treatment loads and jeopardize intake reliability:

- (i) Riverbank intakes and riverbed infiltration galleries require flood-proof plinths, scour protection, and bypass channels, while raw-water storage should be upsized to buffer multi-week low-flow spells.
- (ii) In groundwater-fed schemes, prolonged droughts increase drawdown and salinity risk in the coastal strip, calling for conservative safe yields, step-testing of boreholes, and monitoring of electrical conductivity.
- (iii) Diversifying sources—linking resilient wellfields with elevated storage, emergency bulk-transfer connections, and solar-pumped mini-grids—improves service continuity when grid power or a single source fails.
- (iv) For sanitation, flood hotspots imply high probability of pit latrine inundation and wastewater overflows. Designs should favour sealed and raised on-site systems, containment liners in high water-table areas, flood-protected faecal sludge transfer points, and modular wastewater treatment units with protected access roads.
- (v) Across the basin, utilities should adopt drought contingency triggers in Water Safety Plans, pre-position mobile treatment capacity, and prioritize surface–groundwater conjunctive operation to smooth volatility in yield and quality.

Table 20. Hazard levels in the Kunene River Basin for SSP2-4.5 and SSP5-8.5 scenarios and 2020-2039, 2040-2059 2060-2079 and 2080-2099 time slices.

Hazards	SSP2-4.5 Hazard Level by time periods			
	2020–2039	2040–2059	2060–2079	2080–2099
Heat Stress	High	Very High	Extreme	Extreme
Drought	High	High	High	High
Pluvial Flash floods	Low	Moderate	High	High
Fluvial floods	Low	Low	Low	Low
Wildfire	Extreme	Extreme	Extreme	Extreme

Hazard	SSP5-8.5 Hazard Level by time periods			
	2020–2039	2040–2059	2060–2079	2080–2099
Heat Stress	High	Extreme	Extreme	Extreme
Drought	High	High	Very High	Extreme
Pluvial Flash floods	Moderate	High	High	High
Fluvial floods	Low	Low	Low	Moderate
Wildfire	Extreme	Extreme	Extreme	Extreme

In the Kunene Basin, multi-hazard hotspots concentrate along the lower valley and across the north-central plains, where high and very-high fluvial and flash-flood hazards intersect with existing and planned bulk-water conveyance routes, urban centres and service hubs. These areas face increased likelihood of inundation of river intakes, damage to embankments and culverts, erosion at canal and pipeline crossings, and temporary isolation of treatment plants and storage facilities. At the same time, a progressive rise in drought and heat-stress hazard across much of the basin indicates that systems will increasingly operate under low-flow conditions, higher water temperatures and stronger evaporative losses, with implications for treatment performance, energy demand and water-quality management.

For the Kunene-related NWSISP II investments, these patterns imply that siting and routing should, as far as feasible, avoid the core of contiguous multi-hazard hotspots in the lower basin and adjacent plains, or at least minimise the number of critical nodes (major offtakes, main pumping stations, large reservoirs) located within them. Where infrastructure must traverse hotspot areas, conservative design standards will be needed, including higher flood-protection levels, robust scour and erosion control at crossings, elevated platforms for electro-mechanical equipment, and redundancy in supply routes and storage. Integrating these basin-scale hazard signals into subsequent scheme-level feasibility work will be essential to secure reliable service over the full design life of the Kunene investments.

3.7.2. Okavango basin hazard conclusions

In the Okavango Basin, climate pressures cluster in a different pattern than Kunene. Heat stress starts moderate hazard and rises to high hazard by late-century in both pathways, raising evaporation losses and thermal wear on equipment. Drought remains high hazard throughout—persistent rather than escalating—so dependable yields and seasonal deficits need to be managed as a constant design constraint. Pluvial flash-flood hazard is high hazard already and stays high hazard, so episodic stormwater shocks (surcharging drains, silt-laden intakes, access washouts) are a recurring concern. Fluvial flood hazard also reads high hazard at basin scale in the proxies used; site checks against hydrologic extremes will still be needed for low-lying intakes, river crossings and floodplain assets. Wildfire shifts from moderate hazard to high hazard later in the century, so defensible space and fire-resistant materials remain prudent around exposed assets.

For the **Okavango river basin** hotspots emerge sparsely in the near term, then grow along the lower Okavango

corridor and across parts of Kavango West and Kavango East, with notable concentrations around Rundu and Nkurenkuru and progressive spread under longer horizons.

For surface-water systems drawing from the Okavango River and adjacent floodplains, design must accommodate strongly seasonal hydrology and high sediment and organic loads during pluvial bursts:

- (i) Resilient intakes set back from primary thalwegs, floating pumps or adjustable screens, bank stabilization, coarse pre-sedimentation, and rapid-response coagulant dosing are essential.
- (ii) Treatment plants should be modular with duty–standby units to handle sharp turbidity surges without service disruption, and clear well plus elevated storage should cover at least several days of demand to bridge raw-water outages.
- (iii) Groundwater provides strategic redundancy in the Kalahari sands but requires conservative abstraction limits and systematic quality surveillance for iron, manganese, and pathogens where pit latrines are common.
- (iv) Sanitation planning in floodplain settlements should avoid siting new containment within flood-prone polygons. Raised, sealed containment and engineered wetlands above design flood levels reduce failure risk, while decentralized faecal sludge management hubs outside hotspots protect access during floods.
- (v) WASH investments should phase critical assets outside mapped hotspots when feasible; where relocation is impossible, elevate and flood-harden facilities, establish multi-source supply with interlinked zones, deploy early-warning tied to river stage and rainfall thresholds, and embed drought and flood triggers in operating procedures.

These measures maintain potable supply, protect sanitation performance, and enhance recovery capacity as concurrent drought–flood pressures intensify along the Okavango system.

Table 21. Hazard levels in the Okavango River Basin for SSP2-4.5 and SSP5-8.5 scenarios and 2020-2039, 2040-2059 2060-2079 and 2080-2099 time slices.

Hazard	SSP2-4.5 Hazard Level by time periods			
	2020–2039	2040–2059	2060–2079	2080–2099
Heat Stress	Moderate	High	High	High
Drought	High	High	High	High
Pluvial Flash floods	High	High	High	High
Fluvial floods	High	High	High	High
Wildfire	Moderate	Moderate	High	High

Hazard	SSP5-8.5 Hazard Level by time periods			
	2020–2039	2040–2059	2060–2079	2080–2099
Heat Stress	Moderate	High	High	High
Drought	High	High	High	High
Pluvial Flash floods	High	High	High	High
Fluvial floods	High	High	High	High
Wildfire	Moderate	High	High	High

In the Okavango Basin, hazards cluster in a different configuration. Heat-stress hazard evolves from moderate to high by late century in both scenarios, increasing evaporative losses and thermal stress on equipment. Drought remains a persistent high hazard, so dependable yields and seasonal deficits must be treated as a structural design constraint rather than a future contingency. Pluvial flash-flood hazard is already high and remains high, pointing to recurrent stormwater shocks that can surcharge drains, load intakes with sediment and debris, and wash out access routes. Fluvial flood hazard is also assessed as high at basin scale, requiring careful verification of low-lying intakes, river crossings and floodplain assets against extreme events, while

wildfire shifts from moderate to high hazard, reinforcing the need for defensible space and fire-resistant design around exposed assets.

The hotspot analysis reveals an elongated belt of high and very-high multi-hazard conditions along the lower Okavango corridor and a pronounced cluster around the Rundu–Nkurenkuru urban area. These zones combine elevated fluvial and flash-flood hazard on the floodplain with increasing drought and heat-stress pressure in the surrounding hinterland.

This spatial pattern aligns closely with the NWSISP II priority investments, in particular the Kavango Link bulk-water transfer and the planned Rundu 100-km rural water-supply extensions. For these schemes, the basin-level conclusions provide a screening framework to phase critical assets outside the mapped hotspot belt wherever feasible and, where alignments and sites must cross hotspot areas, to ensure protected and stabilised riverbank intakes, modular treatment plants capable of handling sharp turbidity surges, clear-water and elevated storage to bridge raw-water outages, conservative groundwater abstraction and flood-safe locations for new sanitation facilities. Localised hazard maps covering the conceptual alignments around Rundu and the specified segments of the Kavango Link are presented in Section 7 and should be used to refine siting, layout and design standards during subsequent stages of project preparation.

4 PART IV. CLIMATE EXPOSURE ASSESSMENT

Part IV builds on the hazard and multi-hazard hotspot analysis presented in Part III and translates it into a climate exposure assessment for existing and planned WASH infrastructure in the Kunene and Okavango River Basins. In this report, “exposure” is defined as the spatial intersection between the WASH asset inventory and the hazard bands for the selected climate hazards. All hazard layers are referenced to the common historical baseline 1995–2014, and exposure is quantified for the three projection horizons 2020–2039, 2040–2059 and 2060–2079 under SSP2-4.5 and SSP5-8.5. The near-term period 2020–2039 is taken as a proxy for the current planning horizon of NWSISP II, while the mid- and long-term horizons are used to test the robustness of investments under progressively more severe climate futures. For each hazard, exposure results are presented following a consistent basin-wise sequence, with the Kunene Basin discussed first and the Okavango Basin second, and are summarised by region and constituency to support basin-level and subnational decision-making.

In addition to the single-hazard exposure metrics, this part also examines WASH infrastructure located within the multi-hazard hotspots defined in Section 3.6, that is, grid cells where drought, pluvial flash floods and fluvial floods jointly reach High+ levels for a given scenario and time slice. These multi-hazard hotspots are used as a complementary screening layer to the single-hazard maps, not as a substitute for them. They help identify sub-areas where compound or sequential impacts on WASH systems are more likely, and where siting, design and operational standards may need to be more conservative, particularly for critical nodes such as intakes, treatment plants, main pumping stations and key storage facilities.

4.1 Exposure to Heat stress

4.1.1. Kunene north and south

Under SSP2-4.5, exposure of WASH assets to heat stress is already near-universal in the near term and consolidates to uniformly Extreme by mid-century; under SSP5-8.5 the same saturation is reached as quickly or earlier and persists through the long term. Constituency tables across Kunene North and South indicate Extreme shares at or near full coverage for most asset types (boreholes, public taps, tanker points, pump stations and treatment units), offering negligible spatial discrimination. Given this basin-wide signal, maps add limited value.

4.1.2. Kavango West and East

Under SSP2-4.5, WASH assets throughout Kavango West and Kavango East register near-universal High to Extreme heat-stress exposure in the near term, becoming uniformly Extreme by mid-century; under SSP5-8.5, the pattern is similarly saturated and endures into the long term. Constituency tables along the Rundu–Nkurenkuru corridor and surrounding districts show Extreme coverage across principal asset classes, indicating system-wide thermal stress rather than localized hotspots.

4.2 Exposure to drought

4.2.1. Kunene north and south

In **Kunene North**, constituencies such as Opuwo and Khorixas already show High/Very High pockets by mid-century. By 2060–2079 under SSP5-8.5, Opuwo records Extreme exposure for a large share of boreholes (around 89) with tanker points, wells and public taps frequently flagged at or near 100 for High+—a signal of systemic water-supply stress and heavy reliance on emergency supply in dry years. Khorixas also transitions into Extreme exposure for multiple asset types (e.g., pump-served or point sources reported at or near full coverage in High+/Extreme classes), indicating that both production and distribution nodes are vulnerable when deficits peak. Kamanjab and Sesfontein trend from Low/Moderate to High/Very High by mid-century, with Very High to Extreme shares by late century under SSP5-8.5; in several mid/late-century slices, specific asset classes (e.g., boreholes or tanker points) are reported at 100 in the upper hazard bands, underscoring the need for conservative safe yields and fallback water sources.

In **Kunene South**, Outjo rises from Low/Moderate to Very High/Extreme in late-century SSP5-8.5 slices for selected asset classes (e.g., public taps reaching 100 in upper hazard bands), while adjacent areas show increasing shares of High+. The pattern implies growing volatility in production and last-mile service, particularly for dispersed settlements and systems with limited storage.

4.2.2. Kavango West and East

Kavango West transitions from mostly Low/Moderate exposure in 2020–2039 to basin-relevant High by 2040–2059 in constituencies like Mpungu and Kahenge, and to Very High/Extreme pockets under SSP5-8.5 by 2060–2079. In Mpungu, a late-century split shows sizeable shares in Extreme and Very High across certain asset types, with pump-station exposure reaching 100 in some slices—highlighting vulnerability of energized conveyance where supply deficits force longer lifts and starts. Kahenge similarly accumulates Very High/Extreme shares across boreholes and public taps late-century, indicating stress on both production and distribution points.

In **Kavango East**, the Rundu Urban/Rural corridor, Mukwe, Ndiyona, and Mashare stay largely Moderate to High through mid-century, then increase into Very High and Extreme pockets late-century in SSP5-8.5. For example, Rundu Rural West/East and Ndiyona show very high to extreme shares for several asset types (with some classes at or near 100 in the upper bands), signalling design conditions where both raw-water availability and pressure at public taps deteriorate during dry spells.

Figure 38. **Kunene Region-North. WASH assets exposure to drought** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

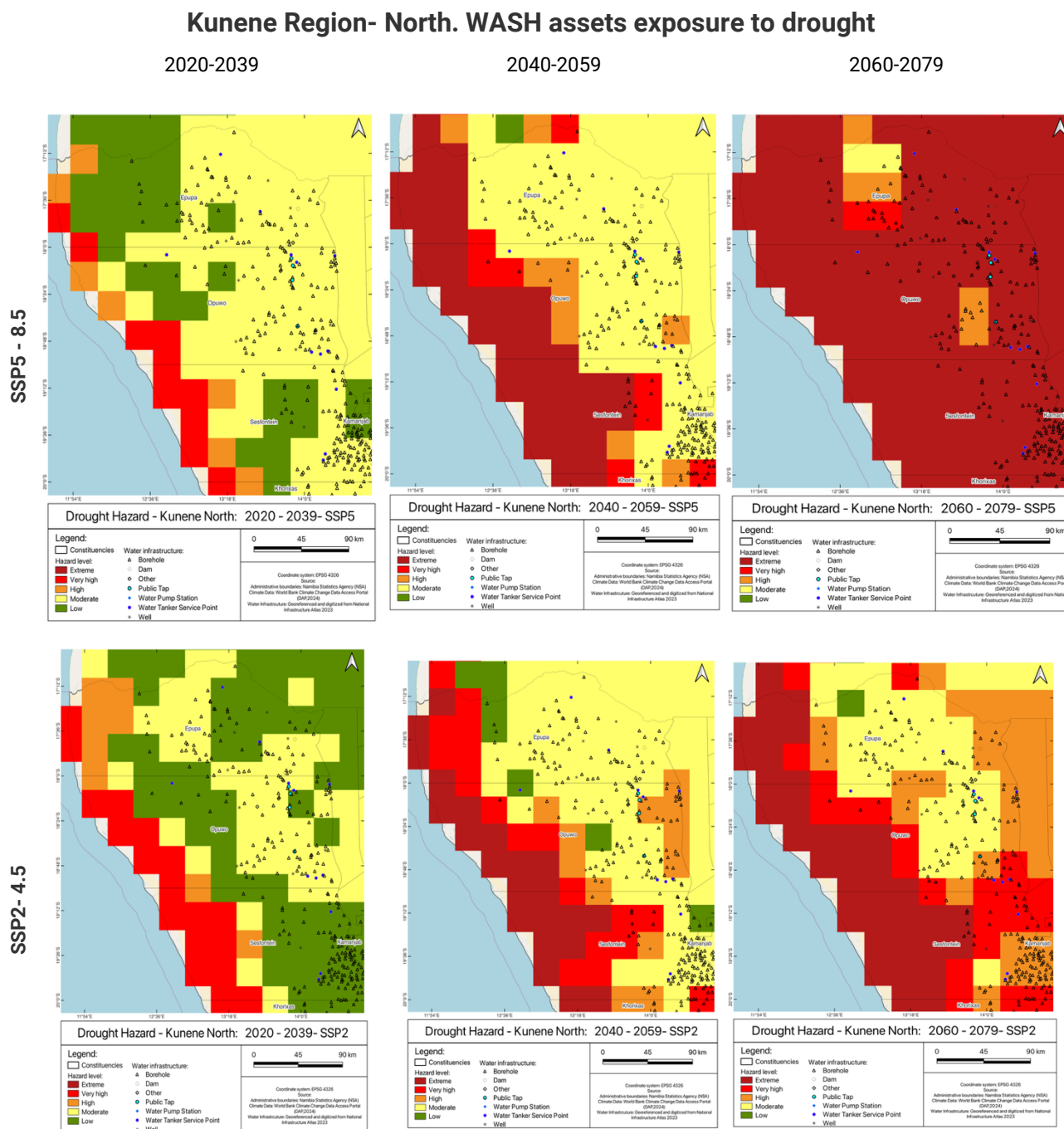


Figure 39. **Kunene Region-South.** WASH assets exposure to **drought** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

Kunene Region-South. WASH assets exposure to drought

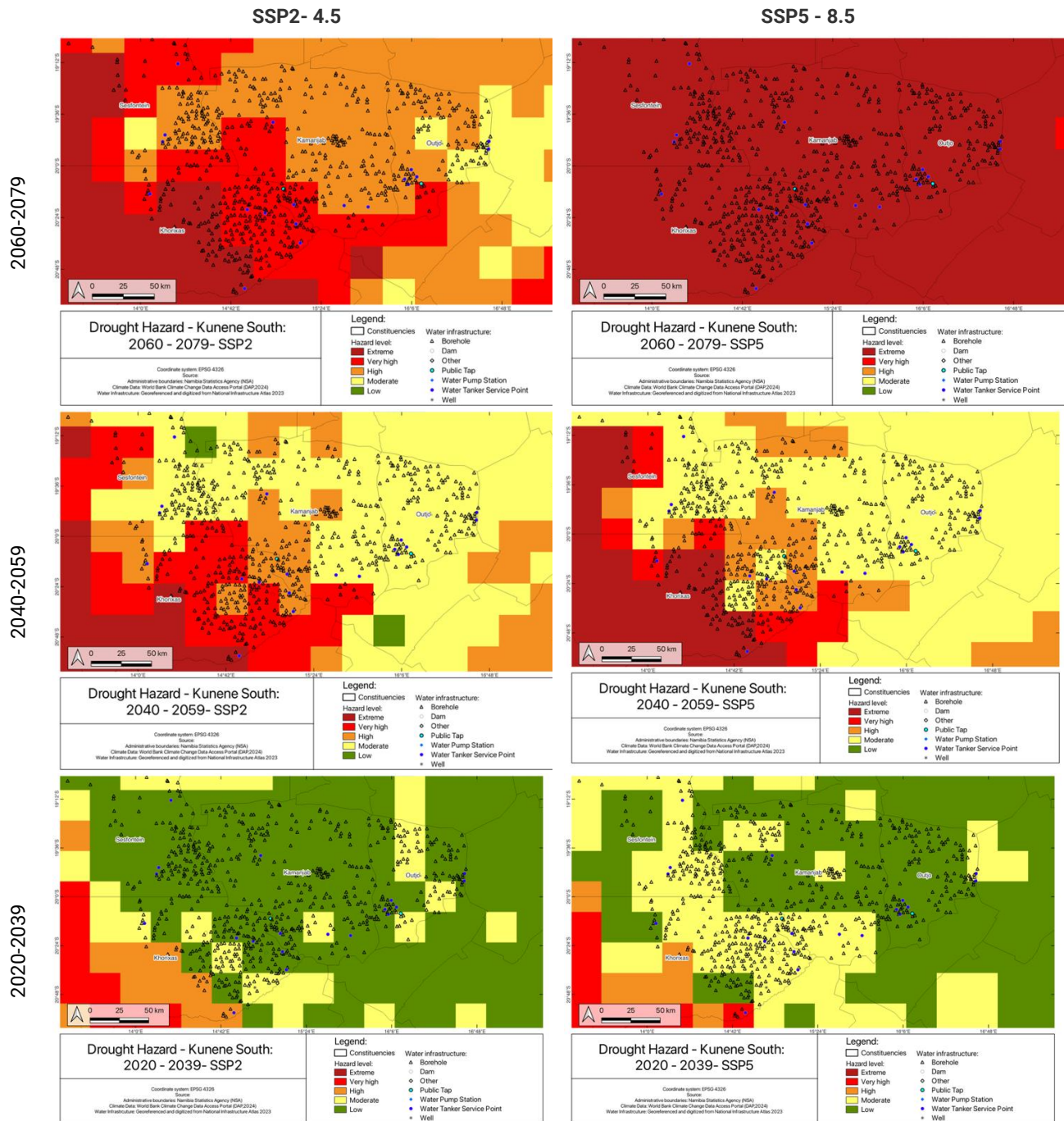


Figure 40. **Kavango West region.** WASH assets exposure to **drought** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

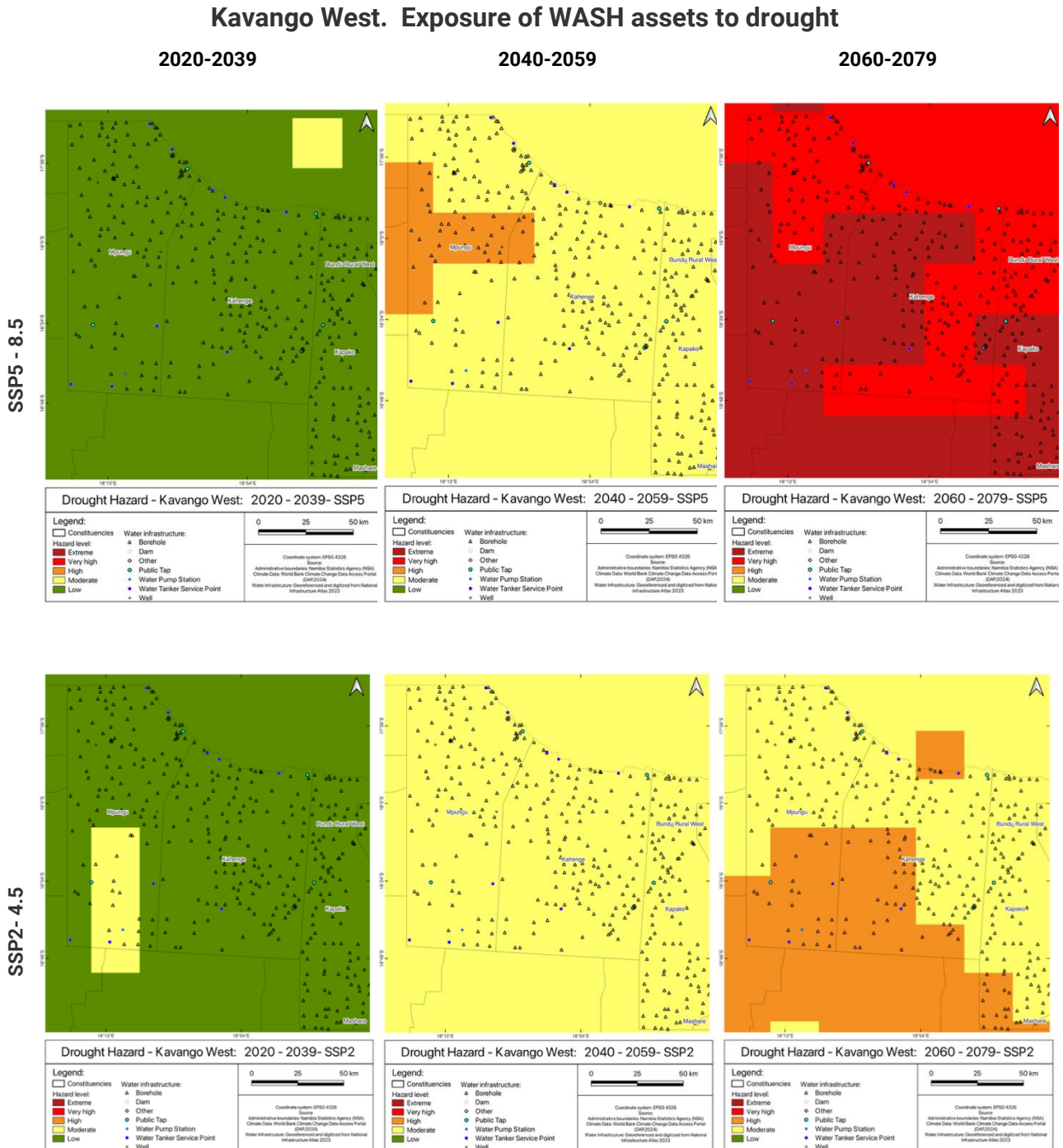
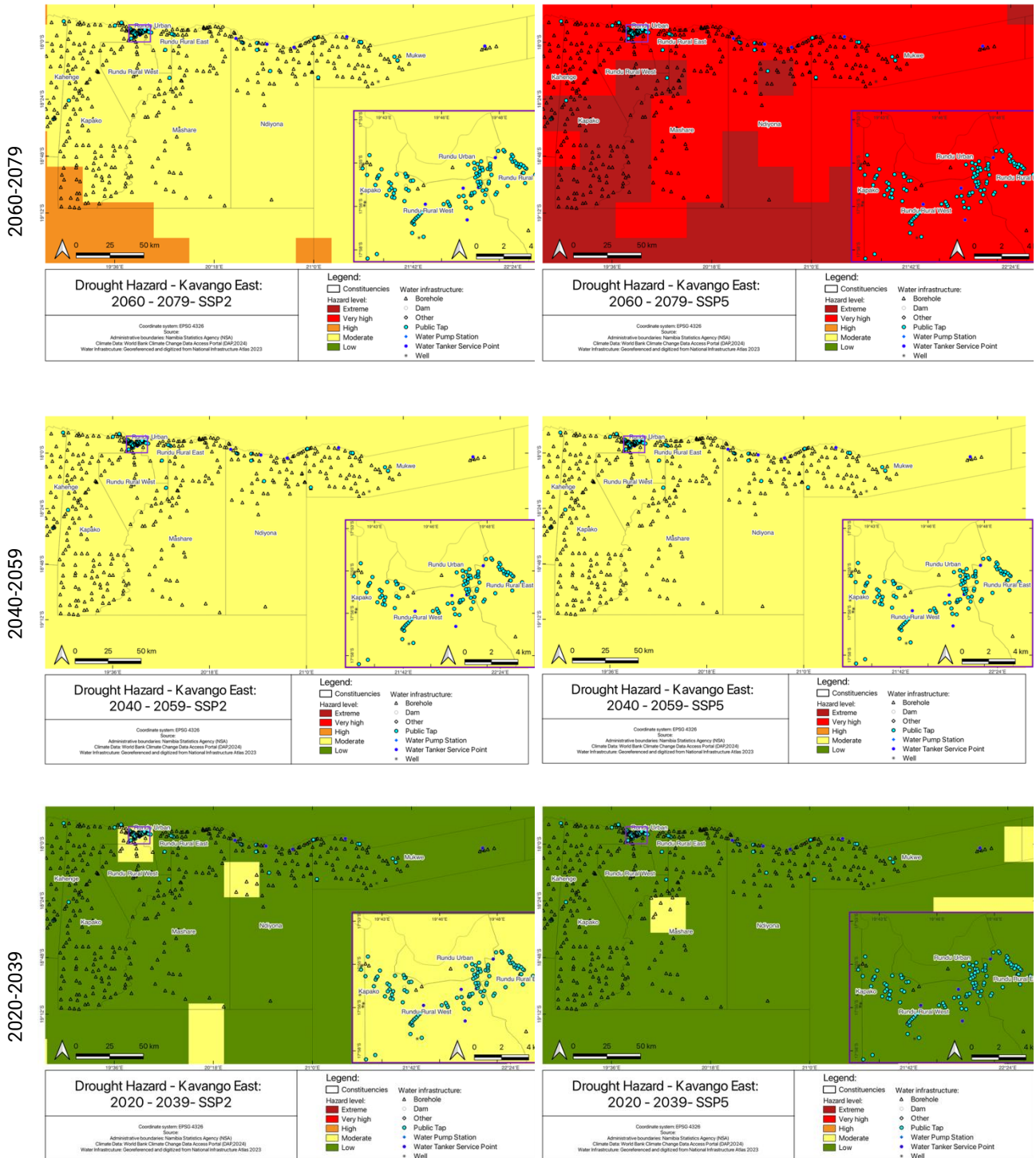


Figure 41. **Kavango East region. WASH assets exposure to drought** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

Kavango East. WASH assets exposure to drought

SSP2- 4.5

SSP5 - 8.5



4.3 Exposure to Pluvial Flash Floods

4.3.1. Kunene north and south

Across Kunene, pluvial flash-flood exposure is already substantial in the near term and becomes widespread by mid-century, with late-century SSP5-8.5 approaching basin-wide High conditions across most asset classes. In Kunene North, Kamanjab and Khorixas are flagged High for essentially all mapped assets in 2020-2039; entries show 100 for boreholes and, where present, dams, tanker points and public taps. Opuwo is split between Moderate and High early on, but by 2040-2059 the High band dominates for boreholes, tanker points and public taps, and remains elevated thereafter. Epupa is persistently High across all asset types in every period. In Kunene South, Outjo and Otavi register High values from the start (many asset classes at or near 100) and retain High in later slices. By 2060-2079 under SSP5-8.5, the table reflects saturation of the High band across Kunene constituencies and asset types, including pump stations where data are available, indicating that intense short-duration runoff affects both production points and energized conveyance.

4.3.2. Kavango West and East

In Okavango, High exposure is already common along the Rundu urban-rural corridor and the main road spine, and it spreads into surrounding constituencies through mid-century. Rundu Rural East, Rundu Rural West and Rundu Urban appear High for multiple asset types from the outset (many entries at or near 100). Downstream and lateral constituencies—Ndiyona, Mukwe, Mashare, Kahenge, Kapako—also concentrate High values for boreholes, tanker points and public taps; several rows show pump stations at 100 in High, underscoring vulnerability where energized lifts coincide with intense runoff and access washouts. Mpungu begins with mixed Moderate/High but shifts toward High for tanker points, public taps and pump stations as horizons advance. By 2060-2079, SSP5-8.5 shows High exposure for almost all mapped assets across the corridor and floodplain-adjacent settlements.

Figure 42 .Kunene Region-North. WASH assets exposure to **pluvial flash floods** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

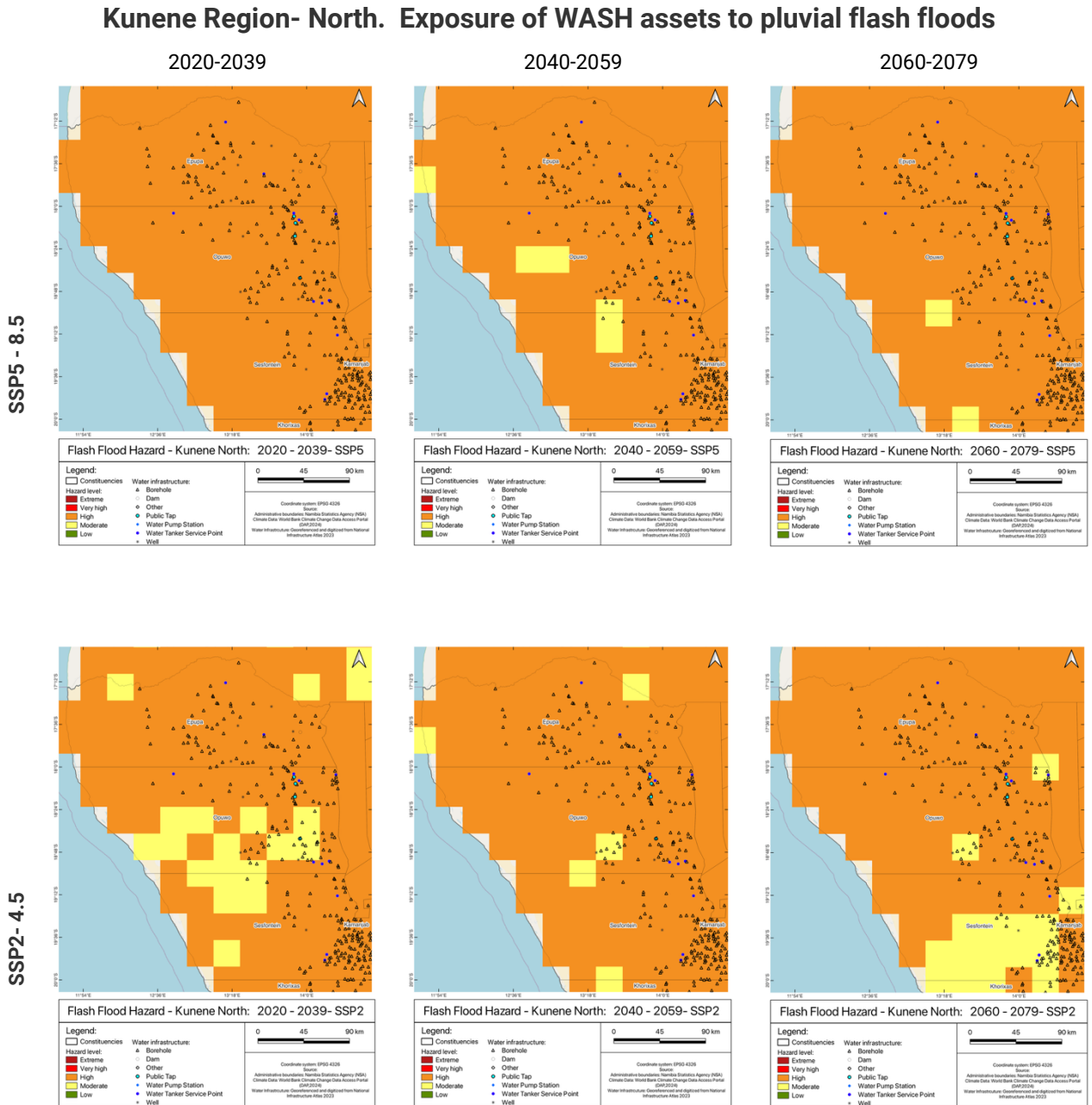


Figure 43. **Kunene Region-South.** WASH assets exposure to **pluvial flash floods** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

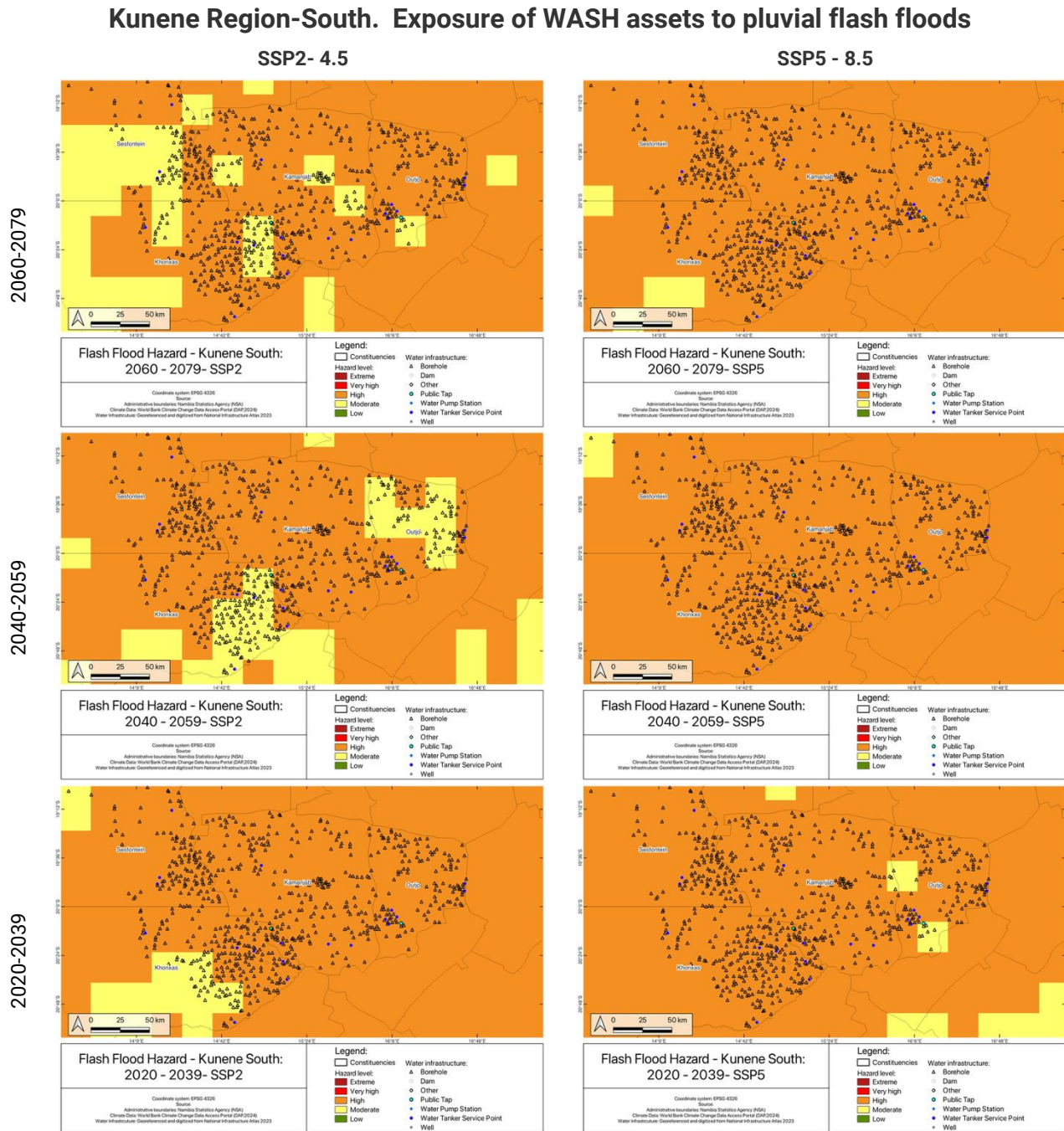


Figure 44. **Kavango West region**. WASH assets exposure to **pluvial flash floods** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

Kavango West. Exposure of WASH assets to pluvial flash floods

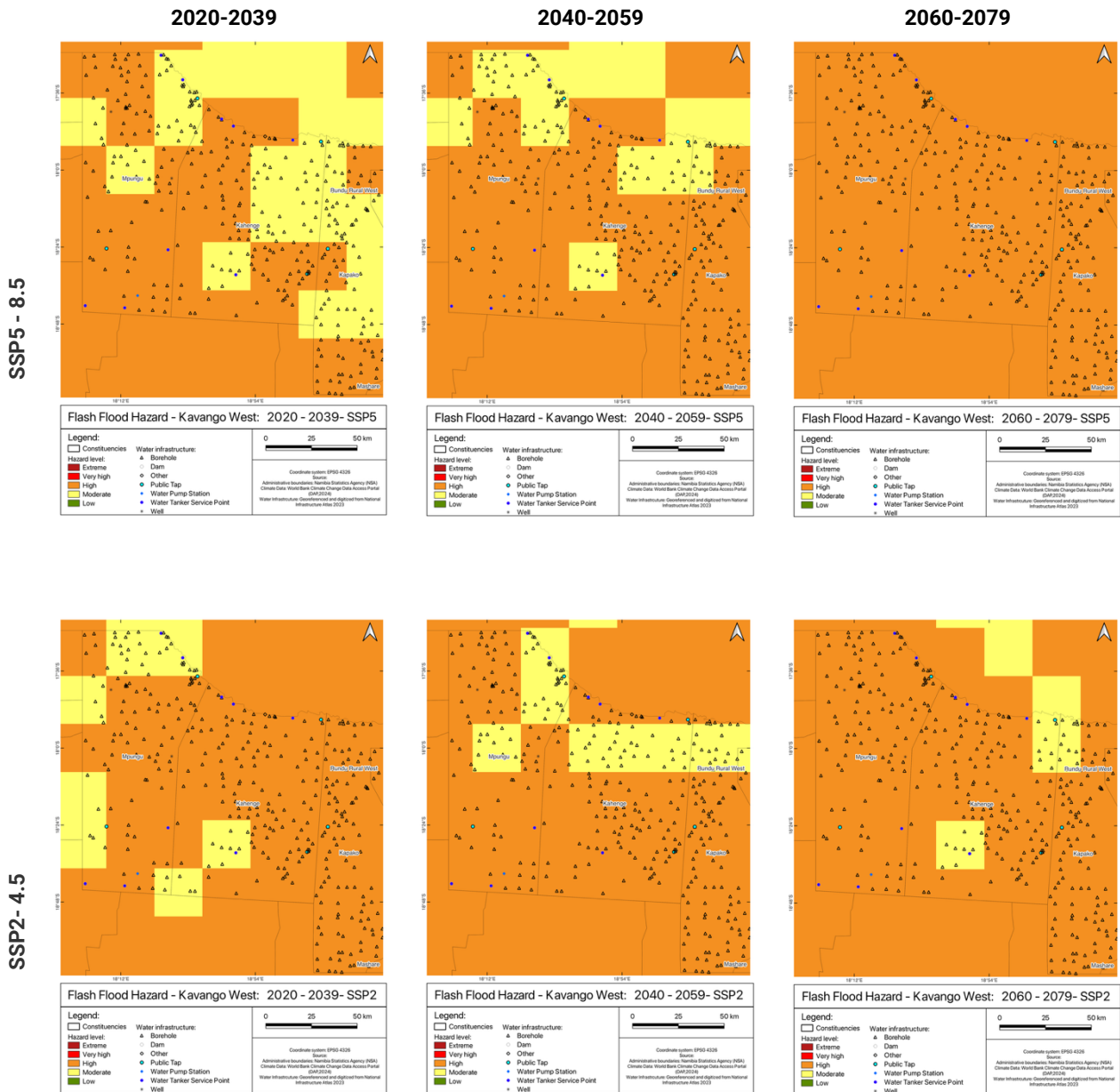
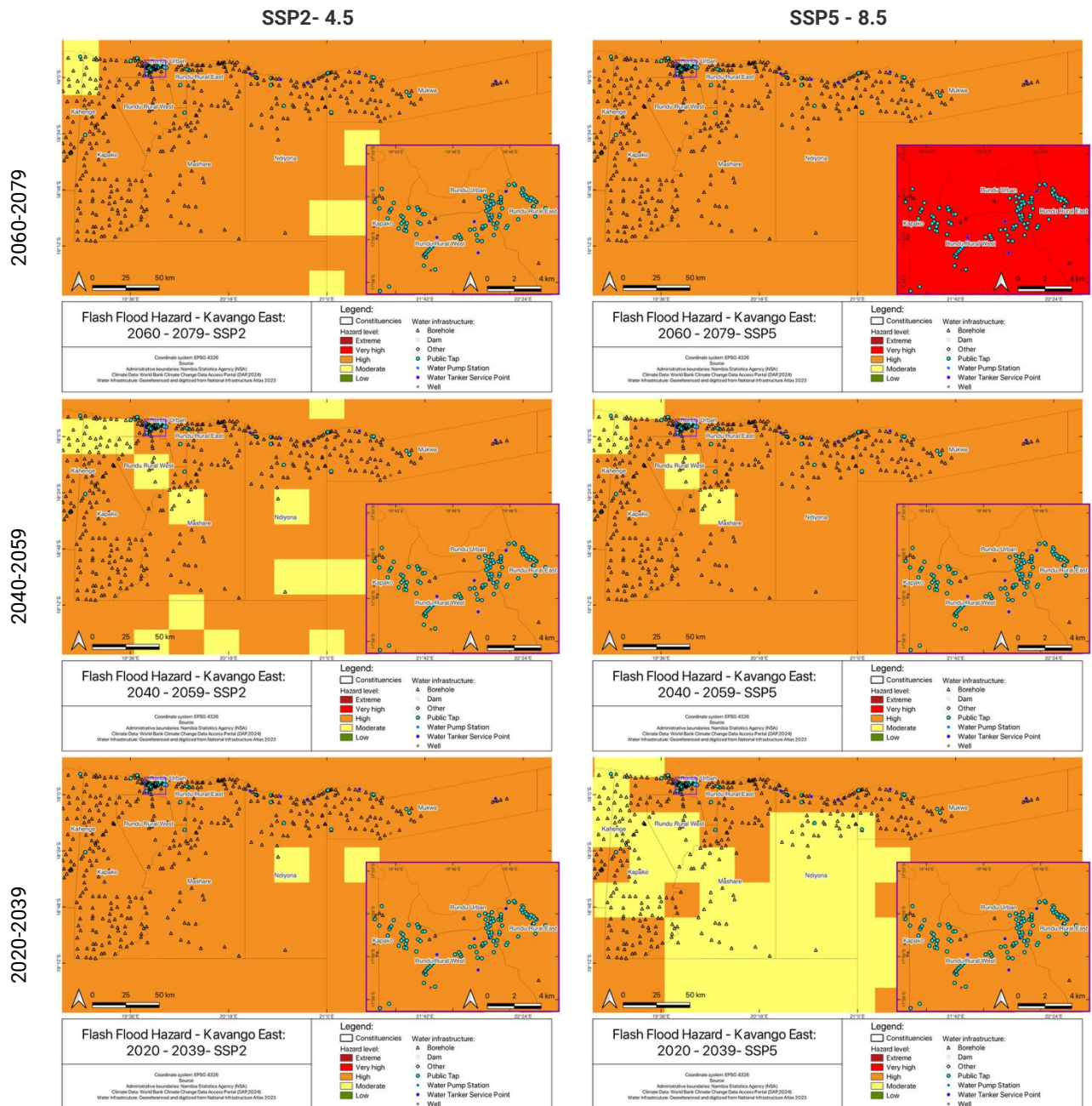


Figure 45. **Kavango East region.** WASH assets exposure to **pluvial flash floods** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

Kavango East. Exposure of WASH assets to pluvial flash floods



4.4 Exposure to Fluvial Flash Floods

Across both basins, fluvial flood exposure is already widespread in the near term and remains persistently high across time slices, with only localized escalation from high to very high or extreme under SSP5-8.5. This pattern reflects the strong control of main-stem rivers and floodplains: in Kunene, high exposure dominates river-adjacent constituencies from the outset. In the Okavango basin, the corridor along the main channel and floodplain assets around Rundu and downstream distributaries stay consistently high, with some cells tipping to very high in mid- and late-century horizons.

4.4.1. Kunene north and south

In Kunene North, Opuwo combines a basin-wide high background with smaller cells stepping into the top bands: near- to mid-century slices include very high and even extreme shares for boreholes, while tanker points, wells and public taps often sit at or near full coverage in the high band—consistent with floodplain access routes and low-lying crossings being disrupted during channel rises. Epupa shows a notable very high fraction of boreholes already in the early horizon, rising toward the mid-century in SSP5, while the remainder of asset types there stay fully high. Khorixas maintains a full high status for all reported classes across horizons, including dams, taps and tanker points, signalling persistent fluvial exposure across both production and service nodes. In Kunene South, Outjo carries a stable high background for most assets, with selected classes (such as tanker points) intermittently reaching very high in some time slices, and Otavi records very high for boreholes throughout—an indicator that even interior wellfields are not insulated from overbank or tributary flooding where conveyance lines traverse flood-prone cells.

4.4.2. Kavango West and East

In Kavango West, a near-term high blanket dominates Mpungu, Kapako and Kahenge for most asset classes, with pockets stepping into very high under SSP5 in mid- to late-century. This aligns with frequent floodplain ponding and backwater effects in local depressions. In Kavango East, the Rundu Urban/Rural area, Mukwe, Ndiyona and Mashare sit in sustained high exposure across assets from the first horizon; tables report 100 shares in high for boreholes, taps and tanker points in multiple constituencies as early as 2020–2039, with small areas moving to very high by 2040–2059 and 2060–2079 under SSP5-8.5. The result is a design environment where both water-production and distribution assets are routinely confronted with overbank flow, levee toe saturation and sediment pulses during channel swells.

Figure 46. **Kunene Region-North. WASH assets exposure to fluvial flash floods** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

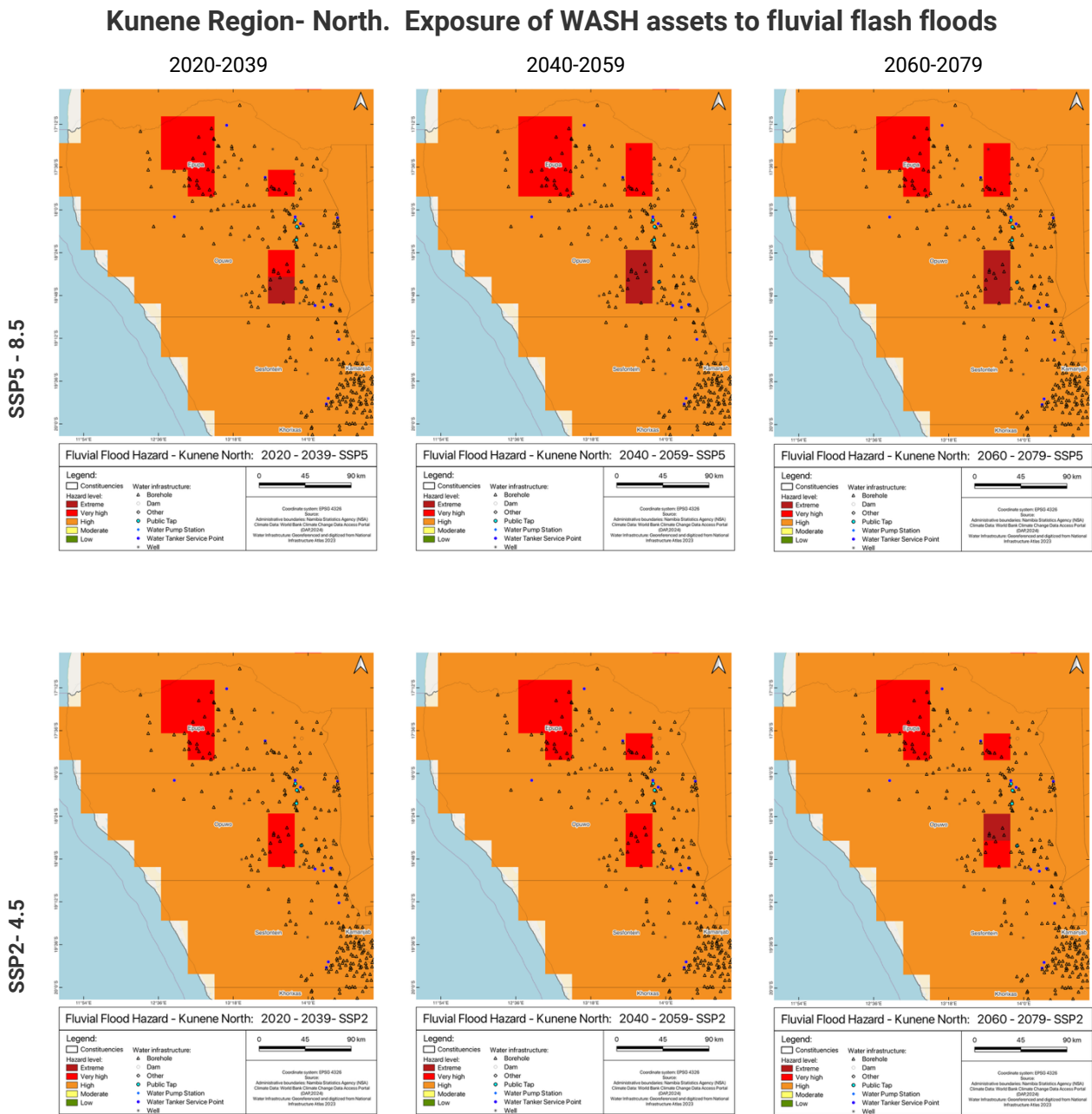


Figure 47. **Kunene Region-South.** WASH assets exposure to **fluvial flash floods** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

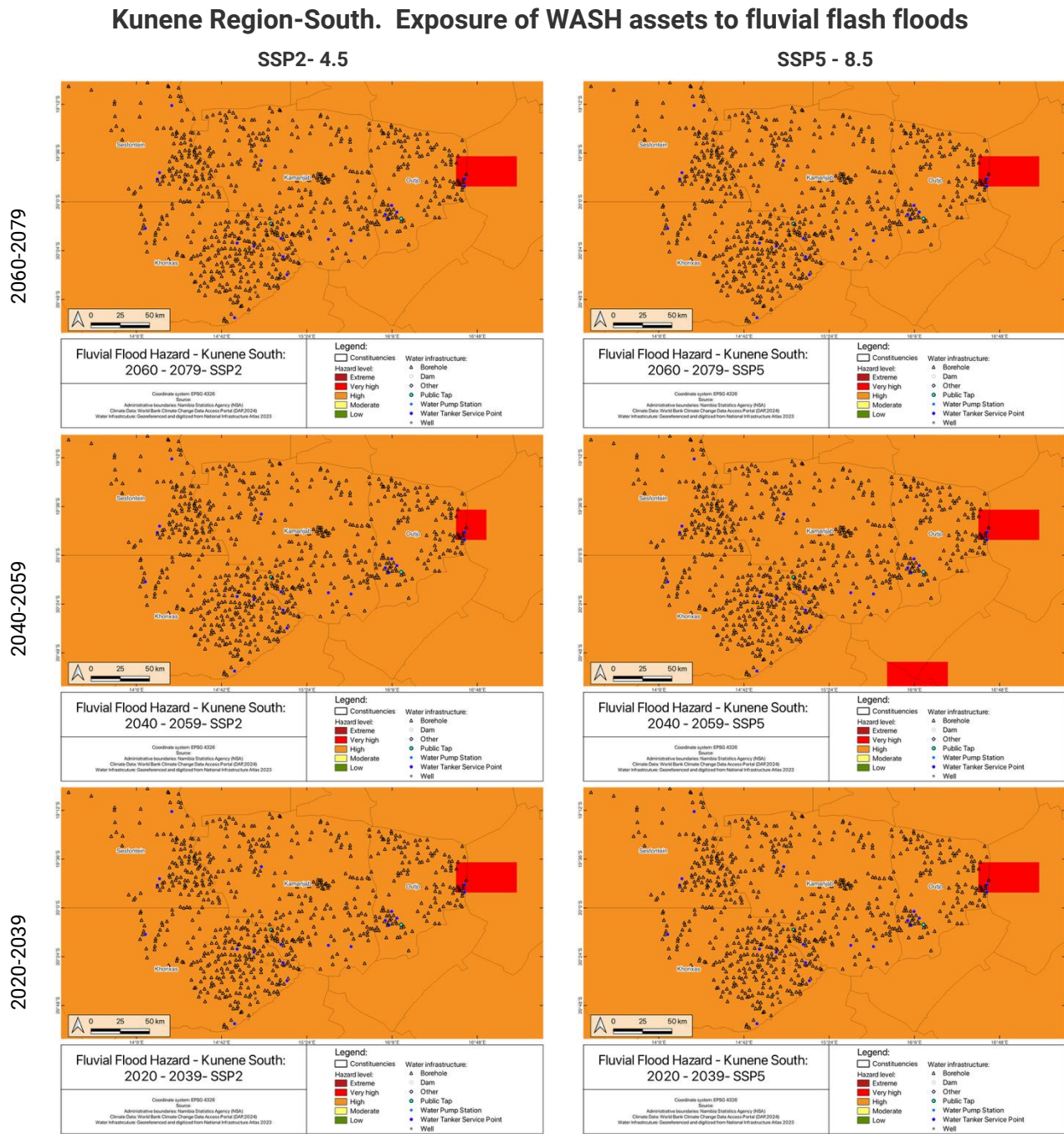


Figure 48. Kavango West region. WASH assets exposure to fluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

Kavango West. Exposure of WASH assets to fluvial flash floods

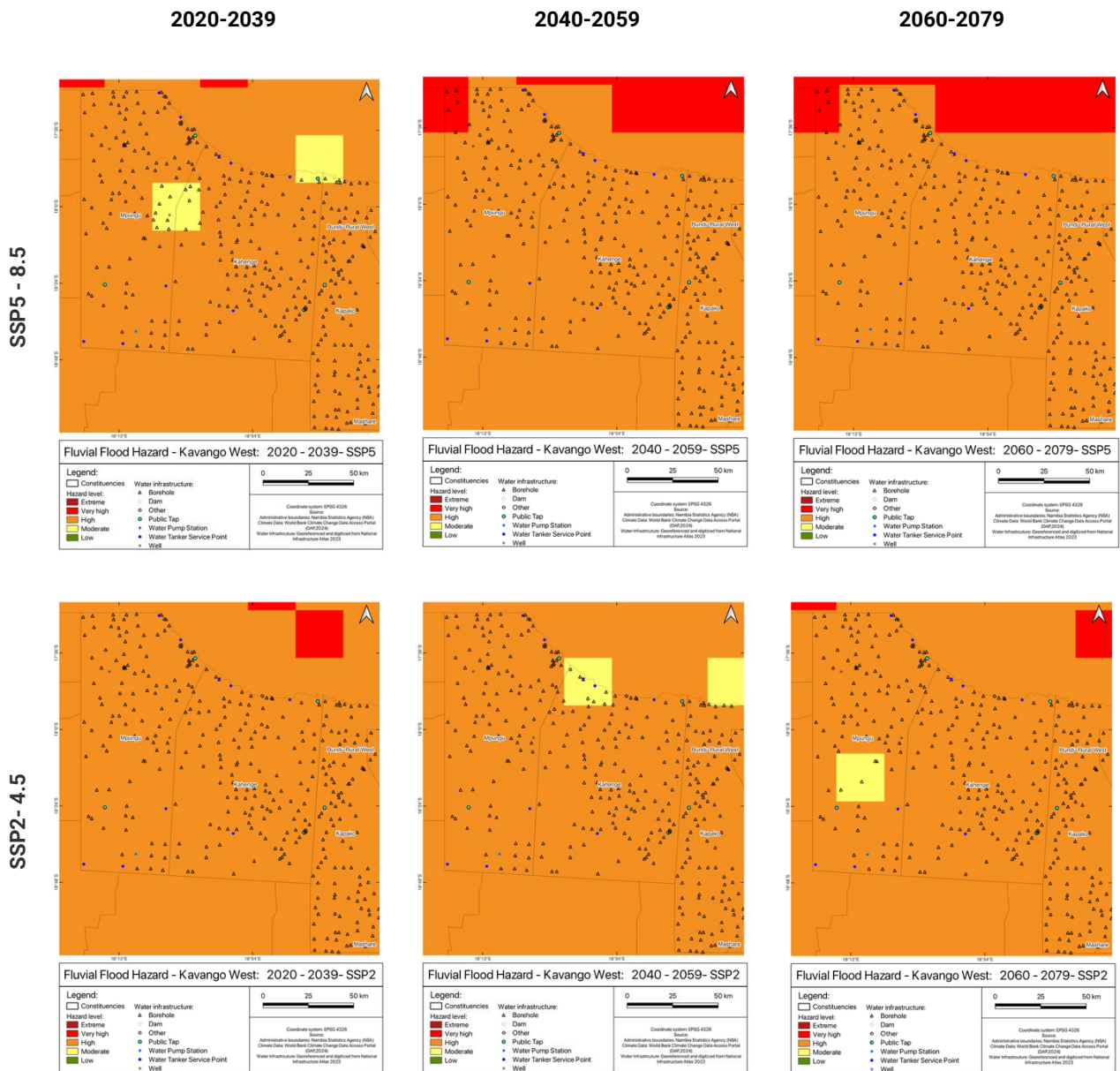
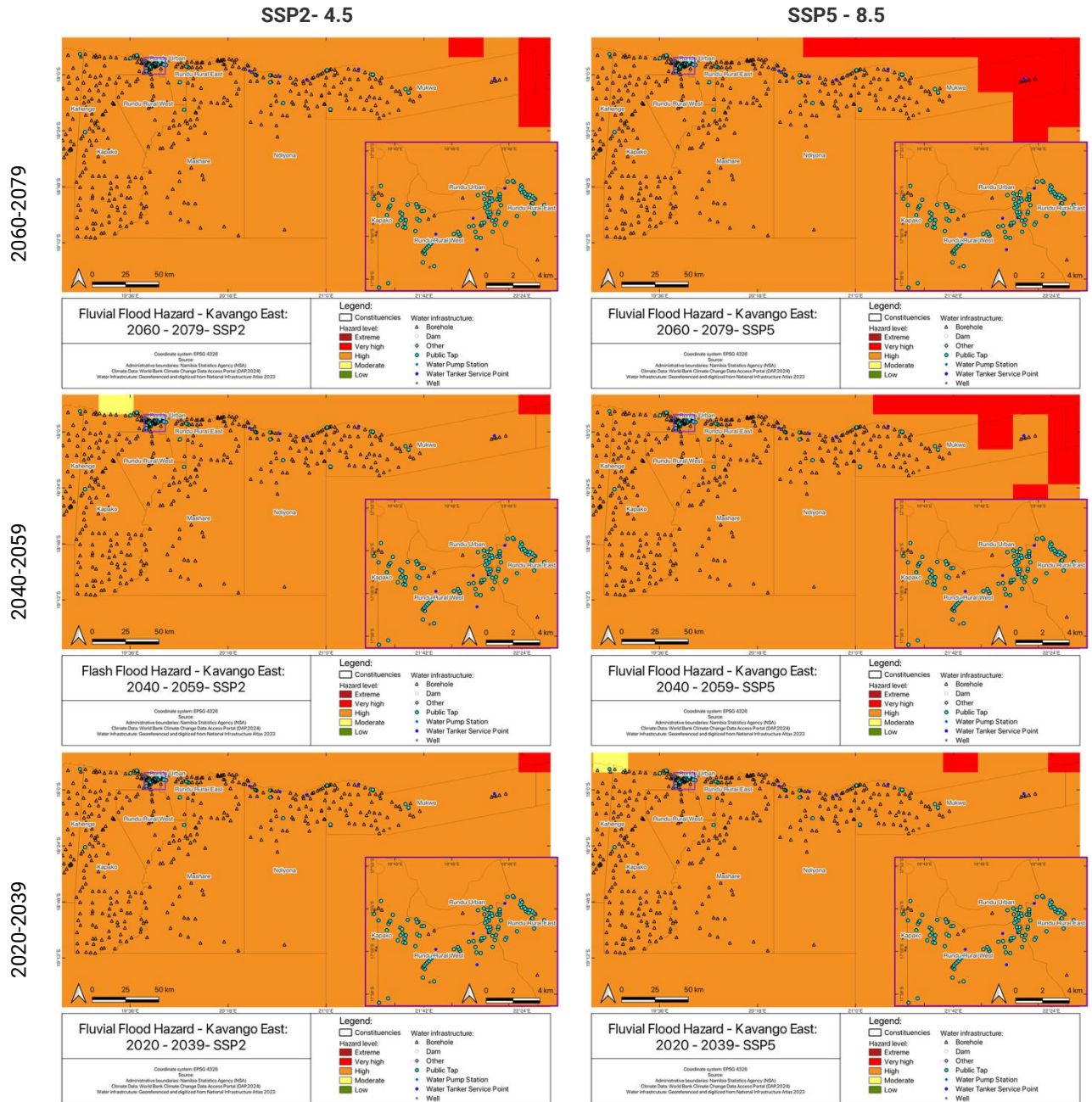


Figure 49. **Kavango East region.** WASH assets exposure to **fluvial flash floods** from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.

Kavango East. Exposure of WASH assets to fluvial flash floods



4.5 Exposure to Wildfire

Wildfire emerges as a basin-wide, high-end stressor in all periods and scenarios, with near-universal classification at Extreme across asset types and constituencies. Minor exceptions appear only in the earliest slice, but by mid-century and beyond the pattern converges to full coverage in the High+ bands frequently up to 100 percent of listed assets per constituency so spatial differentiation is limited, and the planning question shifts from where to how systems are operated under persistent fire exposure.

4.5.1. Kunene north and south

In Kunene North, constituencies such as Epupa, Kamanjab, Khorixas, Sesfontein and Opuwo show Extreme exposure across boreholes, wells, public taps, tanker points and, where present, dams and pump stations, with many asset classes recorded at 100 percent in High+ bands in every time slice and both pathways. The result implies that source works, headworks and last-mile distribution are simultaneously exposed during fire seasons, with little temporal relief as scenarios progress. Kunene South (for example, Outjo) follows the same profile, with repeated 100 percent readings for public taps and tanker service points and Extreme classifications across the inventory, indicating that both production and emergency supply nodes are co-exposed when fire weather peaks and during post-fire runoff events.

4.5.2. Kavango West and East

Kavango West and Kavango East exhibit the same basin-wide pattern: constituencies including Kahenge, Mpungu, Kapako, Mashare, Mukwe, Ndiyona and the Rundu urban or rural corridor are consistently classified Extreme for most asset types, with numerous entries at 100 percent in the High+ bands from the near term onward. This translates into concurrent exposure of river-draw systems, floodplain distribution assets and groundwater wellfields, and it elevates the likelihood of simultaneous operational stress across multiple scheme components during fire outbreaks.

4.6 Wash infrastructure in Hotspots by region and constituency

This subsection focuses on WASH infrastructure located within the multi-hazard hotspots defined in Section 3.6. These hotspots correspond to grid cells where the discriminating hazards—drought, pluvial flash floods and fluvial floods—simultaneously reach High, Very High or Extreme (High+) classes for a given scenario and time slice. Heat stress and wildfire remain basin-wide constraints and are therefore treated as background design conditions rather than as hotspot discriminators. The maps in Figures 50–53 show, for each region, how WASH assets intersect these multi-hazard hotspots across the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5, building on the hotspot patterns described in Section 3.6.

All hotspot calculations are referenced to the historical baseline 1995–2014 used to derive the hazard classes, but only the future time slices (2020–2039, 2040–2059 and 2060–2079) are mapped for WASH hotspots.

4.6.1. Kunene Basin Hotspots

Near-term (2020–2039). As shown in **figure 50** and **figure 51** below, early signal concentrates in Khorixas (Kunene Region), where hotspots already capture boreholes and a dense cluster of water-tanker service points, indicating localized dependence on emergency supply even before mid-century.

Mid-century (2040–2059). Hotspots expand across the western arc in the Kunene Region: Sesfontein shows wells fully captured in hotspots and a rising share of boreholes; Kamanjab adds substantial borehole and tanker-point exposure; Opuwo registers simultaneous hotspot shares in boreholes, wells, tankers and public taps; and Khorixas intensifies, adding dams and higher tanker-point proportions. Under the higher-warming

pathway, Khorixas becomes the standout concentration (hotspot shares nearing or reaching full coverage across several asset types), while Sesfontein maintains wells at full hotspot coverage and Kamanjab and Opuwo continue to rise; Epupa only shows isolated boreholes in hotspots on this century.

Late-century (2060–2079). Under SSP 2, the hotspot field spreads south and east: Outjo emerges with large borehole and tanker-point shares; Kamanjab, Khorixas, Opuwo and Sesfontein all strengthen, and Epupa adds dams and wells. Under SSP 5, saturation becomes widespread: Kamanjab, Khorixas, Opuwo, Epupa, Sesfontein and Outjo frequently register hotspot shares at or near full coverage for boreholes and tanker points, with some places also capturing dams, wells and public taps—evidence of converging drought–pluvial–fluvial stresses across both production and distribution nodes.

Figure 50. **Kunene Region–North.** WASH assets located in multi-hazard hotspots for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classes. Source: the author.

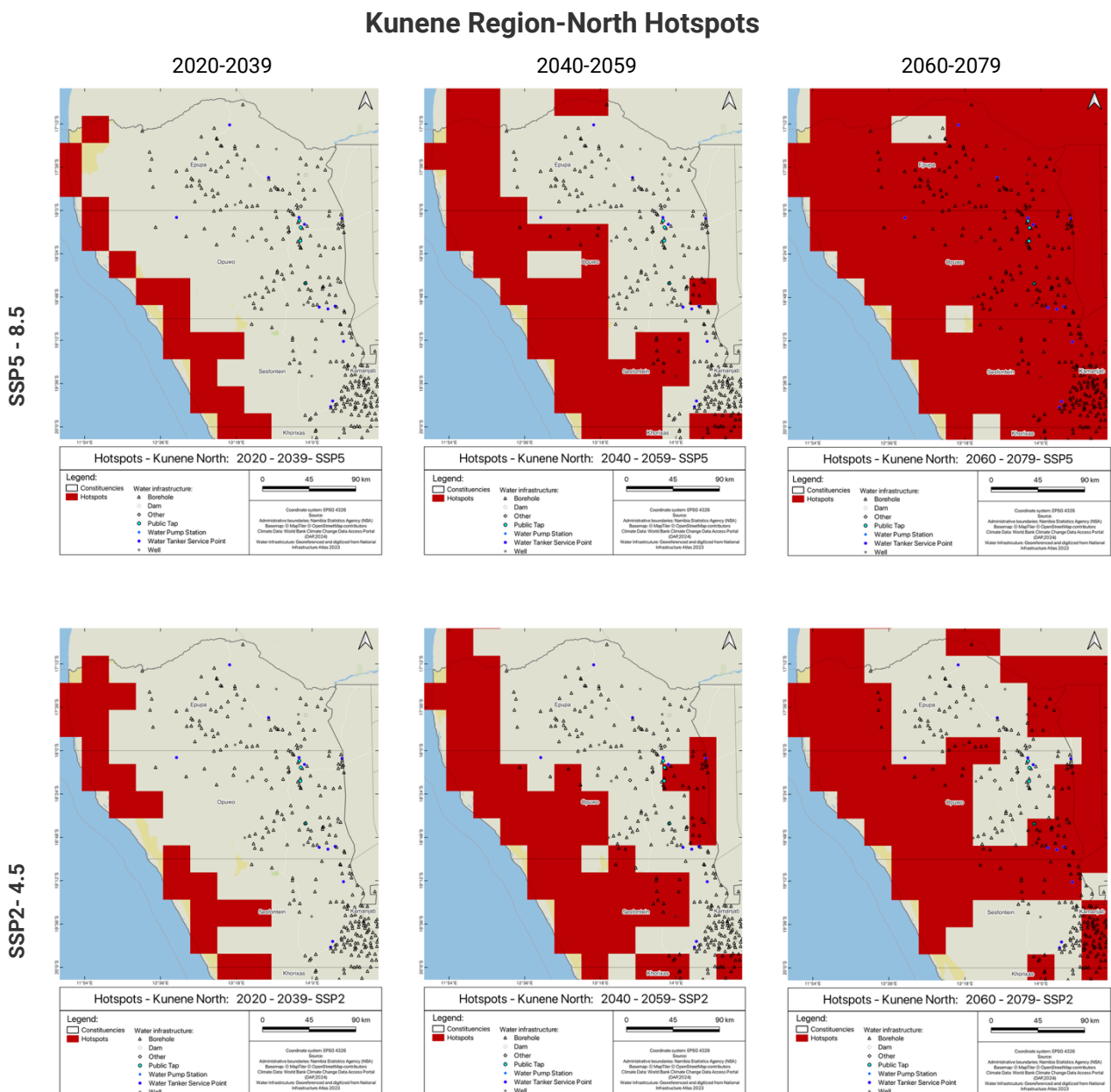
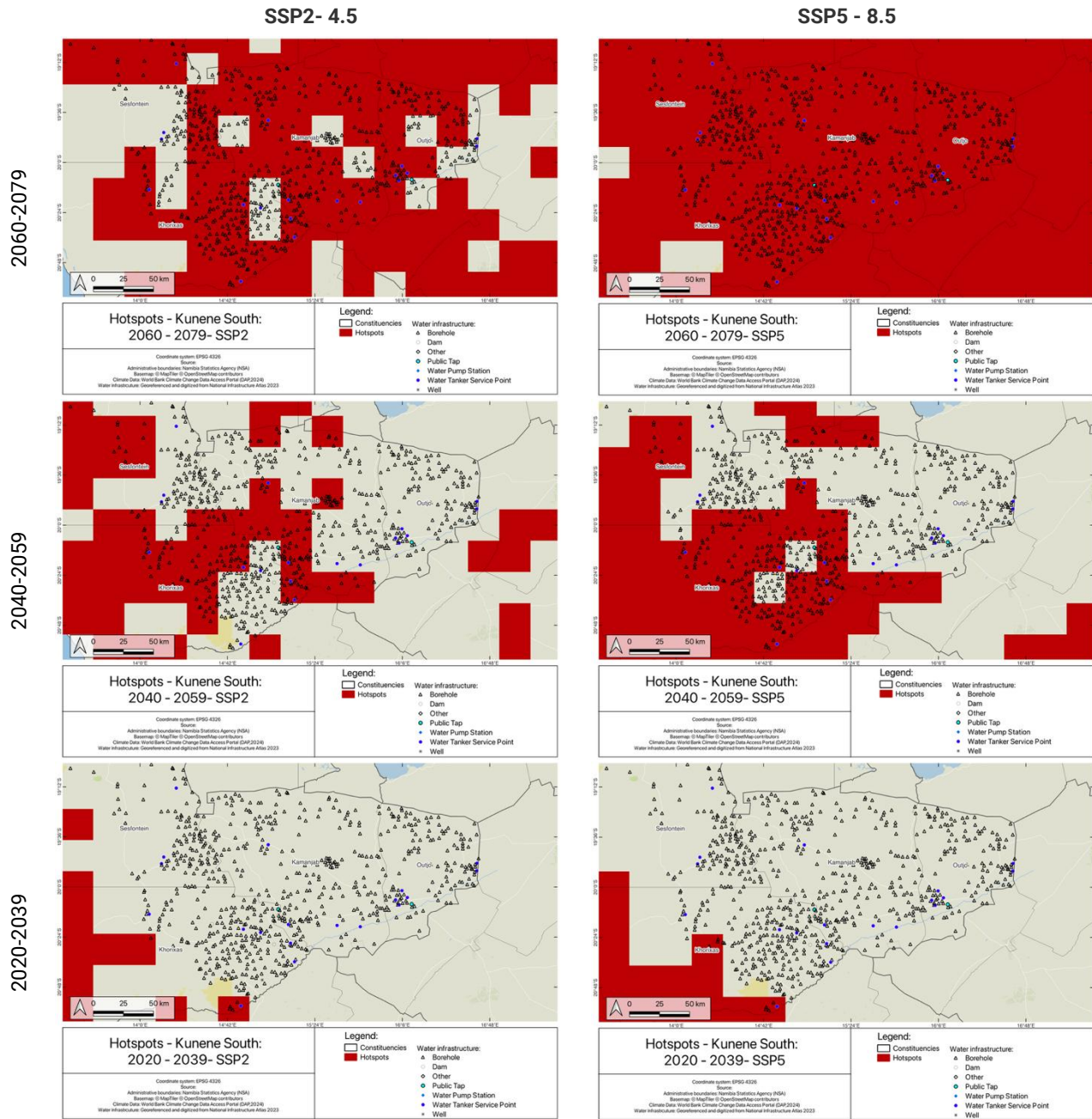


Figure 51. **Kunene Region–South**. WASH assets located in multi-hazard hotspots for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5 Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classe . Source: the author.

Kunene Region-South Hotspots



4.6.2. Okavango Basin Hotspots

Near-term (2020–2039). No major concentrations are flagged in Kavango at basin scale in the earliest slice.

Mid-century (2040–2059). Hotspots first take hold in Kavango West along the central corridor: Mpungu (Kavango West Region) shows growing borehole involvement and public-tap capture, while Kahenge (Kavango West Region) begins to register borehole exposure.

Late-century (2060–2079). Under SSP 2, Kavango West shows hotspots at Mpungu level, with tanker-point and public-tap assets and, critically, pump stations enter hotspots—signalling risk to energized conveyance—while Kapako (Kavango West Region) and Kahenge add boreholes (and in Kahenge also additional water points). Under SSP 5, hotspot saturation becomes broad and operationally significant across Kavango East and Kavango West: Mpungu, Kapako, Kahenge (Kavango West Region) and Mukwe, Ndiyona, Mashare, Rundu Rural West, Rundu Rural East, Rundu Urban (Kavango East Region) frequently reach full hotspot capture across boreholes, wells, tanker points and public taps, with Mpungu also flagging pump stations—together marking multi-asset vulnerability along the Okavango mainstem and its populated corridor (see **figure 52** and **figure 53**).

Figure 52. Kavango West region. WASH assets located in multi-hazard hotspots for long-term (2060–2079) horizon under SSP2-4.5 and SSP5-8.5. Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classes. Source: the author.

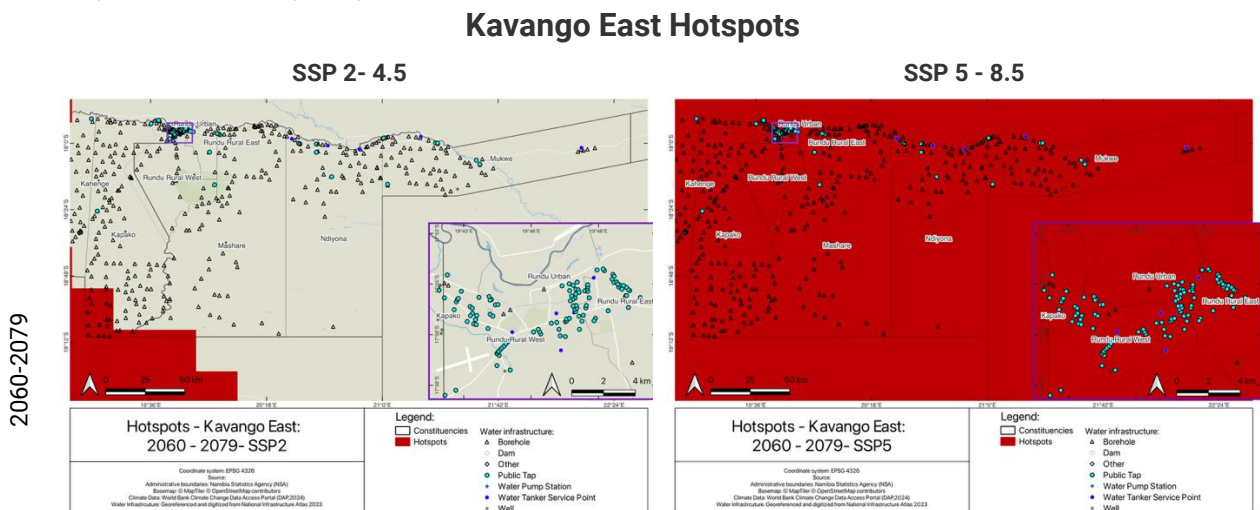
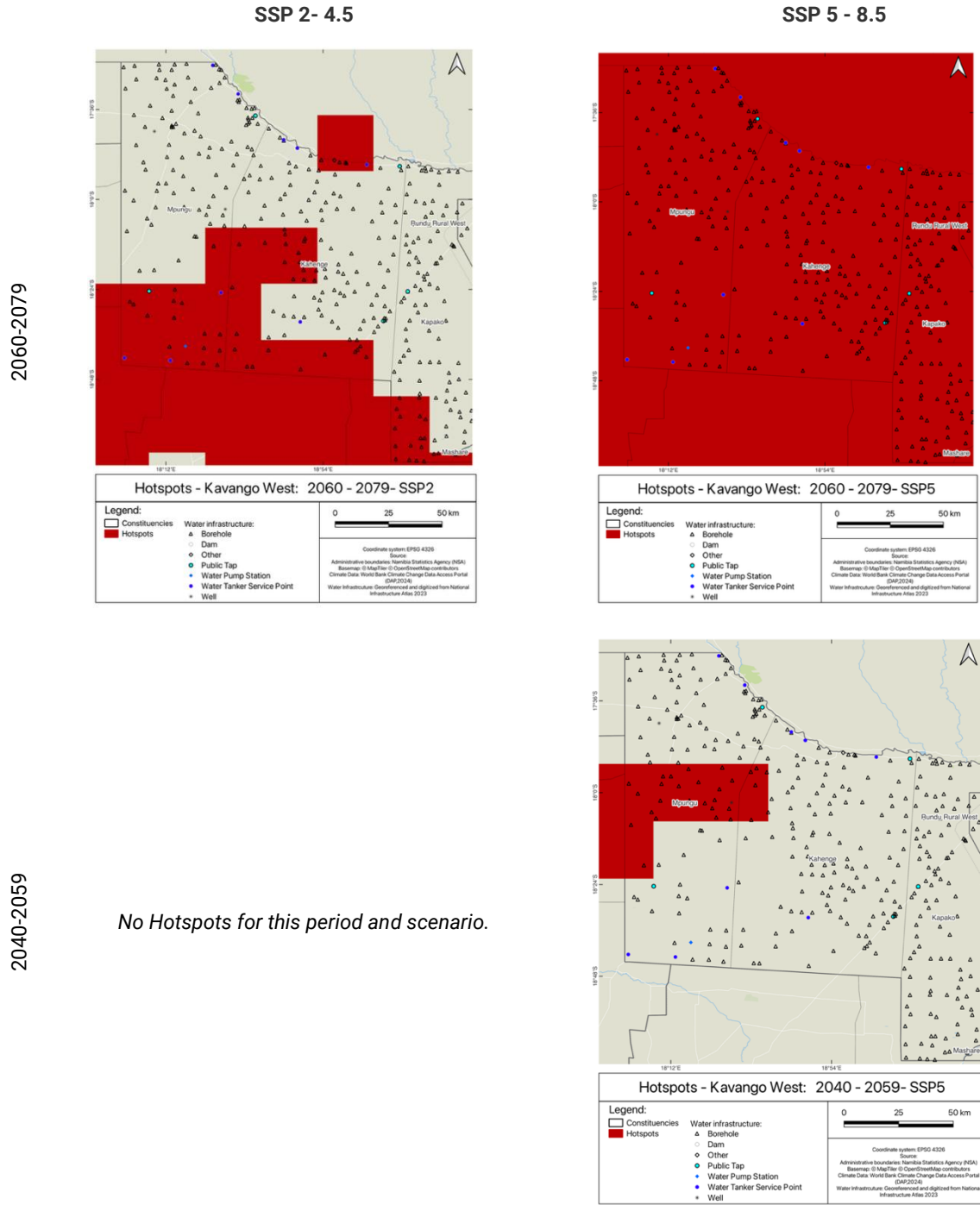


Figure 53. **Kavango East region.** WASH assets located in multi-hazard hotspots for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classes. Source: the author.

Kavango West Hotspots



2060-2079

2040-2059

No Hotspots for this period and scenario.

Table 22. Percentage of WASH infrastructure exposed to Hotspots by constituency in Kunene and Kavango regions (SSP2-4.5 and SSP5-8.5 scenarios and 2020-2039, 2040-2059 time slices). Source: The Water Supply Points, NSA 2022. Ministry of Agriculture, Water & Land Reform. Urban Areas, Ministry of Urban and Rural Development 2022.

2020-2039							
Hotspots SSP 2-4.5							
Constituency	Borehole	Dam	Other	Water Tanker Service Point	Well	Public Tap	Water Pump Station
Khorixas	2	0	0	17	0	0	NA
Hotspots SSP 5-8.5							
Constituency	Borehole	Dam	Other	Water Tanker Service Point	Well	Public Tap	Water Pump Station
Khorixas	4	0	0	17	0	0	NA
2040-2059							
Hotspots SSP 2-4.5							
Constituency	Borehole	Dam	Other	Water Tanker Service Point	Well	Public Tap	Water Pump Station
Sesfontein	24	NA	NA	0	100	NA	NA
Kamanjab	38	NA	NA	50	NA	NA	NA
Opuwo	40	NA	0	29	25	50	NA
Khorixas	47	50	0	67	0	0	NA
Hotspots SSP 5-8.5							
Constituency	Borehole	Dam	Other	Water Tanker Service Point	Well	Public Tap	Water Pump Station
Epupa	1.6	0	0	0	0	NA	NA
Kahenge	4.8	NA	0	0	NA	0	NA
Opuwo	14	NA	0	0	25	0	NA
Sesfontein	21	NA	NA	0	100	NA	NA
Mpungu	21	NA	NA	0	50	0	0
Kamanjab	30	NA	NA	50	NA	NA	NA
Khorixas	75	100	100	83	100	0	NA

Table 23. Percentage of WASH infrastructure exposed to Hotspots by constituency in Kunene and Kavango regions (SSP2-4.5 and SSP5-8.5 scenarios and 2060-2079 period). Source: The Water Supply Points, NSA 2022. Ministry of Agriculture, Water & Land Reform. Urban Areas, Ministry of Urban and Rural Development 2022.

2060-2079							
Hotspots SSP 2-4.5							
Constituency	Borehole	Dam	Other	Water Tanker Service Point	Well	Public Tap	Water Pump Station
Sesfontein	14	NA	NA	NA	0	0	NA
Mpungu	15	NA	NA	60	0	50	100
Kahenge	26	NA	100	25	NA	0	NA
Epupa	30	50	0	0	25	NA	NA
Opuwo	42	NA	0	43	50	25	NA
Sesfontein	65	NA	NA	33	0	NA	NA
Outjo	66	NA	NA	67	NA	0	NA
Khorixas	74	50	100	83	100	0	NA
Kamanjab	80	NA	NA	100	NA	NA	NA
Hotspots SSP 2-8.5							
Epupa	94	100	100	100	100	NA	NA
Kahenge	100	NA	100	100	NA	100	NA
Kamanjab	100	NA	NA	100	NA	NA	NA
Kapako	100	NA	NA	NA	100	100	NA
Khorixas	100	100	100	100	100	100	NA
Mashare	100	100	100	NA	NA	100	NA
Mpungu	100	NA	NA	100	100	100	100
Mukwe	100	NA	NA	100	100	100	NA
Ndiyona	100	NA	NA	100	100	100	NA
Opuwo	100	NA	100	100	100	100	NA
Otavi	100	NA	NA	NA	NA	NA	NA
Outjo	100	NA	NA	100	NA	100	NA
Rundu Rural East	100	NA	NA	100	100	100	NA
Rundu Rural West	100	100	NA	100	100	100	NA
Rundu Urban	100	NA	NA	100	NA	100	NA
Sesfontein	100	NA	NA	100	100	NA	NA

For geographically focused consultation and investment planning, the detailed outputs of the hazard, multi-hazard hotspot and exposure analyses have been consolidated in **Annex 4**. The annex presents all maps, figures and summary tables for the Kunene River Basin and the Okavango River Basin in separate, self-contained sections, allowing basin-specific climate risk information to be reviewed efficiently without navigating the full main report.

5 PART V. CLIMATE VULNERABILITY ASSESSMENT

5.1 Typology-based vulnerability assessment

The typology-based default methodology is a disciplined approach for quantifying asset-level vulnerability when site-specific data are limited, by assigning default scores to groups of assets (typologies) that share design, siting and operational characteristics.

For each hazard, differentiated parameter sets are defined to represent the dominant physical mechanisms and stressors that drive damage and disruption. For example: (i) heat stress relies on temperature thresholds, exceedance duration and cooling demand; (ii) drought emphasizes supply deficits, storage depletion and safe yield; (iii) pluvial and fluvial flooding use flood depth, duration, velocity and debris load; and (iv) wildfire considers radiant heat, ember attack, smoke interference and access constraints. For every asset-hazard pair, default scores are assigned across four engineering dimensions:

Physical Damage (PD), Operability (OP), Service Life (SL) and Productivity (PR) are derived from standard engineering practice, analogous project experience and operator feedback. Defaults are conservative, reproducible and fully documented in the parameter and scoring tables.

The approach produces comparable *Vulnerability Index* values for screening and prioritization. As drawings, measurements or monitoring data become available, default scores are replaced by measured values and results are reissued with improved confidence.

The typology-based defaults make assumptions explicit, auditable and easy to revise, providing a pragmatic, standards-aligned bridge from limited information to actionable vulnerability estimates across hazards and asset classes.

Vulnerability is represented by four engineering dimensions that capture both infrastructure fragility and service performance. Each dimension is scored between 0 and 1 and combined into a single Vulnerability Index as:

- **Physical Damage (PD):** reflects structural or material harm to works and equipment.
- **Operability (OP):** reflects the ability to run and be accessed during and after the event.
- **Service Life (SL):** reflects long term degradation and maintenance burden.
- **Productivity or Functionality (PR):** reflects the capacity to deliver the required service output and quality.

$$VI = (0.35 \times PD) + (0.30 \times OP) + (0.15 \times SL) + (0.20 \times PR)$$

The table below explains the reporting classes for the Vulnerability Index and how they should be interpreted when planning upgrades or operations.

Table 24. *Vulnerability Index reporting classes. Source: the author.*

Class	Vulnerability Index range	Interpretation and action
Low	0.00–0.24	Limited adverse effects under design conditions. Routine monitoring and standard maintenance are adequate. No immediate upgrades required.
Moderate	0.25–0.49	Noticeable performance constraints during hazard events. Targeted low-cost measures reduce disruption. Prepare operational contingencies.
High	0.50–0.74	Frequent service disruption likely under hazard conditions. Prioritise design upgrades and operational changes. Introduce redundancy and storage autonomy.
Very High	0.75–1.00	Severe impact expected without major adaptation. Implement structural hardening, alternative sources and robust emergency procedures.

For each hazard, PD, OP, SL and PR values are attributed using a rationale set out in tables as the table below for the heat stress hazard (as an example). The tables with the rationale for all the hazards are included in **annex 1**.

The Vulnerability Index for each asset type by hazard is computed using the fixed weights and the obtained results are classified in the resulting vulnerability index according to the reporting bands defined. The results can inform design and operation implications.

Table 25. Assignment rationale for Heat Stress by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.

Heat Stress Hazard				
WASH Asset type	PD (0-1) Physical Damage	OP (0-1) Operability	SL (0-1) Service Life	PR (0-1) Productivity/functionality
Borehole	0.20	0.50	0.60	0.50
	Physical harm is limited because key components are underground or submerged; headworks and panels experience moderate heat exposure.	Operability is affected by motor thermal trips, panel derating and operator safety during peak heat.	Heat accelerates insulation ageing, seal wear and lubricant breakdown in motor and headworks.	Output can be constrained during heat waves due to derated motors and higher demand peaks.
Well	0.10	0.40	0.60	0.40
	Structures are simple and mostly passive; physical damage from heat is minor.	Manual or low power operation has moderate sensitivity to heat; access and queuing can limit service.	Inners, ropes and seals age faster with sustained heat and UV exposure.	Throughput falls during peak heat periods; quality excursions are not dominant for heat alone.
Public Tap	0.20	0.40	0.60	0.40
	Kiosk structures can deform or crack at aprons; piping is usually protected.	Operations are constrained by user safety, queuing and lower pressure under heat driven demand.	Gaskets, valves and hose materials age faster at high temperature.	Delivered volumes can drop when upstream sources or pressure are derated.
Water Tanker Service Point	0.30	0.60	0.60	0.50
	Aprons and hoses experience heat related wear; fittings and pavements can degrade.	Operability is sensitive to vehicle and pump overheating and to staff safety limits.	Frequent thermal cycles accelerate wear on hoses, couplings and small pumps.	Throughput is constrained by reduced duty cycles and longer turnaround during heat waves.
Water Pump Station	0.40	0.80	0.70	0.60
	Electrical cabinets, cables and seals are sensitive to high temperature; enclosures can exceed ratings.	Operability is strongly affected by thermal trips, derating of drives and need to limit exposure for staff.	Elevated temperatures accelerate insulation ageing, gasket hardening and bearing wear.	Output is curtailed by derated equipment and protection settings during sustained heat.
Dam	0.10	0.40	0.50	0.70
	Embankments and structures rarely suffer direct heat damage; localized cracking possible at surfaces.	Operations can be constrained by staff safety and by thermal effects on appurtenances.	Liners, seals and exposed appurtenances age faster; evaporative stress increases maintenance.	Available yield and head are reduced through evaporation and temperature induced losses.
Other	0.20	0.50	0.60	0.50
	Heterogeneous small assets with some exposed components; limited structural harm expected.	Operability moderately affected by heat related access and minor equipment derating.	Typical small pumps and fittings age faster under heat and UV exposure.	Service volumes can be reduced under heat driven demand and minor derating.

An example of the calculation procedure. For a Water Pump Station under Heat Stress the scores are PD-0.40, OP-0.80, SL-0.70 and PR-0.60. The Vulnerability Index is calculated as:

$$VI = (0.35 \times 0.40) + (0.30 \times 0.80) + (0.15 \times 0.70) + (0.20 \times 0.60) = 0.14 + 0.24 + 0.105 + 0.12 = 0.605.$$

This value would fall in the High Vulnerability Class.

The following tables include the vulnerability index calculations for all the climate hazards considered: Heat stress, drought, pluvial flash floods, fluvial flash floods and wildfires.

5.2 Heat Stress vulnerability assessment

Most asset types are in the Moderate class, indicating material ageing and operational derating without widespread structural failure, but with noticeable service constraints during heat waves. Water Pump Stations are in the High class and require targeted measures such as shading and ventilation, temperature rated electrical equipment, review of protection settings and provision of storage autonomy to buffer output during thermal derating.

Table 26. Vulnerability index results for heat stress hazard (Typology-based calculation).

Vulnerability index results for Heat Stress						
Asset type	PD	OP	SL	PR	VI	Class
Borehole	0.20	0.50	0.60	0.50	0.410	Moderate
Well	0.10	0.40	0.60	0.40	0.325	Moderate
Public Tap	0.20	0.40	0.60	0.40	0.360	Moderate
Water Tanker Service Point	0.30	0.60	0.60	0.50	0.475	Moderate
Water Pump Station	0.40	0.80	0.70	0.60	0.605	High
Dam	0.10	0.40	0.50	0.70	0.370	Moderate
Other	0.20	0.50	0.60	0.50	0.410	Moderate

5.3 Drought vulnerability assessment

Across asset types, drought produces high vulnerability, with wells, tanker service points, pump stations and dams clustering in the high class, and public taps at the lower end of high.

Physical damage is limited for most typologies, but operability, service life and productivity are consistently stressed by drawdown, heat-related derating and longer duty cycles. Pumped and energy-dependent assets show the greatest sensitivity because sustained deficits translate into longer lifts, hotter operating conditions and tighter intake hydraulics. Gravity kiosks and simple taps experience fewer structural issues, yet their delivered volumes still fall when upstream sources lose yield or pressure.

For planning and design:

- Schemes should be sized for multi-week storage autonomy and conjunctive use of sources so that demand can be met during extended deficits.
- Groundwater works require conservative safe-yield assumptions, step-testing and continuous head and conductivity monitoring to control drawdown and salinity creep.
- Pumping systems benefit from high-temperature-rated motors and drives, generous cooling and shaded or ventilated housings, plus variable-speed operation to reduce thermal stress.
- Distribution design should include district metering, pressure management and prioritized service levels for essential facilities.

- Operationally, pre-agreed tanker logistics, protected filling points and modular package treatment units allow surge supply without compromising quality.

Table 27. Vulnerability index results for drought hazard (Typology-based calculation).

Vulnerability index results for drought						
Asset type	PD	OP	SL	PR	VI	Class
Borehole	0.20	0.70	0.60	0.80	0.53	High
Well	0.30	0.70	0.60	0.80	0.57	High
Public Tap	0.10	0.60	0.40	0.70	0.42	Moderate
Water Tanker Service Point	0.20	0.70	0.50	0.80	0.52	High
Water Pump Station	0.30	0.80	0.60	0.80	0.60	High
Dam	0.40	0.60	0.50	0.80	0.55	High
Other	0.20	0.60	0.50	0.70	0.46	Moderate

5.4 Fluvial Flash Floods vulnerability assessment

Riverine flash flooding drives high to very high vulnerability, with pump stations at very high due to inundation of electrical gear, forced outages during high sediment loads and access constraints.

Wells also rate very high because shallow intakes and headworks are exposed to scour, debris impact and contaminated floodwater. Boreholes, dams and tanker points sit in the high band, reflecting episodic but damaging shocks: overtopping of embankments and appurtenances, apron cracking, erosion of access roads and rapid turbidity excursions that overwhelm treatment.

Design must assume short, intense flood pulses with high sediment and debris:

- Intakes need resilient siting away from thalweg scour lines, flood-proof plinths, trash racks, floating or adjustable screens and bank stabilization.
- Treatment should be modular with duty–standby trains and rapid-response coagulant and polymer dosing to handle spikes in turbidity and organic load.
- Electrical and control equipment require elevation above design flood levels, water-tight enclosures and safe egress routes.
- Bridge and pipe crossings should use buried or armoured crossings with scour protection and accessible isolation valves.
- Sanitation in floodplains should avoid new low-lying containment; where unavoidable, use sealed, raised units and flood-protected sludge transfer points.

Table 28. Vulnerability index results for fluvial flash floods hazard (Typology-based calculation).

Vulnerability index results for fluvial flash floods						
Asset type	PD	OP	SL	PR	VI	Class
Borehole	0.60	0.80	0.40	0.50	0.610	High
Well	0.90	0.90	0.50	0.60	0.780	Very High
Public Tap	0.70	0.80	0.50	0.50	0.660	High
Water Tanker Service Point	0.70	0.90	0.50	0.40	0.670	High
Water Pump Station	0.90	0.90	0.60	0.70	0.815	Very High
Dam	0.80	0.70	0.60	0.70	0.720	High
Other	0.80	0.80	0.50	0.60	0.715	High

5.5 Pluvial Flash Floods vulnerability assessment

Convective storm runoff produces urban and peri-urban exposure that rates high across all typologies. With pump stations near the top of the band because frequent shallow, inundation and debris, cause repeated outages. Tanker service points and public taps are affected by ponding, apron failures and contaminated runoff, which degrade service and create access hazards.

Structural damage is usually moderate, but repeated wetting accelerates wear of gaskets, valves and small pumps, and operational downtime rises due to safety constraints and water quality upsets.

Planning and design should:

- Prioritize surface drainage, raised platforms and water-tight housings for at-grade assets.
- Site layouts must include graded aprons, curb and gutter control and independent power and communications for pump stations to shorten restart times.
- Package treatment should include bypass sedimentation and washable media to absorb short spikes.
- For kiosks and tanker stands, specify slip-resistant surfacing, sealed joints and sacrificial fittings that are easy to replace after events.
- Network operations should implement rainfall-triggered operating regimes with pre-emptive storage drawdown, targeted valve configurations and temporary chlorination boosts to protect residuals.

Table 29. Vulnerability index results for pluvial flash floods hazard (Typology-based calculation).

Vulnerability index results for pluvial flash floods						
Asset type	PD	OP	SL	PR	VI	Class
Borehole	0.50	0.70	0.30	0.40	0.510	High
Well	0.80	0.80	0.40	0.50	0.680	High
Public Tap	0.60	0.70	0.40	0.40	0.560	High
Water Tanker Service Point	0.60	0.80	0.40	0.30	0.570	High
Water Pump Station	0.80	0.90	0.50	0.60	0.745	High
Dam	0.60	0.60	0.50	0.60	0.585	High
Other	0.70	0.80	0.40	0.50	0.645	High

5.6 Wildfires vulnerability assessment

Wildfire vulnerability is mixed, with moderate values for simple sources such as boreholes, wells and public taps, and high for tanker service points and pump stations. The dominant drivers are: (i) smoke and ash contamination of raw water; (ii) heat exposure to cables, seals and control cabinets; and (iii) loss of power or access during fire incidents. Structural damage to civil works is usually limited except where brush or structures are adjacent to facilities, but operability and productivity fall as intake screens clog, equipment derates in high ambient temperatures and staff access is restricted.

Design should considerate:

- Defensible space around all exposed assets, with cleared perimeters, fire-resistant fencing and non-combustible surfaces.
- Electrical and control equipment require heat-rated cables, sealed cabinets and filtered ventilation that can be quickly swapped post-event.
- Raw-water intakes benefit from pre-sedimentation or strainers designed for ash pulses and from flexible chemical dosing to address taste, odour and organics.
- Power resilience through dual feeds or standby generation reduces outage risk.
- For sanitation, sealed containment and engineered wetlands with fire-safe access paths limit overflow risk when operations are disrupted.

- Preparedness plans should pair stage-of-fire alerts to specific operating modes, tanker pre-positioning and rapid cleaning protocols for ash and soot.

Table 30. Vulnerability index results for wildfires hazard (Typology-based calculation).

Vulnerability index results for Wildfires						
Asset type	PD	OP	SL	PR	VI	Class
Borehole	0.40	0.50	0.50	0.30	0.425	Moderate
Well	0.50	0.60	0.50	0.30	0.490	Moderate
Public Tap	0.50	0.60	0.50	0.30	0.490	Moderate
Water Tanker Service Point	0.60	0.70	0.50	0.30	0.555	High
Water Pump Station	0.80	0.80	0.60	0.50	0.710	High
Dam	0.30	0.40	0.50	0.20	0.340	Moderate
Other	0.60	0.70	0.50	0.40	0.575	High

Across all the hazards, vulnerability consistently rises: (i) where assets depend on powered pumping; (ii) where access is easily cut; and (iii) where water quality can swing rapidly.

Portfolio-level design should therefore standardize on modular treatment, elevated and sealed electrical systems, conservative source yields, storage autonomy sized to local hazard profiles, and multi-source architectures that allow graceful degradation rather than failure.

Operations should adopt trigger-based playbooks tied to rainfall, river stage, temperature and air quality thresholds, supported by telemetry for head, flow, pressure, turbidity and conductivity. These measures convert the observed vulnerability patterns into practical resilience gains at both scheme and basin scales.

6 PART VI. CLIMATE RISK ASSESSMENT

6.1 Heat Stress risk

Heat Stress poses a rapidly intensifying threat to WASH systems across the Kunene and Okavango basins, as rising temperatures increase evaporative losses, intensify thermal stress on mechanical and electrical equipment, and generate growing operational instability for pumped infrastructure.

Across all time horizons, Heat Stress risk escalates sharply, with many constituencies shifting from High or Very High to fully Extreme exposure by mid-century under both SSP2-4.5 and SSP5-8.5. Constituencies such as Epupa, Khorixas, Mpungu, Mukwe, Ndiyona and Rundu Rural West already show widespread Extreme exposure by 2040–2059, and in later horizons exposure saturates across most high-risk areas, reflecting the pervasive nature of regional warming.

Vulnerability is driven primarily by operational and mechanical degradation of assets. Pump stations show the highest vulnerability due to heat-related derating of motors, increased energy demand, seal and insulation damage, reduced efficiency and more frequent failures. Motorised boreholes experience similar stress, as increasing lift heights and hotter operating conditions accelerate component fatigue and shorten pump and controller lifetimes. Tanker service points, often located in remote and unshaded environments, are highly sensitive during heat waves, with reduced safe operating hours and constraints on storage. Surface water schemes, particularly dams and open reservoirs, show moderate vulnerability through enhanced evaporation, algal growth and oxidation processes that degrade water quality and reduce effective storage. By contrast, wells and public taps have lower direct structural sensitivity, but their performance depends heavily on upstream sources and conveyance systems that are themselves highly vulnerable to Heat Stress, so failures in pumps, canals or treatment plants rapidly cascade down to users.

Spatially, Heat Stress risk is concentrated and persistent in constituencies where saturated exposure coincides with infrastructure portfolios dominated by pumps and boreholes. Mpungu, Khorixas, Rundu Rural West, Mukwe, Ndiyona and Opuwo consistently emerge as high-risk hotspots, whereas areas such as Otavi and Sesfontein retain lower risk levels, either because exposure remains comparatively lower or because there is a more limited presence of thermally fragile infrastructure.

Temporally, the risk profile steepens between 2020–2039 and 2040–2059 as exposure shifts from partial to fully Extreme in many locations; by 2060–2079, total risk continues to rise even though exposure classifications cannot increase further, because vulnerability and operational fragility accumulate over time.

Thermal fatigue, electrical instability, material ageing and declining pump efficiency compound across decades, leading to more frequent and longer service disruptions. Comparing scenarios, Heat Stress risk is marginally higher under SSP5-8.5, particularly in constituencies transitioning from Very High to Extreme exposure, but once exposure saturates, risk levels under SSP2-4.5 and SSP5-8.5 converge, indicating that the warming already embedded in a “middle-of-the-road” pathway is sufficient to push many systems beyond critical thermal thresholds. This makes Heat Stress a robust concern across all plausible climate futures.

For WASH resilience, the analysis underscores the need to systematically integrate heat-proofing into design, operation and planning. Priority measures include deploying heat-resistant pump motors and electrical components, improving cooling and ventilation for pump stations, and adopting variable-speed drives to reduce thermal and mechanical stress.

System configuration should favour multi-week storage autonomy so that schemes can maintain supply during periods of reduced pumping productivity, while conjunctive use of groundwater, surface water and, where feasible, reclaimed water can distribute stress across multiple sources and reduce pressure on individual boreholes during peak heat periods. At the operational level, operators will require enhanced monitoring of groundwater levels, pump and motor temperatures, energy consumption and flow rates to detect incipient heat-related failures and adjust duty cycles before breakdowns occur. Given their combination of persistent Extreme exposure and high infrastructure vulnerability, Mpungu, Khorixas, Rundu Rural West, Mukwe, Ndiyona and Opuwo should be treated as priority constituencies for early, targeted adaptation

investments. Overall, Heat Stress is likely to become a defining constraint on reliable water and sanitation service delivery in the Kunene and Okavango basins, and early investment in heat-resilient design, expanded storage autonomy and proactive asset management will be essential to safeguard WASH services under accelerating climate change.

6.2 Drought risk

Drought emerges as one of the dominant climate hazards affecting WASH systems in the Kunene and Okavango basins, as progressive reductions in groundwater levels, diminished surface-water yield, increased operational temperatures and cumulative stress on pumping and mechanical systems propagate through asset portfolios. Drought risk increases consistently across all future horizons under both SSP2-4.5 and SSP5-8.5, driven by higher evaporative demand, reduced recharge and intensifying climatic aridity. Across constituencies, exposure to High, Very High and Extreme drought hotspots become increasingly widespread in the mid- and late-century horizons. Constituencies that initially exhibit partial drought exposure in 2020–2039 gradually transition toward near-universal Extreme exposure by 2040–2059 and fully saturate by 2060–2079, a shift that is particularly pronounced in groundwater-dependent locations where prolonged deficits enhance susceptibility to abstraction stress.

Drought vulnerability is strongly typology dependent. Pump stations experience operational derating under high temperatures, with reduced efficiency, increased energy consumption and accelerated mechanical wear. Motorised boreholes face additional strain as declining water tables increase lift heights and friction losses, shortening equipment lifetimes and raising the probability of failure. Dams are exposed to elevated sedimentation, higher evaporation losses and drying-related structural stress, which together reduce effective storage and reliability. Public taps and wells are structurally less sensitive to drought itself but remain highly vulnerable to upstream supply loss when boreholes, intakes or treatment facilities become inoperative. Tanker service points play a critical role during extended deficits but are highly sensitive to source depletion and logistical constraints, especially where road conditions and fuel supply are compromised during protracted dry spells.

Spatially, drought risk intensifies non-linearly across constituencies. High-risk clusters emerge in Khorixas, Opuwo, Mpungu, Rundu Rural West, Mukwe and Ndiyona, where Extreme exposure combines with highly sensitive asset portfolios dominated by pumps, boreholes and abstraction points. Moderate-risk constituencies such as Sesfontein, Kapako and Outjo maintain lower risk levels due either to reduced initial exposure or to a smaller concentration of sensitive assets, while Otavi and Mashare show consistently lower exposure-driven risk across horizons. Temporally, drought risk accelerates sharply from 2020–2039 to 2040–2059 as exposure transitions from partial to fully Extreme in many areas. By 2060–2079, exposure saturates in most constituencies, yet operational fragility continues to accumulate due to compounded thermal and mechanical stress, illustrating that risk escalation arises from both climatic intensification and the progressive fatigue and ageing of infrastructure systems. Differences between SSP2-4.5 and SSP5-8.5 remain modest for drought: SSP5-8.5 displays slightly higher risk in constituencies approaching saturation, but once systems reach Extreme exposure levels, scenario-driven variation becomes less influential and risk levels converge, implying that adaptation priorities remain broadly consistent across emission pathways.

For WASH resilience, the analysis highlights the need to systematically integrate drought-proofing into design, operation and planning. Groundwater development should prioritise increased borehole depth where hydrogeologically feasible, optimised screen intervals and pumping systems designed with high-temperature tolerance, enhanced cooling and variable-speed operation to reduce mechanical stress during prolonged deficits. Multi-week storage autonomy at scheme level, combined with conjunctive use of groundwater, surface water and, where feasible, alternative sources, is essential to maintain supply when yields decline. Operationally, continuous monitoring of groundwater levels, electrical conductivity and drawdown is required to manage abstraction within sustainable limits and to detect early signs of aquifer stress, while preventive maintenance on pumps, motors and control systems becomes critical to avoid cascading failures under prolonged drought conditions. Tanker logistics should be planned with redundancy in sources and routing to ensure that emergency supply can be sustained during multi-season events. Based on cumulative multi-horizon risk, Khorixas, Opuwo, Mpungu, Rundu Rural West, Mukwe and Ndiyona should be treated as priority constituencies for drought adaptation, given their persistent high risk and systemic fragility under all conditions. Overall, drought poses a pervasive and escalating threat to WASH systems across the Kunene and

Okavango basins, and the convergence of climatic aridity, groundwater stress and operational vulnerability makes it a top adaptation priority under all SSP scenarios. Early and sustained infrastructure reinforcement, enhanced monitoring and proactive asset management will be essential to safeguard water security in the face of increasing drought pressure.

6.3 Fluvial flash floods risk

Fluvial flash floods represent one of the most disruptive climate hazards for WASH systems in the Kunene and Okavango basins, as short and intense flood pulses with high sediment loads, debris movement and rapid changes in river stage propagate along riverine corridors and into critical water infrastructure. Although their direct impacts are spatially concentrated near river channels, the operational consequences are basin-wide: intakes are contaminated, pump stations are forced offline, access routes are cut, and treatment processes are overwhelmed. Exposure to fluvial flooding intensifies across all time horizons, with constituencies located close to major river systems such as Epupa, Rundu Rural West, Ndiyona and Mukwe showing consistent increases in High, Very High and Extreme exposure categories. The progressive expansion of Very High and Extreme hotspot classifications under both SSP2-4.5 and SSP5-8.5 reflects the projected intensification of extreme rainfall events and the resulting increase in hydrological volatility across the basins.

Vulnerability to fluvial flash floods is consistently higher than for any other hazard and is strongly asset dependent. Pump stations are particularly sensitive, as they are prone to inundation of electrical and control equipment, sudden sediment shocks, damage to pumps and motors, and forced shutdowns to prevent catastrophic failure. Wells and boreholes located in or near floodplains are exposed to scour, debris impact and direct contamination, which can degrade water quality and compromise structural integrity. Dam infrastructure is exposed to overtopping, erosion of embankments and rapid turbidity spikes that overwhelm conventional treatment systems and reduce safe yield. Public taps and tanker service points, while not always directly damaged, frequently become inaccessible due to flooding of aprons, surroundings and access roads, interrupting service exactly when demand for safe water is highest. As a result, fluvial flash floods tend to generate short, sharp but highly disruptive service outages across multiple asset types simultaneously.

Spatially, the highest fluvial flood risk is concentrated in Epupa, Rundu Rural West, Mukwe, Ndiyona and Opuwo, where Extreme exposure converges with infrastructure portfolios that are structurally and operationally sensitive to rapid flooding. In these constituencies, the presence of major intake points, high reliance on pumped systems, and proximity to dynamic river channels amplify risk and create recurrent service disruption hotspots. Moderate-risk constituencies such as Sesfontein, Outjo and Kapako are typically characterised by fewer fluvial-prone assets or only partial exposure zones, while constituencies like Otavi remain minimally affected due to their greater distance from active floodplains. Temporally, risk increases sharply between 2020–2039 and 2040–2059 as extreme rainfall events and high-flow episodes become more frequent, driving a step change in both exposure and disruption potential. By 2060–2079, exposure reaches Extreme saturation in most flood-prone constituencies; beyond this point, further risk escalation is driven less by additional exposure and more by accumulated vulnerability and the growing criticality of the assets at risk.

Differences between SSP2-4.5 and SSP5-8.5 are moderate but consistent, with fluvial flood risk generally higher under SSP5-8.5 due to stronger projected intensification of rainfall extremes and associated peak flows. However, once constituencies cross into Extreme exposure, the difference between scenarios narrows, indicating that the physical thresholds for damaging fluvial flooding are exceeded under both pathways. This convergence implies that key adaptation requirements remain broadly similar regardless of the global emissions trajectory. For WASH resilience, the analysis underlines the need for systematic flood-proofing of critical infrastructure, including elevating pump stations above design flood levels, enclosing electrical and control equipment in waterproof housings, and securing protected access routes that remain viable during flood events. Vulnerable boreholes and wells located in high-scour zones should be relocated where feasible or structurally reinforced and protected against debris impact and erosion. Intakes along major rivers require resilient designs with trash racks, flexible or moveable screens and bank stabilisation measures to manage sediment pulses and shifting channels, while modular treatment capacity with rapid-response coagulation and sedimentation units is needed to handle turbidity spikes without prolonged service interruptions.

Network configuration should incorporate redundancy and isolation valves so that sections of the system can be temporarily disconnected without collapsing overall service. Given their persistent Extreme exposure and high vulnerability, Epupa, Rundu Rural West, Mukwe, Ndiyona, Mpungu and Opuwo emerge as priority

constituencies for early, targeted fluvial flood adaptation investments. Overall, fluvial flash floods pose a severe and escalating threat to WASH service continuity in the Kunene and Okavango basins. Their destructive potential, coupled with the projected increase in hydrological extremes under climate change, makes proactive infrastructure reinforcement, access management and adaptive treatment capacity essential elements of any strategy to sustain safe and reliable water supply in the coming decades.

6.4 Pluvial flash floods risk

Pluvial flash floods, generated by intense short-duration convective storms, are emerging as a rapidly expanding hazard for WASH systems in the Kunene and Okavango basins. Unlike fluvial floods, which propagate along river channels, pluvial events are primarily an urban and peri-urban phenomenon, driven by localised cloudbursts interacting with limited drainage capacity. These events produce shallow but highly dynamic inundation, with rapid runoff, ponding and overland flows that overwhelm surface drainage, flood at-grade infrastructure and mobilise contaminants across streets and informal settlements. As a result, they generate localised but severe impacts on WASH services, repeatedly disrupting at-grade assets, contaminating distribution points and forcing operational interruptions.

Exposure to pluvial flooding increases progressively across all future horizons under both SSP2 and SSP5. Constituencies with expanding built-up areas and weak stormwater management, such as Khorixas, Opuwo, Outjo, Mukwe and Rundu Rural West, move quickly into High and Very High exposure classes, and by 2040–2059 most urban constituencies display widespread Extreme exposure. This pattern reflects the projected strengthening of convective storm activity under climate change and the tendency for sealed surfaces and unplanned drainage to concentrate runoff in low-lying areas. By 2060–2079, many pluvial-prone constituencies reach near-saturated Extreme exposure, indicating that intense localised flooding will become a recurrent feature of the urban climate risk profile.

Vulnerability to pluvial flash floods is consistently high across asset types, as even shallow inundation can trigger service interruptions, mechanical failures and public health risks. Pump stations experience repeated wetting of electrical and control equipment, water ingress into cable ducts and housings, debris accumulation around intakes and valves, and associated electrical instability and forced outages. Public taps and kiosks are affected by apron failures, ponding around tap stands and direct contamination of points of use, increasing exposure to faecal and chemical pollutants. Tanker service points are disrupted when aprons and access areas become flooded or slippery, creating unsafe operating conditions and forcing temporary shutdowns at times of peak demand. Boreholes located near depressions, gullies or eroded zones are exposed to contaminated runoff, erosion of wellheads and accelerated mechanical wear on riser pipes and headworks. Treatment systems, particularly those with limited coagulation and filtration flexibility, face sudden turbidity and contaminant spikes that exceed standard design assumptions, requiring emergency bypass or temporary derating and further constraining supply.

Spatially, the highest pluvial flood risk is concentrated in Khorixas, Rundu Rural West, Mukwe, Opuwo, Mpungu and Ndiyona, where sensitive infrastructure coexists with rapidly expanding settlement footprints and poor drainage, creating recurrent hotspots of shallow flooding and service disruption. Moderate-risk constituencies such as Outjo, Kapako and Sesfontein exhibit lower exposure but remain prone to repeated operational interruptions during heavy rainfall events, while Otavi consistently shows minimal risk due to its distance from major storm-runoff concentration zones. Temporally, risk increases sharply between 2020–2039 and 2040–2059 as intense convective systems become more frequent, driving step changes in both exposure and disruption potential. By 2060–2079, many pluvial-prone constituencies reach Extreme exposure saturation; beyond this point, further risk escalation is driven less by additional exposure and more by accumulated vulnerability, as assets experience repeated wetting–drying cycles, corrosion, seal degradation and chronic downtime.

Scenario differences are moderate: pluvial flood risk is generally higher under SSP5 due to stronger intensification of convective rainfall, but once constituencies cross into Extreme exposure the divergence between SSP2 and SSP5 narrows. This indicates that thresholds for damaging pluvial flooding are exceeded under both pathways and that core adaptation priorities for WASH infrastructure are robust to the emissions trajectory. For WASH resilience, the analysis highlights the need for systematic management of urban runoff and protection of at-grade assets against shallow, rapidly evolving floods. Priority measures include upgrading

surface drainage around pump stations, kiosks and tanker points through improved site grading, open channels, culverts and kerb-and-gutter controls that divert stormwater away from critical equipment. Assets located in known ponding areas should be raised on platforms, with watertight housings for electrical and control components and non-slip surfacing to maintain safe access in wet conditions. Treatment plants require enhanced rapid-response turbidity management, including flexible coagulation, washable media and, where feasible, modular units that can be cycled on and off without long restart times following storm-induced shutdowns. Power resilience is also critical to reduce delays in restarting systems after lightning, short-circuits or localised grid failures associated with convective storms. Given their persistent Extreme exposure and high vulnerability, Khorixas, Rundu Rural West, Mukwe, Opuwo, Mpungu and Ndiyona should be treated as priority constituencies for early intervention on pluvial flood resilience. Overall, pluvial flash floods are projected to intensify significantly across the basins, and their rapid onset, shallow but widespread inundation and strong water quality impacts make proactive drainage upgrades, electrical protection and operational preparedness essential to maintain safe and continuous WASH services under future climate conditions.

6.5 Wildfire risk

Wildfires represent an increasingly significant climate hazard across the Kunene and Okavango basins, as rising temperatures, prolonged dry seasons and expanding vegetative dryness amplify both the likelihood and intensity of fire events.

For WASH systems, the primary pathways of impact are through operability and water quality rather than direct structural loss: ash contamination of raw water sources, heat-induced degradation of electrical and mechanical equipment, smoke-related access constraints and recurrent power outages combine to create prolonged service instability. Although the spatial footprint of individual wildfires is more diffuse and variable than flood-related hazards, their operational disruptions are often widespread and persistent, particularly in remote and heavily vegetated constituencies.

Exposure to wildfire hazards increases steadily across all scenarios and time horizons. Constituencies with dense vegetation, remote settlements or limited firebreaks—such as Epupa, Opuwo, Sesfontein, Mukwe, Mpungu and Khorixas—progressively shift into High and Very High exposure categories, with localised Extreme hotspots emerging where dry fuel loads and access constraints coincide. By the 2040–2059 horizon, most rural constituencies show expanded wildfire exposure under both SSP2-4.5 and SSP5-8.5, and this trend strengthens further under SSP5, where accelerated warming and aridity drive more frequent and intense fire seasons. Although exposure does not saturate to fully Extreme levels in all constituencies, wildfires become a recurrent and unavoidable feature of the climate risk landscape in the most affected areas.

Vulnerability to wildfires is driven mainly by heat exposure, smoke, ash deposition and power interruptions rather than by complete destruction of facilities. Pump stations exhibit high vulnerability, as above-ground equipment is exposed to radiant heat that degrades cables, seals and insulation, while smoke and airborne ash block air intakes and filters and cause repeated tripping of electrical systems. Tanker service points are operationally fragile during fire events due to reduced visibility, restricted access, unsafe working conditions for staff and users, and the reallocation of tanker fleets toward emergency fire-fighting or evacuation support. Boreholes and wells experience moderate vulnerability: although their subsurface components are largely shielded, wellheads, seals and above-ground appurtenances are exposed to heat and ash, and abstraction may be curtailed when operators cannot safely reach facilities. Dams are similarly moderately vulnerable, as post-fire sediment and ash pulses degrade inflow quality, reduce effective storage and increase treatment burdens. Public taps and kiosks are affected less by direct heat but suffer from access restrictions, smoke-related safety concerns and deterioration of water quality when upstream sources are compromised by fire-related contamination.

Spatially, **high wildfire risk** concentrates in Opuwo, Mpungu, Khorixas, Rundu Rural West, Mukwe and Ndiyona, where rising exposure overlaps with portfolios dominated by electrically driven and access-dependent assets. Large, wooded landscapes, limited alternative access routes and dispersed settlement patterns in these constituencies increase the probability that fire fronts or smoke plumes will cut roads, disrupt power supply and impede routine operation and maintenance. **Moderate-risk** areas such as Kapako, Outjo and Sesfontein

combine significant vulnerability with more spatially limited exposure, while constituencies with less vegetative fuel or better access options remain at comparatively **lower risk**.

Temporally, wildfire risk grows steadily from 2020–2039 to 2040–2059, with a further but more moderate increase by 2060–2079. This trajectory reflects the combined effect of expanding exposure, as hotter and drier climatic conditions lengthen the fire season and dry out fuel loads, and increasing asset fragility, as repeated heat and smoke episodes cumulatively weaken electrical and mechanical components. Unlike flood hazards, wildfire exposure does not typically reach full saturation across all constituencies; however, the frequency and persistence of disruptive events increase to the point that high-risk constituencies face almost annual operational disturbance. Differences between SSP2-4.5 and SSP5-8.5 are more pronounced for wildfires than for other hazards: SSP5 yields substantially higher exposure due to accelerated warming, prolonged drought cycles and expanded fuel dryness. While High and Very High exposure levels occur under both scenarios, Extreme exposure becomes more widespread under SSP5, implying more frequent and longer service outages in the absence of adaptation.

For WASH resilience, the analysis points to the need for a proactive, fire-aware approach to infrastructure design, siting and operation. Around all critical WASH facilities, defensible space should be established through systematic vegetation clearance, fire-safe perimeter zones and the removal of combustible materials adjacent to structures. Electrical and control systems require heat-resistant components, sealed control cabinets and protected ventilation paths that minimise smoke and ash ingress, while key assets should be equipped with backup power systems or dual-feed electrical configurations to reduce dependence on single vulnerable lines.

On the water quality side, intakes and treatment works need pre-sedimentation or straining stages capable of handling post-fire ash and debris pulses, along with flexible coagulation and filtration regimes that can be rapidly adjusted following burn events in upstream catchments. Operationally, dedicated fire-stage protocols are required, including the pre-positioning of tankers, provision of personal protective equipment for operators, and rapid procedures for cleaning and reinstating ash-affected equipment after fire passage. Given their combination of high exposure, significant operational vulnerability and limited access, Opuwo, Mpungu, Khorixas, Rundu Rural West, Mukwe and Ndiyona emerge as priority constituencies for early wildfire adaptation investments. Overall, wildfires are projected to intensify substantially under climate change, and their diffuse but persistent impacts on operability and water quality mean that fire-resilient infrastructure design, access management and recovery capacity must become integral components of strategies to safeguard WASH service delivery in the Kunene and Okavango basins under future climate conditions.

7 PART VII. PROJECT SITE CLIMATE RISK AND VULNERABILITY ANALYSIS

7.1 Kavango Link- CAN water project

7.1.1 Project site context

Namibia's Central Area (CAN) faces chronic water shortages caused by limited local water resources and recurrent droughts. The region depends primarily on the Eastern National Water Carrier (ENWC) system, which integrates the Grootfontein–Omatoko canal and the three main storage dams – Omatoko, Swakoppoort, and Von Bach – as well as the Windhoek aquifer and the New Goreangab Water Reclamation Plant.

However, these sources have proven insufficient to meet increasing demand, particularly during prolonged drought periods. To address this persistent deficit, the Government of Namibia, through NamWater and with support from development partners, has identified the Okavango River as the most viable long-term augmentation source for the CAN.

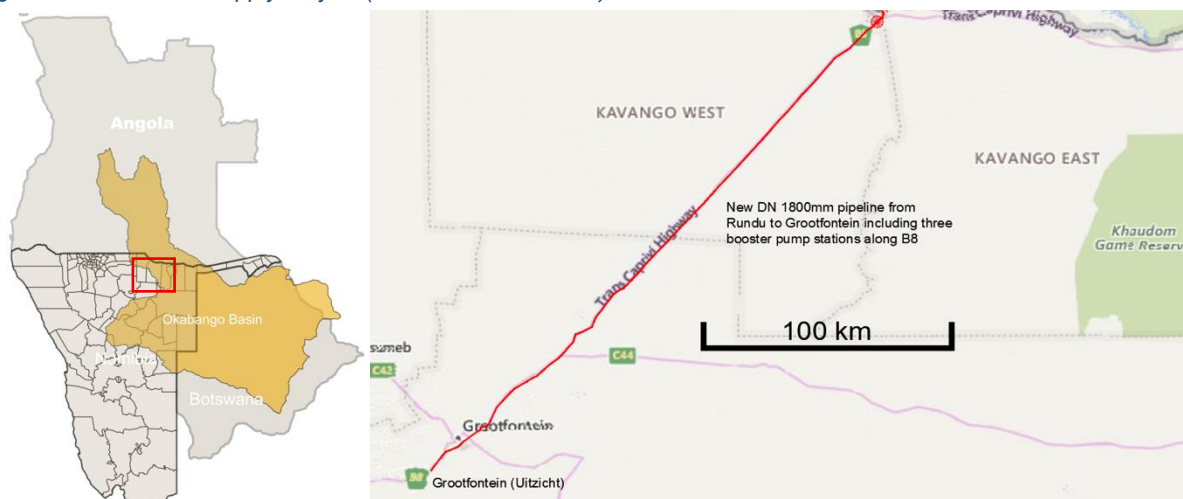
The proposed Okavango Link (CAN Water Supply Project) will transfer raw water from the Okavango River near Rundu to Grootfontein and subsequently to the ENWC system, thereby reinforcing the water supply to Windhoek and surrounding towns.

The infrastructure includes:

- A river abstraction pump station on the Okavango River at Rundu.
- A Base pump station and three in-line booster pump stations.
- Approximately 277 km of parallel DN1300 mm Ductile Iron pipelines (or one DN1800 mm alternative).
- Associated reservoirs, power supply systems, and SCADA controls.

This large-scale inter-basin transfer is a cornerstone of Namibia's long-term water security strategy and aligns with the Government's objective of securing resilient supply systems for the central region under increasing climate stress.

Figure 54: CAN Water Supply Project (Rundu – Grootfontein)



7.1.2 Water demand

Comprehensive studies have established the projected shortfall in water availability within the CAN area (Element, 2025). Table 31 summarizes the estimated water demand, existing supply capacity, and expected annual deficits.

Table 31. Estimated CAN water demand.

Planning Horizon	Estimated Central Area of Namibia (CAN) Water Demand Requirement (Mm ³ /Annum)	Supply Capacity (Mm ³ /Annum)	Estimated Deficit or Shortfall / Annum
2030	42.28	31.52	10.77
2035	54.34	33.51	20.83
2040	62.75	35.12	27.63
2045	66.58	36.86	29.72
2050	68.77	38.73	30.04

By 2050, the projected deficit reaches 30.0 Mm³ per year. Accounting for operational losses and design contingencies, the target design capacity of the Okavango Link has been set at 35 Mm³ per year, primarily serving the Windhoek metropolitan area.

Hydrological modelling determined that abstraction will be restricted to 180 days per year, corresponding to high-flow periods in the Okavango River to minimize environmental impacts. With NamWater's operational standard of 20 pumping hours per day, the design flow rate was established at 9,720 m³/h.

7.1.3 Planned Infrastructure

7.1.3.1. Pipeline

The Okavango Link design proposes two parallel DN1300 mm Ductile Iron pipelines (or one DN1800 mm alternative) spanning 277 km between Rundu and Uitzicht Farm, approximately 17 km southwest of Grootfontein, where it connects with the ENWC system. The pipelines will operate at a 25-bar pressure rating and will be buried along most of the alignment except where topography or geology dictate above-ground.

7.1.3.2. River Abstraction Pump Station

The river abstraction station will be located on the southern bank of the Okavango River near Rundu. It will comprise a reinforced concrete and brick structure with five intake bays (four duty, one standby) fitted with screening and adjustable intake gates. Currently each intake bay allows for a high and low intake weir gates.

- Intake elevation: 1059.82 m above mean sea level (amsl). This water level has not been reached in the wet months of the 79 years of river height measured data and can thus be regarded as safe (Element, 2025). It was determined that the 100-year flood line is 1064.60 m amsl. Therefore, the top of the concrete roof of inlet structure was taken as 1066.05 m amsl, leaving a freeboard or safety of 1.45 m which was felt to be adequate (Element, 2025).
- Pump configuration: five dry-submersible horizontal pumps (4 duty + 1 standby).
- Pump capacity: 2,430 m³/h each at 62 m total head.
- The pump will be installed each with their own variable speed drive (VSD) and the operating voltage of the pump station will be 690 V.
- The total peak power demand required at the pump station will be approximately 2.6 MW at 690 V.
- The Variable Speed Drives (VSDs) will be liquid cooled allowing flow regulation.
- All piping will be galvanised mild steel piping which will be epoxy lined internally.
- The pump station will be equipped with a Motor Control Centre (MCC) and SCADA and it would be possible to monitor / control the pump station externally (Rundu WTP/ Windhoek Head Office).

- Hybrid energy supply: 70% grid power and 30% photovoltaic (PV) contribution. The pump station will be fed from the existing 11 kV reticulation. Supplementary photovoltaic (PV) power supply will also be provided. The PV power plant will be able to generate 30 % of the annual energy load of the pump station as allowed by the Electricity Control Board (ECB) of Namibia.

The pump station will pump the raw water from the river to the Base Pump Station pressure break reservoir which will be approximately 14.62 km from the river abstraction pump station.

7.1.3.3. Base Pump Station

The proposed Base Pump Station will be constructed approximately 14.62 km from the River Abstraction Pump Station and will include a 20 Ml concrete pressure break / storage reservoir.

The pumps will be housed in a brick building.

The base pump station will consist of five horizontal split casing centrifugal pumps installed in a four duty plus one standby configuration. Each pump will have a flow capacity of 2 430 m³/h at a total head of 130 m. The pump will be installed each with their own variable speed drive (VSD) and the operating voltage of the pump station will be 690 V. The total peak power required at the pump station will be approximately 5.25 MW. The VSD and the pump motors will be liquid cooled.

All piping will be galvanised mild steel piping which will be epoxy lined internally.

The pump station will be fed from a new proposed MV supply. Supplementary photovoltaic (PV) power supply will also be provided. The PV power plant will be able to generate 30 % of the annual energy load of the pump station as allowed by the ECB.

The pump station will pump the raw water from the Base Pump Station to the first inline booster pump station situated approximately 100.62 km from the Base Pump Station.

7.1.3.4. Booster Pump Stations

The booster pump stations will essentially be the same as the Base Pump Station with the only difference being that they will be in-line booster stations and will only have a pressure balancing reservoir at each station. The pressure balancing reservoir will have a capacity of 2 Ml and they are proposed to be concrete reservoirs.

It is proposed to install three inline booster pump stations along the pipeline route. The first being 100.62 km from the Base Pump Station, the second being 104.76 km from Booster Pump Station 1, and the third being 23.32 km from Booster Pump Station 2. The pipeline then ends at Uitzicht, which is then another 33.4 km away from the third inline booster pump station.

7.1.3.5. Pump Station and Termination Location

The table below provides the GPS coordination of each of the pump stations as well as the final termination point of the Okavango Link pipeline which is at Uitzicht near Grootfontein.

Table 32. CAN-Okavango Link Pump station and termination location.

Node No	Description	GPS Coordinate		Elevation amsl (m)
		South	East	
1	River Abstraction Pump Station	17.9095°	19.7613°	1 056.00
2	Base Pump Station	17.9788	19.7081°	1 120.78
3	Booster Pump Station 1	18.6285°	19.0862	1 188.91
4	Booster Pump Station 2	19.3385°	18.3684°	1 254.47
5	Booster Pump Station 3	19.4867°	18.2292°	1 373.73
6	Termination Point (Uitzicht / Start of the ENWC Canal)	19.6787°	17.9953°	1 477.43

It should be noted that the base as well as the booster pump station nodes positions and number are not fixed and may vary significantly depending on the final design of the DB contractor

7.1.3.6. Design Build Contract

The Okavango Link will be executed under a Design–Build (DB) contract. While the conceptual design provides the baseline configuration, the appointed contractor may recommend optimized solutions for pipeline materials, pressure classes, pump types, station locations, and power configurations, provided performance and environmental safeguards are maintained.

The final design will adhere to NamWater and ECB standards, ensuring long-term operational resilience, cost efficiency, and minimal ecological impact on the Okavango River system.

7.1.4 Climate Hazards

This section summarises how climate hazards may affect the Okavango Link water transfer system in Namibia. It focuses on the planned river intake, trunk main, pump stations and the Eastern National Water Carrier (ENWC) It compares the two scenarios Shared Socioeconomic Pathway 2–4.5 (SSP2–4.5) and Shared Socioeconomic Pathway 5–8.5 (SSP5–8.5) for two time periods: 2020–2039 and 2040–2059.

7.1.4.1. Temperature - Heatwaves and seasonal heat

Heat affects electrical and mechanical equipment, polymeric materials and operational productivity. The most sensitive elements are enclosed electrical rooms, motors and Variable Frequency Drives (VFDs), instrumentation and seals/gaskets.

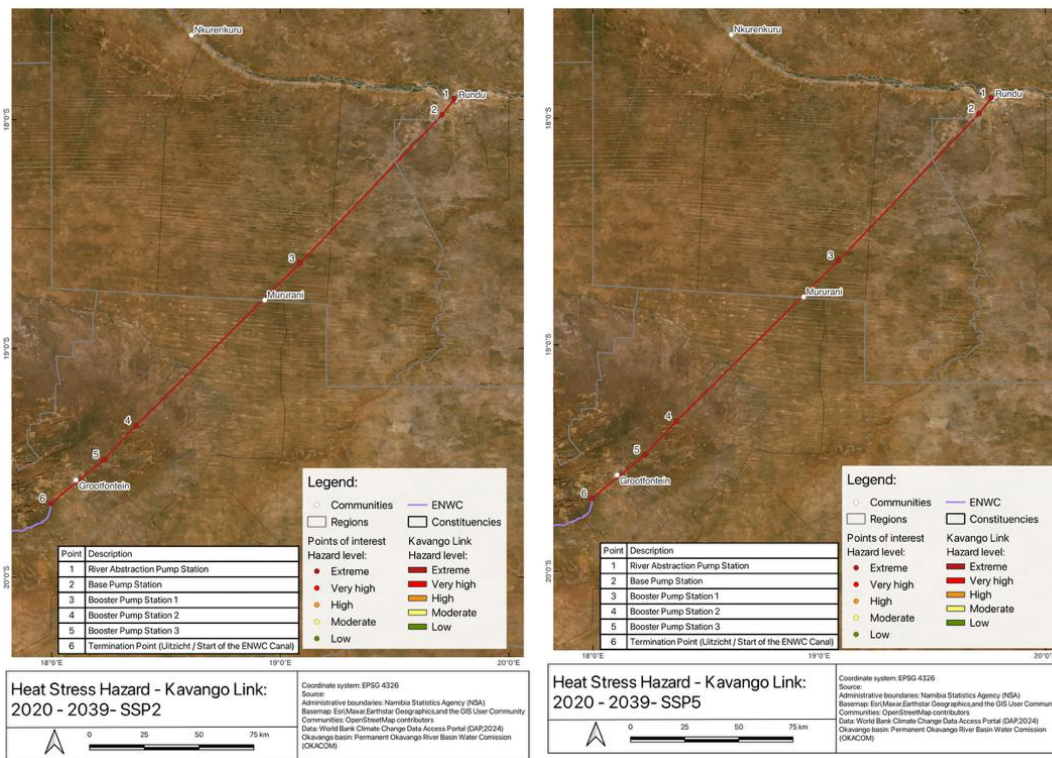
Impacts on assets

- Room overheating at pump stations and intake: higher ambient temperatures reduce Motor Control Centre (MCC) thermal headroom and increase Heating, Ventilation and Air Conditioning (HVAC) loads; Supervisory Control and Data Acquisition (SCADA) sensors may drift at high enclosure temperatures.
- Equipment derating: motors and Variable Frequency Drives (VFDs) require conservative ambient design temperatures; frequent hot days increase hours when derating applies.
- Material ageing: gaskets, liners and cable insulation age faster with heat cycles; expansion at above-ground spools requires flexibility and proper restraint.
- Operational productivity: prolonged hot spells reduce safe working hours for outdoor crews (hydration and rest cycles).

Assessment observations

- Intake and Base Pump Station show higher sensitivity to room overheating and sensor drift than buried pipeline reaches. Heat-related risk increases from 2020–2039 to 2040–2059 and is higher under SSP5–8.5 than under SSP2–4.5 for the same period.
- Booster 1 and Booster 2 electrical rooms show similar patterns; buried pipe is largely insensitive to heat except for polymeric appurtenances. SSP5–8.5 yields more very hot days and longer clusters of hot days than SSP2–4.5.
- Booster 3 and the Eastern National Water Carrier (ENWC) interface have moderate sensitivity; long-term (2040–2059) conditions push room heat balances closer to limits, particularly under SSP5–8.5.

Figure 55. Heat Stress Hazard. Kavango Link-CAN Water Supply Project 2020-2039. SSPs 2-4.5 (left) and SSPs 5-8.5(right). Source: the author.



7.1.4.2. Fluvial flooding - River stage and duration

River flooding is most critical at the intake (S0). High stages increase debris loading, bank instability and the probability of platform inundation and access loss. Prolonged elevated water levels raise sediment deposition in the sump and challenge safe operations.

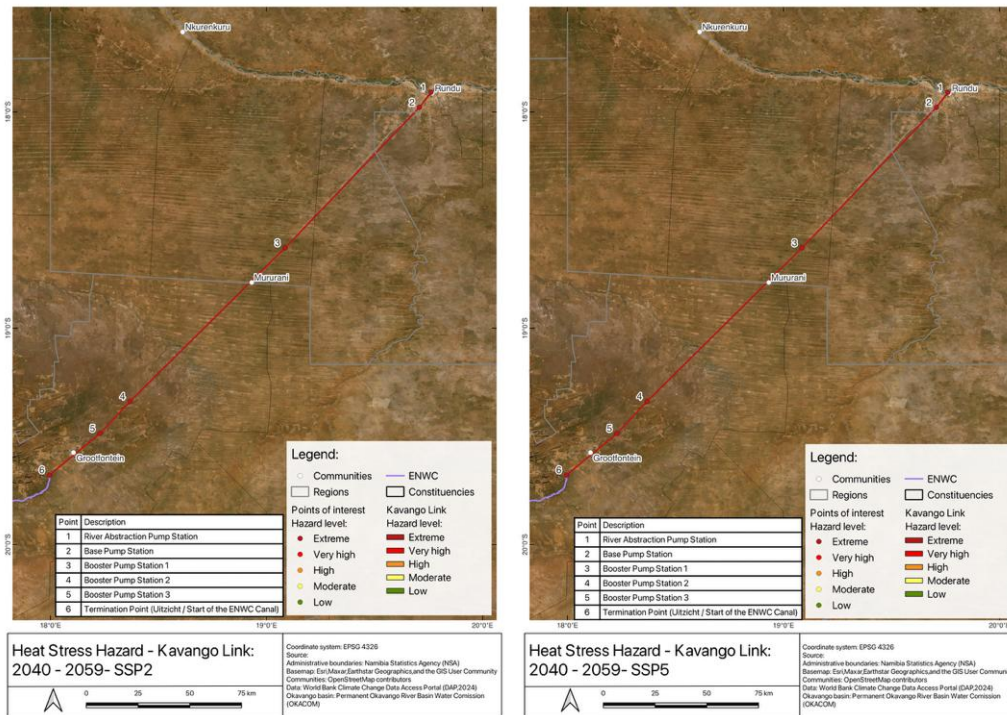
Impacts on assets

- Intake platform overtopping or near-overtopping; debris rafts impacting screens and structures; increased sediment load in the sump and manifold.
- Bank erosion and instability near the intake works; damage to riprap, armour and toe protection; access jetty submergence.
- Electrical exposure if Motor Control Centre (MCC) rooms and cable routes at the intake are not sufficiently elevated or sealed.
- Access constraints due to submerged roads and culverts during high river stages.

Assessment observations

- Fluvial flood risk dominates physical and service-delivery dimensions. For the same period, SSP5–8.5 shows higher likelihood of platform level exceedance than SSP2–4.5. Moving from 2020–2039 to 2040–2059 increases floodplain activation frequency and inundation duration.
- Fluvial flooding is secondary; effects are indirect (for example, delayed access) rather than direct asset damage.

Figure 56. Heat Stress Hazard. Kavango Link-CAN Water Supply Project 2040-2059. SSPS 2-4.5 (left) and SSPS 5-8.5(right). Source: the author.



7.1.4.3. Pluvial flooding – Short-duration high-intensity rainfall

Short, intense storms drive local flooding and drainage exceedance at platforms, valve chambers and crossings. The main sensitivities are chamber inflow, erosion at outfalls and bedding washout at sag points.

Impacts assets

- Chamber inflow through covers and penetrations; need for dewatering and temporary isolation of local reaches.
- Erosion of side drains and outfalls; washout of bedding at culverts and track crossings; scouring at ephemeral channels.
- Temporary loss of access to stations and valve sites due to surface water and soft ground.

Assessment observations

- Pluvial flooding is a primary driver. For a given period, SSP5–8.5 shows larger increases in short-duration design rainfall than SSP2–4.5, raising exceedances of drain capacity and chamber ingress. From 2020–2039 to 2040–2059, the frequency of isolation and dewatering events increases in both scenarios.
- On steeper sections, exceedance of drain capacity couples with erosion and slope processes; see the next section.
- Relevant for platform drainage and chambers but secondary to other drivers.

7.1.4.4. Slope instability and erosion

In the transition to the Otavi Highlands (S4), steeper spot slopes and undulations increase sensitivity to rilling, gullying and trench wall sloughing during intense rainfall.

Impacts on assets

- Loss of cover and exposure of the pipe; displacement of anchor and thrust blocks; need to restabilise trenches with geotextile or geogrid.
- Scour at drain outfalls and crossings; sedimentation of culverts; embankment erosion affecting access and safety.
- Local isolation of pipeline reaches to complete repairs and reinstate cover and restraints.

Assessment observations

- Risk rises under SSP5–8.5 relative to SSP2–4.5 for the same period. From 2020–2039 to 2040–2059, the number and severity of short-duration storms increase, raising repair frequency and affected reach length.
- Other segments: mainly minor effects focused on outfalls and small embankments on localised steeper ground.

7.1.4.5. Strong winds, dust storms and convective storms

Wind-blown dust increases enclosure temperatures by clogging filters and reduces reliability of outdoor cabinets. Gusts load small structures. Convective storms bring lightning and electrical surges that can trip controls and communications.

Impacts on assets

- Ingress of dust into electrical rooms and cabinets; reduced cooling performance; higher failure rates for electronics and sensors.
- Gust loading on masts, shelters, fencing and small structures; increased inspection and tightening cycles.
- Lightning and surge effects on low-voltage and medium-voltage panels, Supervisory Control and Data Acquisition (SCADA) and telemetry.

Assessment observations

- Stations and interface facilities are moderately sensitive. For a given period, SSP5–8.5 shows more windy and dusty days and stronger convective activity than SSP2–4.5. From 2020–2039 to 2040–2059 there is a gradual increase, shortening maintenance intervals for filtration and inspections.

Figure 57. Flash Flood Hazard. Kavango Link-CAN Water Supply Project 2020-2039: SSPs 2-4.5 (left) and SSPs 5-8.5(right). Source: the author.

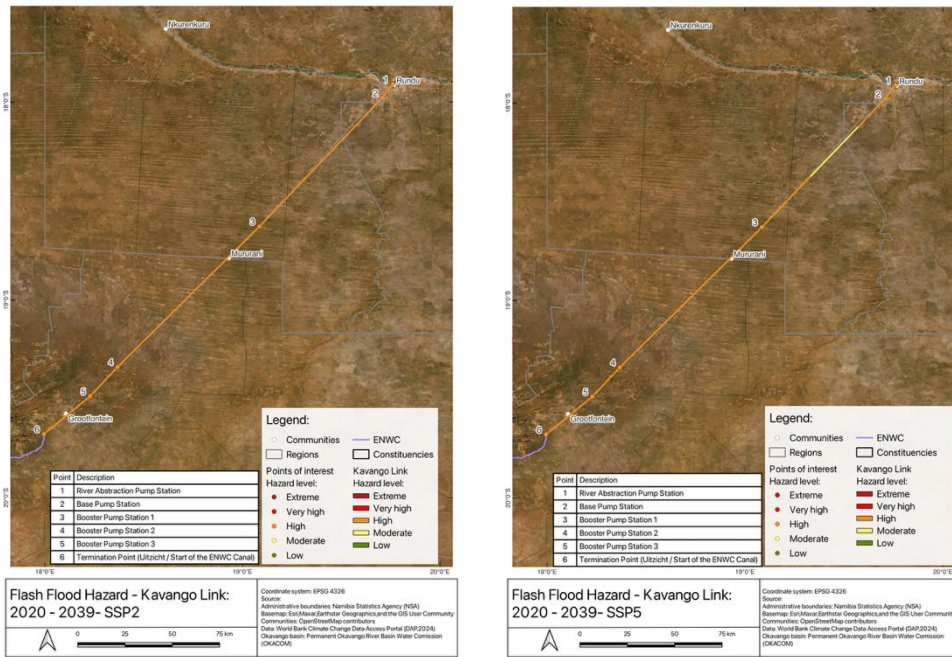
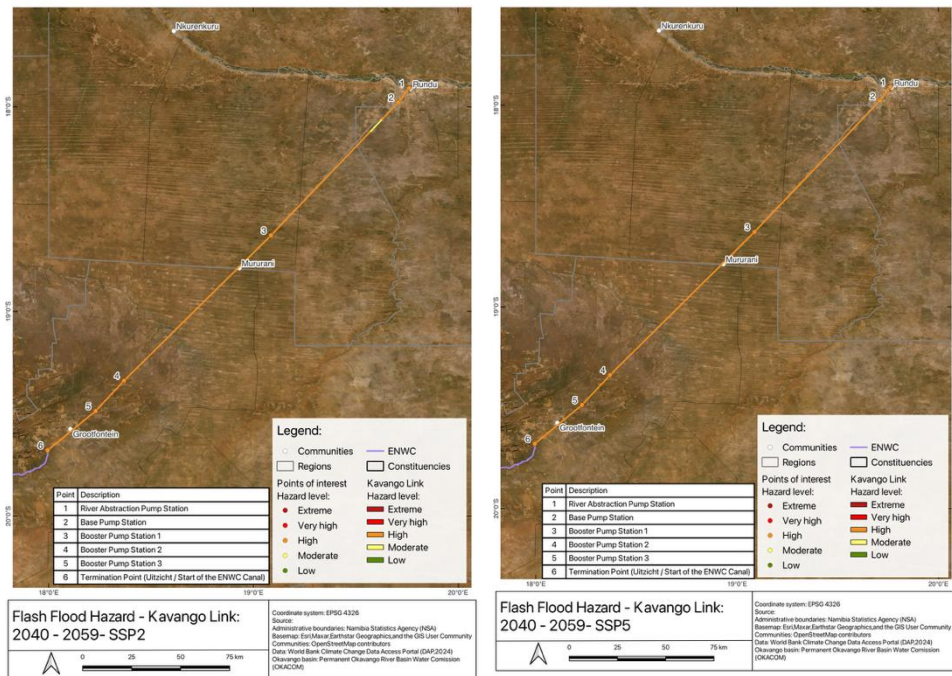


Figure 58. Flash Flood Hazard. Kavango Link-CAN Water Supply Project 2040-2059: SSPs 2-4.5 (left) and SSPs 5-8.5(right). Source: the author.



7.1.4.6. Drought – Multi-season low-flow conditions

Sustained low flows affect intake operability. Reduced suction head increases the risk of cavitation and intake outages; sediment concentrations may rise and cause wear. Lower efficiencies at pumps increase energy costs.

Impacts on assets

- Intake downtime where operational abstraction thresholds are not met, need for curtailment rules and storage buffering at the system level.
- Higher sediment in approach flow with low stages; increased wear on pumps and screens; more frequent cleaning cycles.
- Higher specific energy consumption due to lower pump efficiencies at low heads.

Assessment observations

- Most sensitive to drought. For the same period, SSP5–8.5 tends to show more frequent seasons below operational thresholds than SSP2–4.5. The long-term period 2040–2059 increases the likelihood and persistence of low-flow constraints relative to 2020–2039.
- Downstream segments: impacts are indirect (for example, service-delivery reductions propagated from intake constraints).

7.1.4.7. Wildfire

Wildfire threatens surface appurtenances and restricts access. Smoke and ash can affect filters and outdoor instrumentation. Buried pipelines are generally insulated from direct thermal damage unless exposure occurs due to erosion.

Impacts on assets

- Damage to fencing, cable trays and external cabling near stations; heat effects on exposed polymeric components.
- Temporary loss of access for inspections and repairs; smoke and ash loading of filters and chambers.
- Potential short-term water-quality effects at the intake following catchment burns, requiring process adjustments.

Assessment observations

- Most relevant along vegetated servitudes. Similar likelihood in both scenarios for 2020–2039, with a slight increase in 2040–2059, stronger under SSP5–8.5.

Figure 59. Drought Hazard. Kavango Link-CAN Water Supply Project 2020-2039: SSPs 2-4.5 (left) and SSPs 5-8.5(right). Source: the author.

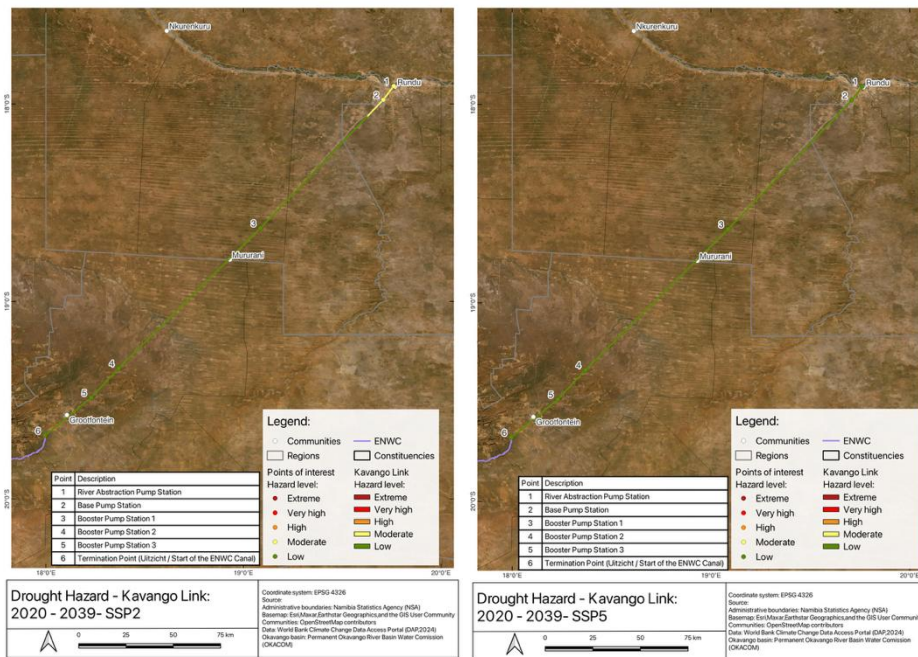


Figure 60. Drought Hazard. Kavango Link-CAN Water Supply Project 2040-2059: SSPs 2-4.5 (left) and SSPs 5-8.5 (right). Source: the author.

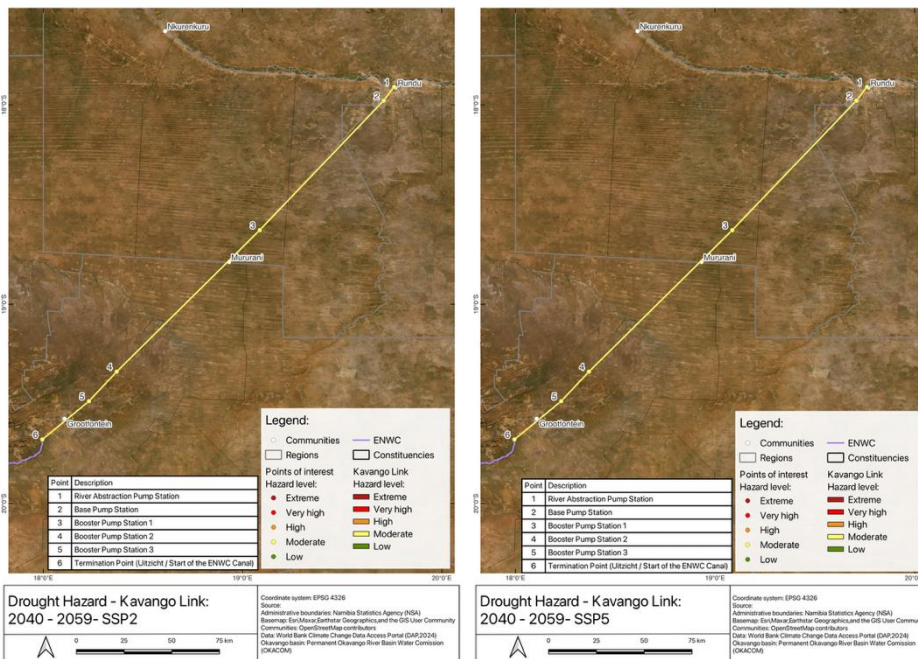


Table 33. Climate hazard summary and rationale.

Climate hazard	Hazard level	Rationale	Comment	Hazard Rating 2020-2039		Hazard Rating 2040-2059	
				SSPS 2 4.5	SSPS 5 8.5	SSPS 2 4.5	SSPS 5 8.5
Heat Stress (Heatwaves and extreme heat)	<ul style="list-style-type: none"> Frequency: percentage of days above the 90th percentile of daily maximum temperature (% days above P90 daily Tmax). Intensity: change in the 90th percentile of daily maximum temperature (ΔT_{90}, in °C). Duration: heatwaves of three or more consecutive days above P90 (≥ 3 consecutive days > P90). Moist-heat constraint: number of days with Wet-Bulb Globe Temperature (WBGT) above 28–30 °C. 	<ul style="list-style-type: none"> Rising temperatures push pump motors and Variable Frequency Drives (VFDs) toward thermal limits. Heating, Ventilation and Air Conditioning (HVAC) demand increases in Motor Control Centre (MCC) and control rooms. Seals and polymer liners age faster; above-ground pipework sees expansion cycles. Supervisory Control and Data Acquisition (SCADA) sensors can drift at enclosure over-temperature; crew productivity falls during prolonged hot spells. 	<ul style="list-style-type: none"> Maintain electrical rooms at or below 35–40 °C with HVAC and dust-filtered positive pressure; provide shading and insulation. Select heat-tolerant components (seals and gaskets rated at or above 60 °C). Allow thermal expansion at any above-ground pipework. Schedule heavy maintenance for cooler hours. 	4	5	5	5
Droughts (Multi-season rainfall deficits).	<ul style="list-style-type: none"> Frequency: years with flow below operational abstraction threshold. Intensity: magnitude of low-flow deficit vs design intake capacity. Duration: multi-season deficits affecting supply reliability. 	<ul style="list-style-type: none"> Reduced dependable river levels cut available abstraction days and raise sediment at the intake. Energy per cubic meter rises as hydraulic efficiencies drop; Operations and Maintenance (O&M) workload increases. 	<ul style="list-style-type: none"> Operate to a seasonal abstraction rule with curtailment triggers and storage buffering. Strengthen screening and sediment management at the intake; monitor upstream basin conditions to plan transfer windows. Coordinate operating rules at the Eastern National Water Carrier (ENWC) interface for blending and buffering. 	1	1	2	2

Climate hazard	Hazard level	Rationale	Comment	Hazard Rating 2020-2039		Hazard Rating 2040-2059	
				SSPS 2	SSPS 4.5	SSPS 2	SSPS 4.5
				2	4.5	4.5	5.8.5
Pluvial Flash Floods (short-duration, high-intensity rainfall)	<ul style="list-style-type: none"> Frequency: change in occurrence of 1–24 h heavy rainfall events (P95–P99). Intensity: design rainfall depth increases for short durations (IDF shift). Exposure: sag points, station platforms, culvert crossings. 	<ul style="list-style-type: none"> Ponding and inflow can flood platforms and chambers; side drains and embankments erode. Local washouts at culverts or tracks can expose or undermine the trunk main. Short service interruptions are common when platforms or chambers take water. 	<ul style="list-style-type: none"> Set Finished Floor Level (FFL) at or above the local 1-in-100-year design flood (Q100) plus freeboard. Grade and line side drains where permissible velocities are exceeded, fit sealed covers and sump pumps for buried chambers. Provide adequate cover and scour protection at crossings; size access-road culverts to pass design flows without backwater. 	3	3	3	3
Fluvial Floods	<ul style="list-style-type: none"> Frequency: years activating the floodplain in the Rundu reach. Intensity: river stage relative to Q100–Q200 reference and associated depth and velocity. Duration: sustained high stages lasting weeks to months. 	<ul style="list-style-type: none"> High stages can overtop intake platforms, degrade banks and restrict access. Debris rafts and sediment loads impact screens and sumps; electrical systems are at risk if not elevated. 	<ul style="list-style-type: none"> Set platforms at or above Q100 with a climate-change allowance and 0.5–1.0 m freeboard. Armour banks and toes; install debris deflectors or booms and easy-clean screens. Ensure flood-safe access and rapid debris-management protocols for peak-flow periods. 	2	2	2	2
Strong winds and storms (including dust storms)	<ul style="list-style-type: none"> Frequency: windy days above a high percentile 	<ul style="list-style-type: none"> Dust ingress elevates enclosure temperatures and 	<ul style="list-style-type: none"> Pressurise electrical rooms with high-efficiency filtration, for example Minimum 	3	3	4	5

Climate hazard	Hazard level	Rationale	Comment	Hazard Rating 2020-2039		Hazard Rating 2040-2059	
				SSPS 2 4.5	SSPS 5 8.5	SSPS 2 4.5	SSPS 5 8.5
	<p>threshold and the frequency of dust events.</p> <ul style="list-style-type: none"> Intensity: peak gusts and airborne particle concentrations. Secondary hazard: lightning and power quality disturbances during convective storms. 	<p>raises failure rates for sensitive equipment.</p> <ul style="list-style-type: none"> Gusts load lightweight structures such as fences, shelters and Photovoltaic (PV) arrays; PV output can drop during pumping windows. Storm surges and lightning increase failure and trip risks for controls and communications. 	<p>Efficiency Reporting Value (MERV) 13 or higher.</p> <ul style="list-style-type: none"> Use outdoor enclosures with Ingress Protection (IP) 66 or National Electrical Manufacturers Association (NEMA) 4X ratings. Install Surge Protective Devices (SPDs) on Low Voltage (LV) and Medium Voltage (MV) panels and on Supervisory Control and Data Acquisition (SCADA); brace small structures; formalise PV inspection and cleaning; adopt work-stoppage rules during severe storms. 				
Wildfires	<ul style="list-style-type: none"> Frequency: days with elevated fire-weather and historical ignition density. Intensity: expected flame length and rate of spread under peak conditions. Exposure: vegetated servitudes and the perimeter of stations. 	<ul style="list-style-type: none"> Fire threatens exposed cable trays, fencing and surface appurtenances, smoke and ash foul intakes and filters. Temporary access restrictions for Operations and Maintenance (O&M) are likely during events. 	<ul style="list-style-type: none"> Maintain 10–20 m firebreaks along servitudes and around stations; prefer non-combustible cladding and cable routing where feasible. Pre-position extinguishers and adopt seasonal patrols; add ash and turbidity steps to emergency O&M and intake screening plans; coordinate with local fire services. 	3	3	4	4
Slope Instability & Erosion	<ul style="list-style-type: none"> Exposure: segments with slopes >10% (moderate) and >30% (high). 	<ul style="list-style-type: none"> Loss of cover/pipe exposure; thrust block displacement; trench instability. 	<ul style="list-style-type: none"> Apply lined side drains, berms and drop structures; reno mattresses/geocells on vulnerable slopes. 	4	5	5	5

Climate hazard	Hazard level	Rationale	Comment	Hazard Rating 2020-2039		Hazard Rating 2040-2059	
				SSPS 2 4.5	SSPS 5 8.5	SSPS 2 4.5	SSPS 5 8.5
	<ul style="list-style-type: none"> • Trigger: intense rainfall events and concentrated runoff. • Indicators: rilling, gullying, and trench wall sloughing. 	<ul style="list-style-type: none"> • Scour at drain outfalls and crossings; sedimentation of culverts. 	<ul style="list-style-type: none"> • Anchors/thrust blocks and trench stabilisation (geotextile/geogrid). • Maintenance plan for post-storm inspections and rapid repairs. 				

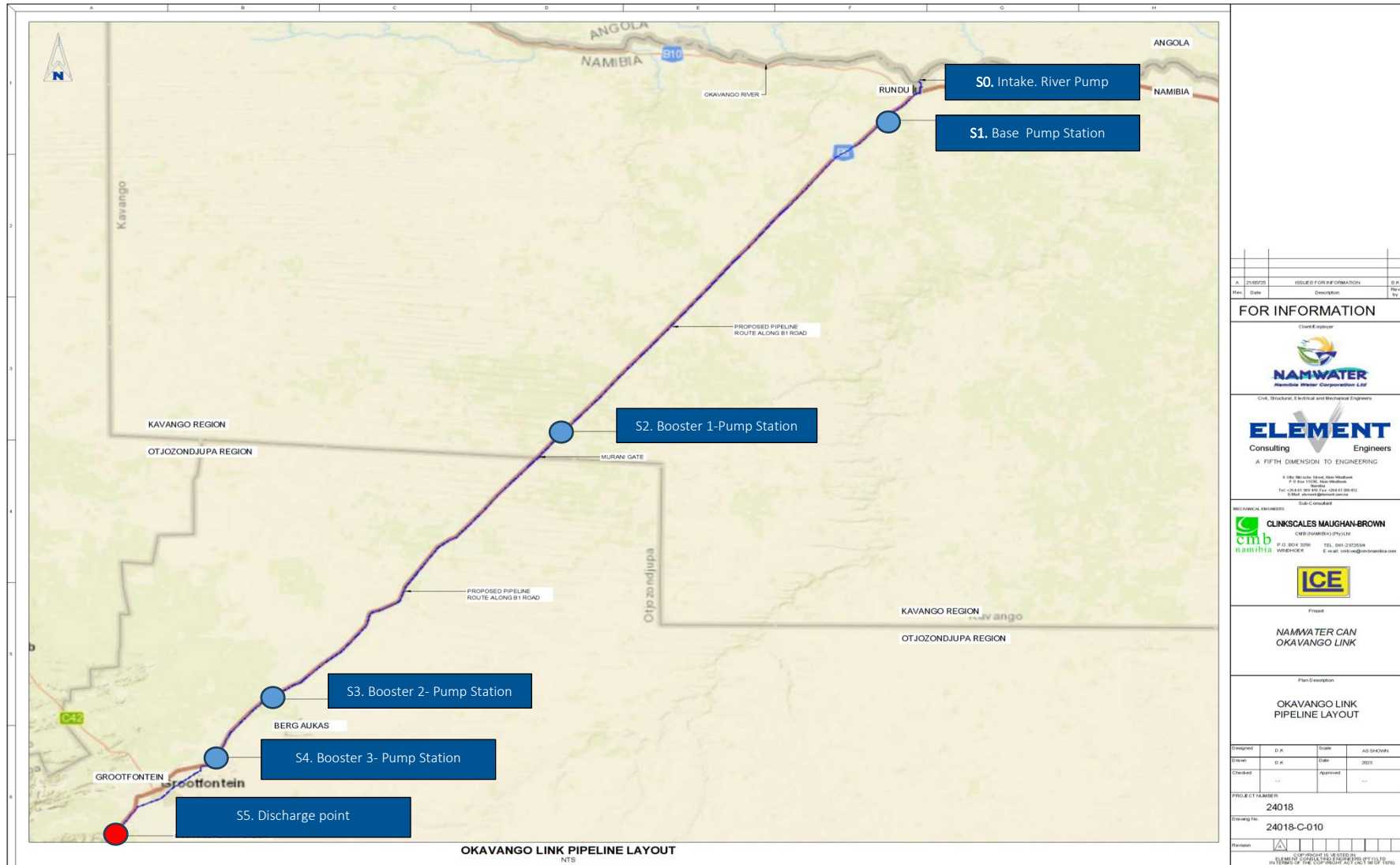
7.2 Assessment of Climate Risks for the Kavango Link Raw-Water Transfer

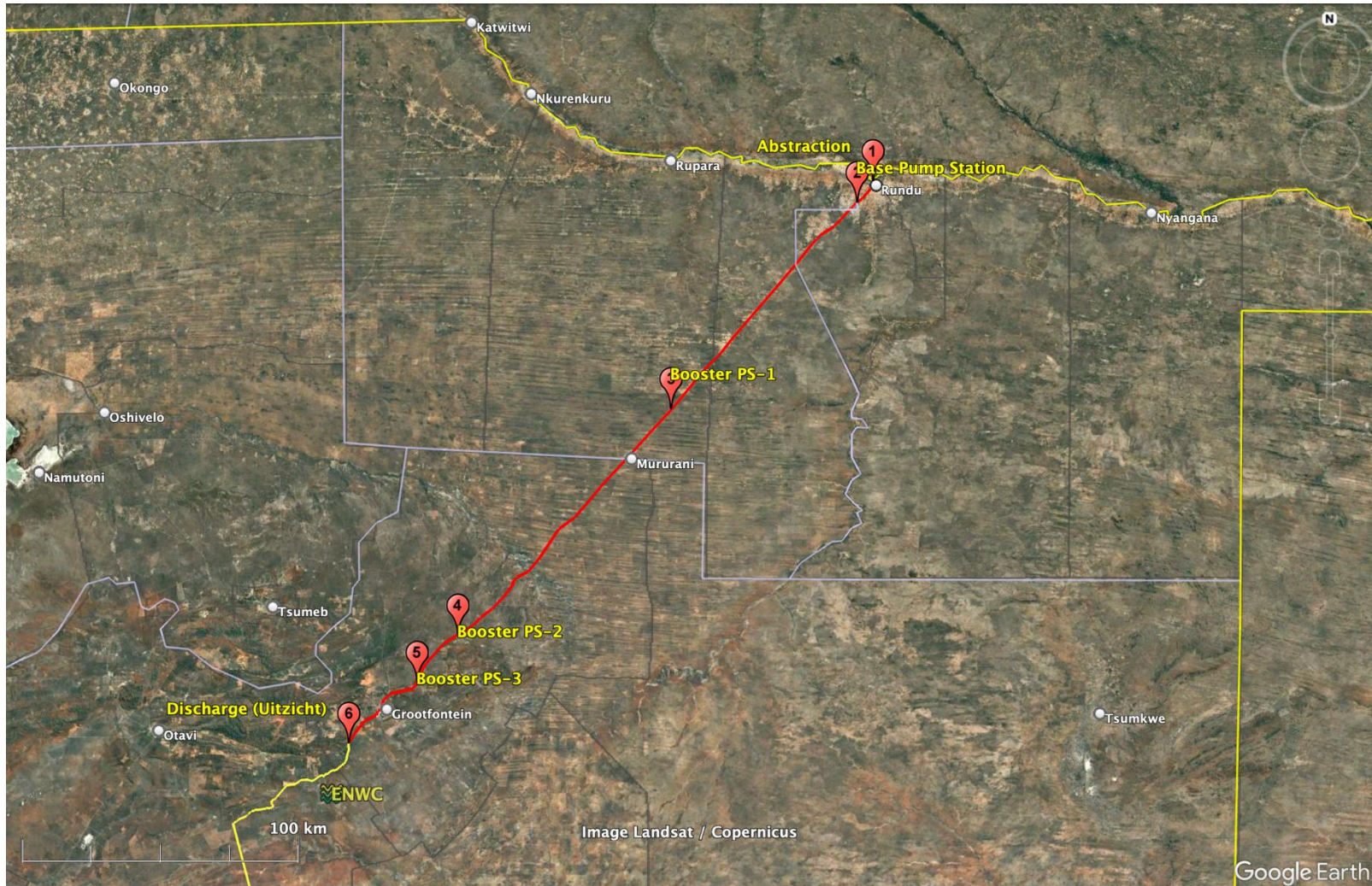
The Kavango Link will abstract raw water from the Okavango River at Rundu and convey it approximately 276–277 km south-west to tie into the ENWC near Grootfontein, supporting the CAN system. The conceptual design includes a new river intake and pump station, a predominantly buried trunk pipeline (DN 1 800 mm or 2 × DN 1 300 mm alternative), and a sequence of base and booster pump stations. Operation targets up to 2 700 L/s during a seasonal abstraction window (up to 180 days/year).

Table 34. Components for risk assessment

Asset/Infrastructure Elements	Comments / relevant information
Note: the following are real components of the assets considered in this CVRA. The information provided by past reports and industry/research literature was used to establish this list	
River intake & low-lift	
River intake & low-lift	Approach, screens (coarse/fine), intake sump, low-lift pumps, intake pipeline, bank protection, flood walls/berms, debris deflectors, access jetty/crane, standby power, lightning protection.
Raw-water transmission pipeline	
Raw-water transmission pipeline	Buried DN 1 800 (or 2×DN 1 300) trunk; line valves, air valves, scour valves; thrust blocks/anchors; culvert/bridge protections; cathodic protection (if steel); trench stabilisation; surge mitigation hardware per transient analysis.
Pump stations (base + boosters)	
Pump stations (base + boosters)	Pumps/motors (VFDs where applicable), suction/discharge manifolds, surge relief devices, HVAC/ventilation, transformers/switchgear/MCC, UPS/SCADA, diesel standby, stormwater & oily-water drainage, building envelope.
Balance tanks / break-pressure (if included)	Small reservoirs for hydraulic management, flow regulation, surge control; optional chlorination dosing point for biofouling control.
ENWC interface	
ENWC interface	Tie-in structures, metering and control to ENWC; dependency on canal condition/losses and downstream dam operations.
Temporary works & construction access	
Temporary works & construction access	Laydown areas, temporary cofferdams at intake, detours/access tracks, dewatering.
Power supply to stations	
Power supply to stations	Overhead/underground feeders, substations/transformers, earthing and surge protection.
O&M and access	
O&M and access	O&M staff, vehicles, section access along B8 corridor, riverbank access at intake, safety equipment and procedures.

Figure 61. Kavango Link. CAN Water Supply Project (Rundu – Grootfontein). Source: Element Consulting Engineers





7.2.1. Proposed Segmentation for the Kavango Link

To assess climate exposure and design requirements coherently, the Okavango–ENWC corridor was divided into six (6) geo-climatic and functional segments (S0–S5). Boundaries follow natural changes in terrain and hazard regime such as floodplain, Kalahari plains and the Highlands transition, and they align with operational nodes including the intake, pump stations and the ENWC tie-in.

This yields homogeneous stretches for CRA scoring and practical works packages, while chainage is referenced from kilometer 0 at the Rundu intake: **S0 - Okavango Intake and River Pump Station**: Riverbank and active floodplain at Rundu where fluvial levels, bank stability and access control dominate design; **S1 - Floodplain Transition to Base Pump Station**: Gently rising ground outside the floodplain, largely parallel to the B8, carrying the initial rising main to the Base Pump Station; **S2 - Northern Kalahari Plains** (Base PS to Booster 1): Low-relief Kalahari sands with predominantly buried trunk main; local low points prone to ponding and dust exposure; **S3 - Central Kalahari** (Booster 1 to Booster 2): Long uniform profiles with multiple ephemeral channel crossings and higher sensitivity to hydraulic transients during power or pump trips; **S4 - Transition to Otavi Highlands** (Booster 2 to Booster 3): Increasing undulation and local cut or fill with steeper spot slopes, elevating risks of erosion, scour and trench stability; **S5 - ENWC/Uitzicht Interface** (Booster 3 to Tie-in): Gentle approach to Grootfontein where interface hydraulics, measurement and control, and integration with ENWC operations are the focus.

Table 35 and figure 63 below presents the proposed segmentation (S0 to S5) with chainage, topo-climatic features, critical assets and dominant climate hazards used for CRA scoring and works packaging.

Table 35. Proposed Segmentation for the analysis (S0–S5) for CRA Scoring and Works Packaging

N°	Segment	Approx. Chainage (km)	Topographic, Climatic & Functional Feature	Critical Assets
S0	Okavango Intake and River Pump Station	0–0.5 Km	Riverbank/floodplain at Rundu; bank levels and protection; fluvial access constraints.	<ul style="list-style-type: none"> • Intake works: bar racks and screens (coarse and fine), debris boom and deflectors, intake sump, low-lift pumps and manifolds, lifting and gantry equipment. • Civil and river works: intake platform and access jetty, bank protection (riprap and armour) with toe, flood berms, scour aprons, access road and culverts. • Electro-mechanical and control: motors, variable frequency drives (VFDs), motor control center (MCC), switchboard, earthing and lightning protection, surge protective devices, Supervisory Control and Data Acquisition (SCADA) panels, sensors and level instruments. • Enclosures and services: electrical room with heating, ventilation and air conditioning (HVAC) and filtration, sealed cable entries, sealed chamber covers, sump pumps.
S1 (1-2)	Floodplain to Base Pump Station (BPS)	0.5 - 14.9 Km	Gentle terrain outside floodplain; corridor near B8; initial rising main to Base Pump Station (BPS).	<ul style="list-style-type: none"> • Buried trunk main: pipe barrel and joints and gaskets, external coatings and cathodic protection (if applicable), anchor and thrust blocks, bedding and backfill, servitude markers. • Appurtenances: air-release valves at crests, scour and washout valves at low points, line isolation valves, chambers (covers and drainage). • Crossings and drainage: road and track and culvert crossings, side drains and soakaways. • Base Pump Station: pumps, VFDs, MCC, switchgear, surge vessel or relief, manifolds and

N°	Segment	Approx. Chainage (km)	Topographic, Climatic & Functional Feature	Critical Assets
				strainers, HVAC and filtration for the electrical room, SCADA and telemetry, building and civil drainage, on-site flow and pressure metering.
S2 (2-3)	Northern Kalahari Plains (BPS to PS-Booster 1)	15 - 95 Km	Low-relief Kalahari sands. Predominantly buried pipe. Intermittent low points.	<ul style="list-style-type: none"> • Trunk pipeline (long reach): pipe and joints, external protection, anchor blocks, bedding and backfill in sandy soils, settlement and void risk points. • High and low points: frequent air-valve assemblies and washouts; valve chambers with sealed covers and sump pumps. • Crossings and access: culvert and track crossings, scour protection at outfalls, patrol and access tracks. • Booster 1 Pump Station: pumps, VFDs, MCC, surge vessel or relief, manifolds, HVAC and filtration, SCADA and telemetry mast, fencing and firebreaks.
S3 (3-4)	Central Kalahari (Pump Station Booster 1 to Booster 2)	95 - 175 Km	Long uniform profiles. Multiple ephemeral channel crossings.	<ul style="list-style-type: none"> • Pipeline (surge-sensitive reach): continuous pipe sections, isolation valves, air valves at grade breaks, scour valves at lows, surge checks for pump or power trips. • Ephemeral crossings: culverts and low-level crossings, invert protection, energy dissipation, bed and bank armoring, utility supports where needed. • Booster 2 Pump Station: pumps, VFDs, MCC, surge vessel or relief, manifolds, HVAC and filtration, SCADA and telemetry, backup communications, access drainage.
S4 (4-5)	Transition to Otavi Highlands (PS-Booster 2 to PS-Booster 3)	175 - 245 Km	More pronounced undulations and local cut/fill. Steeper spot slopes.	<ul style="list-style-type: none"> • Pipeline on undulating ground: pipe, joints and restraint systems, anchor and thrust blocks at steeper grades and bends, trench stabilisation with geotextile or geogrid where needed. • Drainage and erosion control: side drains and lined outfalls, erosion and scour control using reno mattresses or geocells at vulnerable slopes. • Crossings: road and culvert protections, gabions and riprap where velocities exceed permissible. • Booster 3 Pump Station: pumps, VFDs, MCC, surge control, manifolds, HVAC and filtration, SCADA, platform drainage and slope protection around the site.
S5 (5-6)	ENWC/Uitzicht Interface (PS-Booster 3 to Discharge point)	245 -276.7 km	Gentle approach to Grootfontein. Interface hydraulic controls.	<ul style="list-style-type: none"> • Interface works: control and measurement chamber (flow meters; pressure control or pressure reducing valves), energy dissipation and energy break structures, surge relief tank or valve, tie-in spools and isolation valves, bypass arrangement, thrust blocks, chamber sealing and dewatering, instrumentation (pressure and flow transmitters) linked to SCADA. • Integration items: telemetry link to the Eastern National Water Carrier (ENWC) control, sample points and quality monitoring, access hardening and drainage.

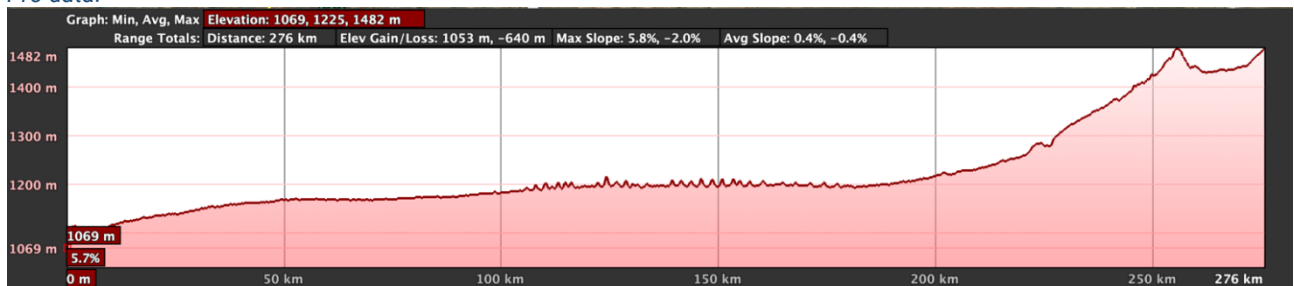
From a climate-hazard perspective, the six segments (S0–S5) correspond to distinct exposure regimes. S0 (Okavango intake and river pump station) lies within the lower Okavango floodplain and is dominated by fluvial flooding and pluvial flash-flooding, with secondary exposure to storms and debris loads. S1 and S2 (urban and peri-urban corridor south of Rundu) are still influenced by riverine flooding at low-lying crossings but progressively transition to a regime controlled by pluvial flash floods and surface runoff on Kalahari sands. S3 and S4 traverse the elevated Kalahari plateau where drought, heat stress and wind- and dust-storms are the primary hazards, with only localised flash flood sensitivity at ephemeral channels and depressions. S5, near the ENWC interface, retains this heat- and drought-dominated profile but benefits from relatively low fluvial-flood hazard due to the distance from major rivers. These contrasted hazard regimes underpin the segment-level risk scoring summarised in Table 37 and guide the localisation of design checks in the following sections.

Figure 63 below presents the proposed segmentation (S0 to S5) used for CRA scoring and works packaging and figure 11-17 gives the longitudinal profile by segment with chainage.



Figure 63. Segmentation of the Kavango Link alignment (S0–S5).

Figure 64. Longitudinal profile of the Kavango Link-CAN water project. Source: consultant’s elaboration using Google Earth Pro data.



The Okavango Link – CAN Water Project covers a total distance of approximately 277 km, stretching from Rundu (elevation 1,069 m amsl) on the Okavango River to Uitzicht near Grootfontein (1,482 m amsl). The general topographic gradient is gentle to moderate, with an average slope of 0.4% and a maximum local slope of 5.8%.

From Rundu to Grootfontein, the elevation progressively increases by around 413 m, reflecting a gradual ascent across the Kalahari landscape. The first 180 km of the alignment run through relatively flat terrain with minor undulations typical of the Northern Kalahari Sand Plateau, while the last 90 km present a more pronounced elevation gain as the route climbs toward the Central Plateau.

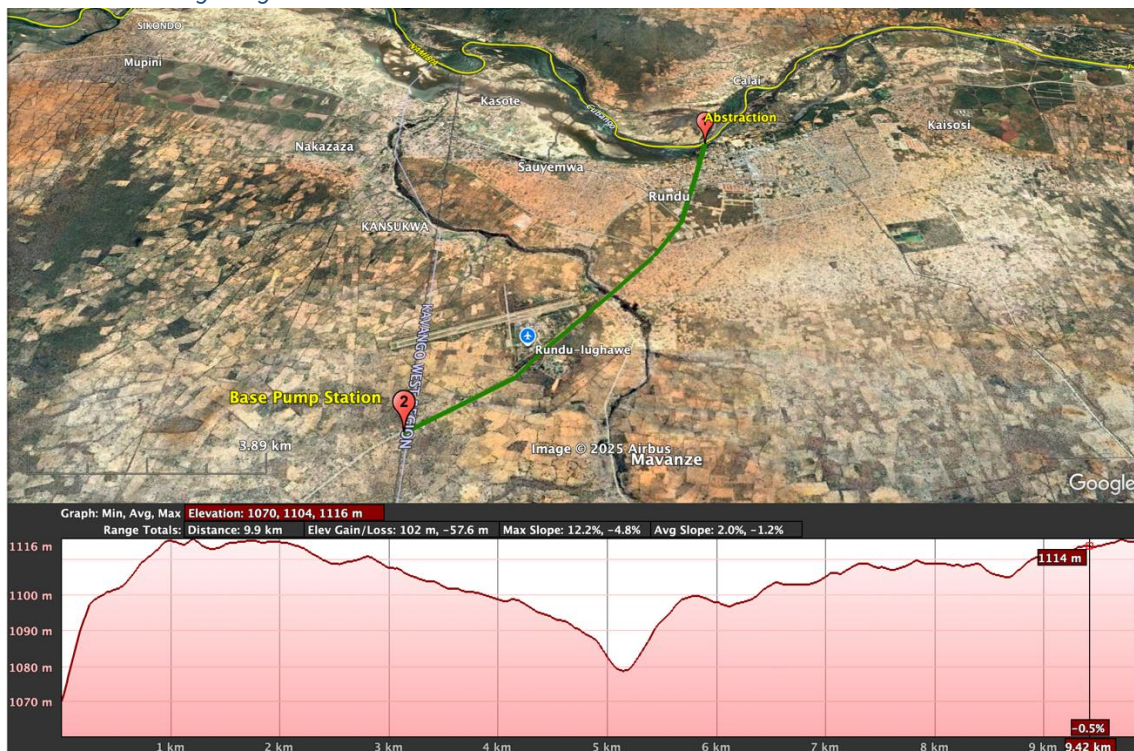
Although the overall gradient is moderate, the local slope variations—particularly in the final third of the alignment—imply increasing pumping head requirements and a need for pressure regulation along the pipeline. These conditions justify the inclusion of three in-line booster pump stations to maintain stable flow and operational efficiency.

The gentle to moderate relief is favorable for pipeline construction and maintenance, but localized depressions and undulating terrain near Rundu and the transitional plateau zones may require specific engineering considerations, such as:

- Enhanced drainage control to prevent local flooding during heavy rainfall events.
- Slope stabilization in sections exceeding 5% gradient to mitigate erosion risks.
- Careful management of pipeline anchoring and thrust blocks to accommodate variable pressure due to elevation change.

Section S1: Abstraction to Base Pump Station (0–10 km). This initial section connects the River Abstraction Pump Station at 1,069 m amsl to the Base Pump Station at 1,116 m amsl, spanning approximately 9.9 km. The maximum slope (12.2%) occurs near the riverbank, where the terrain rises sharply from the floodplain before stabilizing toward the inland plateau. This segment represents the steepest localized gradient in the entire alignment. The slope immediately downstream of the abstraction point will require erosion protection, particularly at the intake and along the first kilometers of the pipeline. The elevated terrain also imposes high initial pumping head requirements, which the design accommodates through the dedicated Base Pump Station located outside the flood-prone area.

Figure 65. Longitudinal profile of the Section n°1 (S1). Kavango Link-CAN water project. Source: consultant's elaboration using Google Earth Pro data.



Section S2: Base Pump Station to Booster Pump Station 1 (10–98 km). Section S2 extends over 98 km from the Base Pump Station (1,116 m amsl) to Booster PS-1 (1,202 m amsl). The profile shows a gradual ascent with an average slope of 0.3%, typical of the Kalahari plains. Elevation changes are smooth, with a maximum local slope of 3.1%. This section is favorable for buried pipeline installation and presents minimal geotechnical constraints. However, the flatness of the terrain implies low natural drainage, which may result in localized ponding or shallow flooding during heavy precipitation. Proper trench compaction, bedding materials, and drainage channels should be incorporated to maintain pipeline integrity and accessibility.

Figure 66. Longitudinal profile of the Section n°2 (S2). Kavango Link-CAN water project. Source: consultant's elaboration using Google Earth Pro data.



Section S3: Booster Pump Station 1 to Booster Pump Station 2 (98–209 km). Covering roughly 111 km, this section rises from 1,189 m to 1,256 m amsl, with an average slope of 0.6% and a maximum slope of 3.9%. The topography alternates between low ridges and shallow valleys, characteristic of transition zones between the Kalahari and Central Plateau. The modest but continuous elevation gain increases energy consumption and pumping pressure requirements. Minor elevation fluctuations may necessitate air release and drain valves at strategic points to prevent air locks and ensure hydraulic stability.

Section S4: Booster Pump Station 2 to Booster Pump Station 3 (209–232 km). This section spans 22.6 km with an elevation increase from 1,256 m to 1,374 m amsl, representing a moderate gradient (average slope 1.0%, maximum slope 3.5%). The route climbs steadily toward the Central Plateau, indicating the beginning of the project's most energy-intensive segment. The slope here may increase pipeline internal pressure during operation and could cause higher thrust forces at bends or fittings. Design measures should include anchor blocks, pressure relief valves, and periodic slope monitoring to prevent potential movement or stress accumulation on the buried line.

Section S5: Booster Pump Station 3 to Discharge Point (Uitzicht) (232–277 km). The final section, approximately 35 km long, ascends from 1,374 m to 1,482 m amsl, crossing through Grootfontein's undulating terrain. The average slope is 0.9%, with local peaks up to 5.6%. This is the most variable terrain of the project, combining moderate ridges and shallow valleys. Such variability requires careful pipeline grading and flexible joint design to accommodate expansion and contraction due to topographic changes. The terminal elevation at Uitzicht determines the final discharge head, influencing both energy optimization and booster station calibration.

Figure 67. Longitudinal profile of the Section n°3 (S3). Kavango Link-CAN water project. Source: consultant's elaboration using Google Earth Pro data.

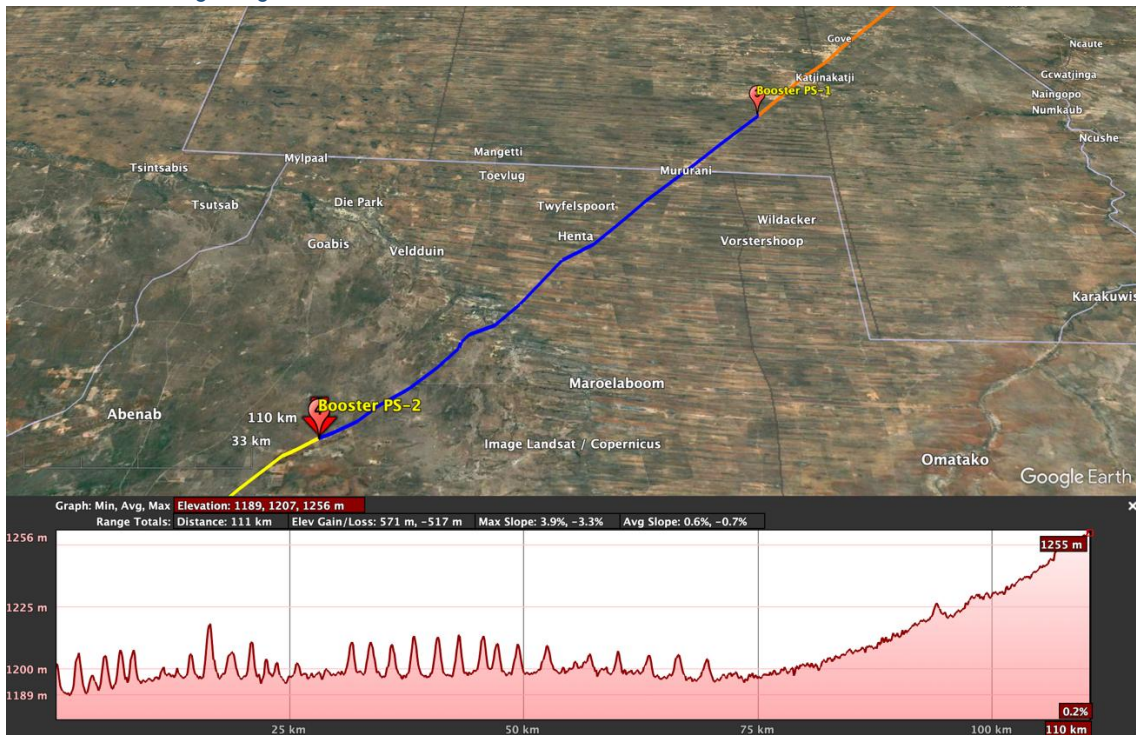


Figure 68. Longitudinal profile of the Section n°4 (S4). Kavango Link-CAN water project. Source: consultant's Elaboration using Google Earth Pro data.

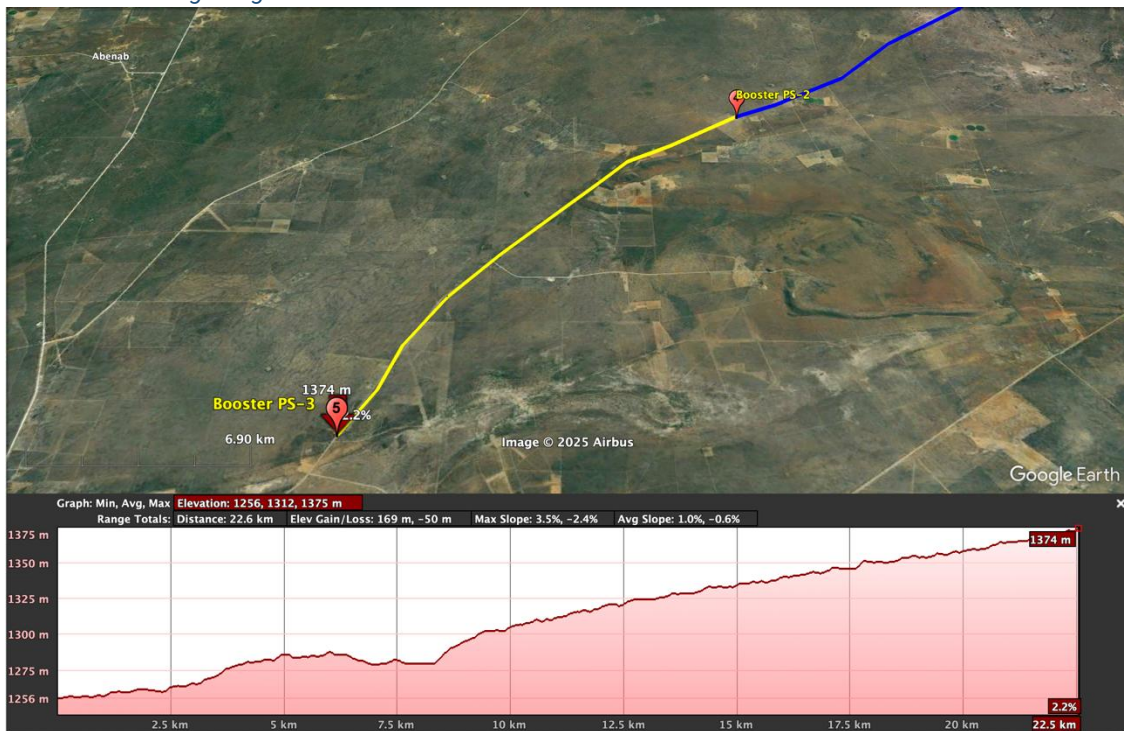


Figure 69. Longitudinal profile of the Section n° 5 (S5). Kavango Link-CAN water project. Source: consultant's Elaboration using Google Earth Pro data.

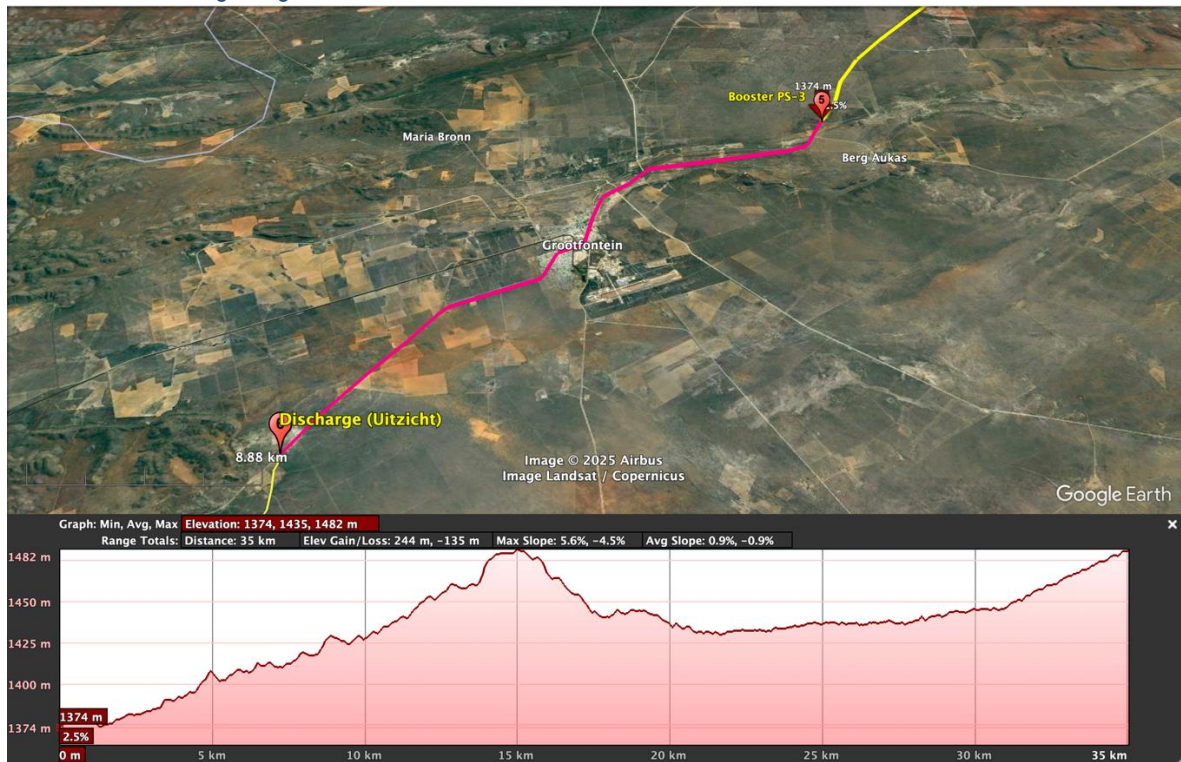


Figure 70. Longitudinal profile of the Section n° 5 (S5). Kavango Link-CAN water project. Source: consultant's Elaboration using Google Earth Pro data.



Overall, the Okavango Link alignment demonstrates a favourable topographic profile for a long-distance water transmission pipeline. The terrain’s gradual ascent ensures manageable pumping energy requirements, while its local undulations necessitate targeted hydraulic and structural adaptations. The strategic positioning of pump stations at elevation transition points effectively mitigates the challenges posed by relief variation, ensuring operational reliability and long-term resilience of the system.

7.2.2. Impact Criteria

The definition of impact criteria is aligned with the objectives of the CRVA. The impact criteria for this assessment are:

- **Physical impacts:** typically used to define the impacts on the structural integrity of the assets (e.g., foundation undermining, bank erosion, pipe rupture, building damage) or components such as fractures, excessive permanent deformations, loss of supporting elements, etc. Can also be applied to “people” assets for some extreme weather events (workers’ health and safety considerations).
- **Service life impacts:** consider the gradual degradation of materials due to progressive changes in climate events’ intensity or frequency which may result in reduced service lives of assets or components. Applicable to assets and components (e.g., accelerated degradation due to heat, UV, corrosion, abrasion, or repeated floods or droughts cycling).
- **Functionality impacts:** mostly related to the loss of capacity of an asset or component to meet demand at its design capacity, or inadequate design capacity to meet current or future climate loads. Applicable to assets and components. Inability to meet design hydraulic capacity/availability targets (e.g., intake outage, pump derating, surge-induced downtime) and also, O&M staff productivity in extreme conditions.
- **Operational impacts:** increased operational activities such as inspections, clearing debris after storms, increase in use of de-icing products, or additional energy used. Includes impacts on the productivity of outdoors workers or delays to access work site. Operational impacts that divert staff from regular O&M may result in maintenance delays and backlogs. Applicable to assets, activities and people. increased O&M burden (screen and debris management, sediment removal, drainage clearing, filter changes, vegetation control, energy use, access delays).

The following table 36 presents the impact criteria and rating scale selected for the elements at risk considered in the CVRA.

Table 36. Impact Criteria and rating scale.

Rating and Description	Physical Impacts Vp	Operational Impacts Vo	Service Life Impacts Vsl	Impacts on Functionality/Productivity Vf
0 No Effect	Fully operational; no damage.	No additional O&M or budget.	No impact on service life.	No service interruption
1 Insignificant	No structural damage	Restored through routine O&M	Slight loss of service life due to climate hazard	Less than < 10% capacity loss
	Superficial erosion (slope < 10%)	Full access to asset and components	Less than < 5% Service life reduction	Less than < 1 hour of service interruption
	H&S employees: No injuries or first aid requirements (minor accident)			< 10% Employees loss of productivity
2 Minor	Minor erosion or scour	Inspection may be required	Minor loss of service life	10% - 20% Capacity loss
	Less than < 10% components affected or damaged	Corrected by current O&M staff within budget	5% - 10% Expected service life reduction	1-6 hours of service interruption
	H&S employees: Slight injury (any minor injury that may require medical treatment) the consequences of which do not exceed the day of the event.			10% - 30% Employees loss of productivity
3 Moderate	Moderate damage	Additional inspections required	Moderate loss of service life	20%-30% Capacity loss
	10% - 25% of components affected (local bank repair, chamber flooding, bedding washout at crossings).	Repairs require external service/parts	10% - 20% Expected service life reduction	6 -12 hours of service interruption
	Slope between 10% and 25%	Additional O&M budget required but can be accommodated within organisation		Quality exceedance managed by throttling or temporary bypass with notification
	H&S Employees: Injury resulting in temporary disability (>1 day), absence from work or functional limitation. Reversible health effects, e.g., fracture.			30% - 50% Employees Loss of productivity

Rating and Description	Physical Impacts Vp	Operational Impacts Vo	Service Life Impacts Vsl	Impacts on Functionality/Productivity Vf
4 Major	Major damage	Inspections by external expert team and equipment required	Major loss of service life	30% - 40% Capacity loss
	25% - 50% of components damaged (flooded control/MCC rooms at intake or stations; significant scour exposure)	External expert assistance to repair required	20%- 40% Expected service life reduction	12- 24 hours Service interruption
		Supplementary budget and possible access to external funding		Risk of non-compliance with water service standards without emergency measures.
		Temporary relocation or alternative supply arrangements.		Alternative service delivery or relocation of service required
	H&S Employees: Major injuries with hospitalization requiring a prolonged absence from work. Irreversible damage to health (disability without loss of life)			50% - 75% Employees loss of productivity
5 Catastrophic	Catastrophic damage	Complete loss of access to key assets	Significant loss of service life	> 40% Capacity Loss
	More than > 50% of components affected (failure of intake structure, long reach pipeline rupture, extensive embankment failure)	Specialised external support required. Impacts propagate to ENWC interface.	> 40% Expected service life reduction	> 24 hours Service interruption
	Full replacement of asset required. Impacts on ENWC interface assets	Potential declaration of emergency and Emergency funding needed		Regional supply shortfall and emergency demand management. Declaration of state of emergency
	Slope > 30%. High level of erosion			
	H&S Employees: 1 or more deaths			> 75% Employees Loss of productivity

- Capacity refers to Okavango Link transfer capacity in cubic meters per day and to abstraction or production where relevant.
- Quality and compliance include raw-water turbidity exceedances requiring throttling and treated-water standards per Namibian regulations.
- ENWC interface refers to tie-in hydraulics and control; any upstream event that forces isolation of the interface is counted as capacity loss.
- Even if occupational health and safety are managed through emergency SOPs and authority coordination the matrix has considered it to not only remain asset- and service-centric.

7.3 Risk Assessment Results

This section presents the asset-specific climate risk results for the Kavango Link raw-water transfer, applying the CRA methodology for projects with detailed asset data described in Section 1.6.2 and the impact criteria in Section 7.2.2 (Table 36). For each of the six segments (S0–S5), representative assets and sub-components (intakes, pump stations, interface facilities, etc.) are evaluated against the priority climate hazards identified: heat stress, drought, pluvial flash floods, fluvial floods, storms, and wildfire.

For every asset–hazard combination, four consequences are scored, covering physical damage (Rp), operational performance (Ro), service life (Rsl) and functional service delivery (Rf). These consequence scores are combined with hazard likelihood to obtain risk indices between 1 and 25, for two future time horizons (2020–2039 and 2040–2059) and both emissions pathways (SSP2-4.5 and SSP5-8.5).

Consistent with the hazard and hotspot patterns in Part III and the project-site analysis in Section 7.1.4, climate risk is strongly dominated by flooding in the upstream floodplain and by heat and convective storms further south. Segment S0, located on the Okavango floodplain at the intake and river pump station, shows the highest risk indices for fluvial and pluvial flooding across all four impact criteria, with increasing scores in the distant-future horizon.

- S0 also registers non-negligible drought-related risk, as multi-season low-flow conditions at the intake can curtail abstraction days and propagate service-delivery constraints along the transfer system.
- In S1 and S2 (floodplain transition and northern Kalahari plains), climate risk is driven primarily by heat stress on MCC rooms, pumps and VFDs at the base pump station and Booster 1 and by pluvial flash flood and erosion effects on hardstands, valve chambers and early trunk-main reaches, with localised wildfire risk along vegetated servitudes in S2.
- In S3 and S4 (central Kalahari and transition to the Otavi Highlands), short-duration pluvial floods at ephemeral crossings, slope instability on steeper cut-and-fill sections and cumulative heat stress on Booster 2 and Booster 3 generate moderate to high indices.
- In S5 (interface with the ENWC/Uitzicht system), risk concentrates on pluvial flash-flood inflow to the interface chamber and on heat and dust impacts on the control room and outdoor instrumentation.

Across all segments and hazards, risk indices tend to increase from the near-future (2020–2039) to the distant-future (2040–2059) horizon and are systematically higher under SSP5-8.5 than under SSP2-4.5, in line with the stronger signal of extreme rainfall, hot-day counts and aridity reported in Part II for Namibia and summarised for the project corridor in Section 7.1.4.

The relative ordering of segments and their dominant hazards nevertheless remains stable: flood-related risks are concentrated in the intake and upper reach (S0–S1), while heat, drought-related supply constraints, wildfire, storms and, locally, slope processes progressively shape the mid- and downstream segments (S2–S5). This stability confirms that climate change amplifies an existing hazard pattern and supports the use of the S0–S5 segmentation and the disaggregated indices in Table 37 as a practical basis for screening and prioritising site-specific adaptation and protection measures along the Kavango Link water project.



Table 37. Okavango Link. Summary Climate Risk Evaluation Table by segment (2020-2039- and 2040-2059 for SSP2 and SSP5).

Asset	Affected components	Climate hazard	Description of the risk Values are risk indices (Likelihood × Consequence, 1–25) for each impact criterion: Rp = Physical, Ro = Operational, Rsl = Service Life, Rf = Functionality (Service Delivery). Ratings are aligned to basin-prioritised hazards and the 2040-2059 horizon.	Risk Rating Rp: Physical / Ro: Operational Rsl: Service Life / Rf: Functional (Blank cells indicate no risk identified or no rating possible)															
				NEAR FUTURE 2020-2039								DISTANT FUTURE 2040-2059							
				SSP2–4.5				SSP5–8.5				SSP2–4.5				SSP5–8.5			
				Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf
S0 – Okavango Intake & River Pump Station (km 0–0.5)																			
Intake works and platform	Screens, sump, low-lift pumps, Motor Control Centre (MCC), access deck	Fluvial Floods	High river stages overtop or approach platform levels; debris rafts and sediment load affect screens and sump; access constrained during peak flows.	16	16	12	16	20	20	15	20	20	20	15	20	20	20	15	20
Intake works and platform	Screens, sump, MCC rooms, access road	Pluvial Flash Floods	Short-duration cloudbursts pond at low points; inflow to valve chambers and MCC rooms; local erosion of side drains and approaches.	9	9	6	9	12	12	8	12	12	12	8	12	15	15	10	15
Intake works (enclosures)	MCC and control rooms; electrical cabinets	Heat Stress	High temperatures stress motors and Variable Frequency Drives (VFDs); Heating, Ventilation and Air Conditioning (HVAC) load increases; polymer seals age faster; drift in Supervisory Control and Data Acquisition (SCADA) sensors.	12	16	12	12	15	20	15	15	15	20	15	15	15	20	15	15
Access and small structures	Fencing, shelters, outdoor enclosures	Storms	Dust ingress elevates enclosure temperatures and failure rates; gusts load lightweight structures; lightning and surges cause nuisance trips.	8	12	8	8	10	15	10	10	10	15	10	10	10	15	10	10

Asset	Affected components	Climate hazard	Description of the risk Values are risk indices (Likelihood × Consequence, 1–25) for each impact criterion: Rp = Physical, Ro = Operational, Rsl = Service Life, Rf = Functionality (Service Delivery). Ratings are aligned to basin-prioritised hazards and the 2040-2059 horizon.	Risk Rating Rp: Physical / Ro: Operational Rsl: Service Life / Rf: Functional (Blank cells indicate no risk identified or no rating possible)															
				NEAR FUTURE 2020-2039								DISTANT FUTURE 2040-2059							
				SSP2–4.5				SSP5–8.5				SSP2–4.5				SSP5–8.5			
				Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf
S1 - Floodplain Transition to Base Pump Station (km 0.5–14.9)																			
Base Pump Station	MCC/control rooms, HVAC, pumps and VFDs	Heat Stress (extreme heat and hot season temperature)	High ambient temperatures challenge room heat balance and equipment thermal ratings; productivity reductions in prolonged hot spells.	12	16	12	12	15	20	15	15	15	20	15	15	15	20	15	15
Base Pump Station and platforms	Hardstand, perimeter drains, valve chambers	Pluvial Flash Floods	Cloudbursts surcharge drains and flood platforms and chambers; potential short service interruptions during dewatering.	9	9	6	9	12	12	8	12	12	12	8	12	15	15	10	15
Rising main (early stretch)	Buried trunk, culvert/track crossings	Pluvial Flash Floods	Local washouts or undermining at crossings and sag points following intense rainfall.	9	9	6	9	12	12	8	12	12	12	8	12	15	15	10	15
Station enclosures and small structures	Outdoor cabinets, shelters	Storms	Dust and gusts affect outdoor enclosures; storm surges increase trip risks for controls and communications.	8	12	8	8	10	15	10	10	10	15	10	10	10	15	10	10
S2 - Northern Kalahari Plains. Base Pump Station to Booster 1 (km 15–95)																			
Trunk pipeline (buried)	Appurtenances, air valves at crests, culvert/track crossings	Pluvial Flash Floods	Ponding at low points and localized erosion can expose or undermine the pipeline at crossings; inflow into chambers.	9	9	6	9	12	12	8	12	12	12	8	12	15	15	10	15

Asset	Affected components	Climate hazard	Description of the risk Values are risk indices (Likelihood × Consequence, 1–25) for each impact criterion: Rp = Physical, Ro = Operational, Rsl = Service Life, Rf = Functionality (Service Delivery). Ratings are aligned to basin-prioritised hazards and the 2040-2059 horizon.	Risk Rating Rp: Physical / Ro: Operational Rsl: Service Life / Rf: Functional (Blank cells indicate no risk identified or no rating possible)															
				NEAR FUTURE 2020-2039								DISTANT FUTURE 2040-2059							
				SSP2–4.5				SSP5–8.5				SSP2–4.5				SSP5–8.5			
				Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf
Electrical rooms at Booster 1	MCC/control rooms, HVAC, pumps and VFDs	Heat Stress (extreme heat and hot season temperature)	Elevated temperatures increase room cooling demand and approach equipment thermal limits.	12	16	12	12	15	20	15	15	15	20	15	15	15	20	15	15
Outdoor enclosures and small structures	Fencing, shelters, Photovoltaic (PV) arrays if present	Storms	Dust ingress raises enclosure temperatures; gusts load small structures; PV output reductions during dust events.	8	12	8	8	10	15	10	10	10	15	10	10	10	15	10	10
Corridor (vegetated servitudes)	Fences, cable trays, access	Wildfire	Fire threatens surface appurtenances; smoke/ash can foul chambers and restrict Operations and Maintenance (O&M) access.	6	6	6	6	6	6	6	6	6	6	6	6	8	8	8	8
S3 - Central Kalahari. Booster 1 to Booster 2 (km 95–175)																			
Trunk pipeline at ephemeral crossings	Crossing embankments, bedding, protection	Pluvial Flash Floods	Intense flows in ephemeral channels can scour protection, wash out bedding and require isolation of a reach for repair.	9	9	6	9	12	12	8	12	12	12	8	12	15	15	10	15
Booster 2 rooms and equipment	MCC/control rooms, pumps and VFDs	Heat Stress (extreme heat and hot season temperature)	Higher ambient and room temperatures approach equipment limits and increase wear on seals and cables.	12	16	12	12	15	20	15	15	15	20	15	15	15	20	15	15

Asset	Affected components	Climate hazard	Description of the risk Values are risk indices (Likelihood × Consequence, 1–25) for each impact criterion: Rp = Physical, Ro = Operational, Rsl = Service Life, Rf = Functionality (Service Delivery). Ratings are aligned to basin-prioritised hazards and the 2040-2059 horizon.	Risk Rating Rp: Physical / Ro: Operational Rsl: Service Life / Rf: Functional (Blank cells indicate no risk identified or no rating possible)															
				NEAR FUTURE 2020-2039								DISTANT FUTURE 2040-2059							
				SSP2–4.5				SSP5–8.5				SSP2–4.5				SSP5–8.5			
				Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf
Outdoor enclosures and small structures	Cabinets, shelters, PV arrays if present	Storms	Dust/gusts raise equipment failure and nuisance-trip risks; lightning affects controls and communications.	8	12	8	8	10	15	10	10	10	15	10	10	10	15	10	10
S4 - Transition to Otavi Highlands. Booster 2 to Booster 3 (km 175–245)																			
Trunk pipeline on slopes	Cut/fill sections, anchors, trench support	Slope Instability & Erosion	Steeper spot slopes combined with intense rainfall can cause rilling/gullying and trench sloughing, expose pipe and displacing thrust blocks.	8	6	6	6	12	9	9	9	12	9	9	9	16	12	12	12
Trunk pipeline and platforms	Side drains, outfalls, crossings	Pluvial Flash Floods	Higher short-duration rainfall can exceed drain capacity and increase scour at outfalls and crossings.	9	9	6	9	12	12	8	12	12	12	8	12	15	15	10	15
Booster 3 rooms and equipment	MCC/control rooms, pumps and VFDs	Heat Stress (extreme heat and hot season temperature)	Room heat loads rise with ambient temperatures; equipment approaches thermal ratings during hot spells.	12	16	12	12	15	20	15	15	15	20	15	15	15	20	15	15
Outdoor enclosures and small structures	Cabinets, shelters	Storms	Gusts and dust increase equipment stress and trip risks.	8	12	8	8	10	15	10	10	10	15	10	10	10	15	10	10
S5 - ENWC/Uitzicht Interface. Booster 3 -Tie-in (km 245–276.7)																			
Interface control/measurement chamber	Meters, valves, control panels, chamber drainage	Pluvial Flash Floods	Short-duration rainfall can flood the chamber and hardstand, requiring temporary isolation for dewatering and inspection.	9	9	6	9	12	12	8	12	12	12	8	12	15	15	10	15

Asset	Affected components	Climate hazard	Description of the risk Values are risk indices (Likelihood × Consequence, 1–25) for each impact criterion: Rp = Physical, Ro = Operational, Rsl = Service Life, Rf = Functionality (Service Delivery). Ratings are aligned to basin-prioritised hazards and the 2040-2059 horizon.	Risk Rating Rp: Physical / Ro: Operational Rsl: Service Life / Rf: Functional (Blank cells indicate no risk identified or no rating possible)															
				NEAR FUTURE 2020-2039								DISTANT FUTURE 2040-2059							
				SSP2–4.5				SSP5–8.5				SSP2–4.5				SSP5–8.5			
				Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf	Rp	Ro	Rsl	Rf
Interface control room and cabinets	MCC/control panels, HVAC	Heat Stress (extreme heat and hot season temperature)	Seasonal temperature increases raise cooling demand and approach equipment thermal limits.	8	12	8	8	10	15	10	10	10	15	10	10	10	15	10	10
Outdoor enclosures and small structures	Cabinets, shelters	Storms	Dust ingress and storm activity elevate failure and trip risks for interface instrumentation and controls.	8	12	8	8	10	15	10	10	10	15	10	10	10	15	10	10

The following sections describe the impacts of the climate hazards on the infrastructure assets for each segment (S1–S5) considering:

- How climate hazards affect each segment of the Okavango Link water transfer.
- Which assets and elements are most sensitive, and
- How effects differ between Shared Socioeconomic Pathway 2–4.5 (SSP2–4.5) and Shared Socioeconomic Pathway 5–8.5 (SSP5–8.5) as well as between the time periods considered: 2020–2039 and 2040–2059.
- Design-check implications to guide detailed design.

S0 – Okavango Intake and River Pump Station (km 0–0.5)

Assets considered

- Intake works bar racks and screens, debris boom and deflectors, intake sump, low-lift pumps and manifolds, lifting and gantry equipment.
- Civil and river works intake platform and access jetty, bank protection (riprap and armour with toe), flood berms, scour aprons, access road and culverts.
- Electro-mechanical and control: motors, Variable Frequency Drives (VFDs), Motor Control Centre (MCC), switchboard, earthing and lightning protection, surge protective devices, Supervisory Control and Data Acquisition (SCADA) panels, sensors and level instruments.
- Enclosures and services: electrical room with Heating, Ventilation and Air Conditioning (HVAC) and filtration, sealed cable entries, sealed chamber covers, sump pumps.

Fluvial floods (river flooding)

High stages in the Okavango can overtop or approach the intake platform and access, destabilise the bank, and drive debris against screens and structures. Prolonged high water increases sediment deposition in the sump. If electrical rooms are not sufficiently elevated, water ingress can disable control and power systems. Under SSP5–8.5, peak stages and the frequency of bankfull events are higher than under SSP2–4.5. Likelihood of platform inundation, access loss and debris loading is therefore higher in SSP5–8.5. The period 2040–2059 shows more frequent floodplain activation and longer elevated stages than 2020–2039, lengthening debris management and inspection windows.

Pluvial flooding (cloudbursts)

Short, intense rainfall events can pond on the platform and around valve chambers. Inflow to chambers and the electrical room is possible if covers and seals are not effective. Side drains and the access road can be eroded or blocked, delaying clean-up and inspection.

SSP5–8.5 has larger increases in short-duration rainfall than SSP2–4.5, so exceedance of drain capacity and chamber inflow are more frequent. Intensities increase from 2020–2039 to 2040–2059, raising the number of isolation and dewatering events.

Heat stress (heatwaves and extreme seasonal heat)

High ambient temperatures raise electrical room heat loads and can push motors and Variable Frequency Drives (VFDs) near thermal limits. Polymer seals and linings age faster. Supervisory Control and Data Acquisition (SCADA) sensors may drift at high enclosure temperatures. Field productivity also decreases during hot spells.

Both scenarios show more very hot days, but SSP5–8.5 has higher likelihood and more persistent extremes. Heating, Ventilation and Air Conditioning (HVAC) capacity and ventilation should be checked for the higher loads in SSP5–8.5. The 2040–2059 period adds degrees to hot-day thresholds compared with 2020–2039, reducing equipment thermal headroom.

Strong winds and dust storms (including convective storms)

Wind-blown dust raises enclosure temperatures by clogging filters and reduces the reliability of outdoor cabinets. Gusts load small structures and shelters. Convective storms add lightning and power quality disturbances that can trip controls and communications.

SSP5–8.5 shows more windy and dusty days and more energetic convective activity than SSP2–4.5. A modest increase from 2020–2039 to 2040–2059 suggests shorter maintenance intervals on filters and inspections of small structures.

Design-check implications for S0

- Verify platform and access levels against river stage with climate allowance and freeboard, check bank protection and debris interception capacity.
- Confirm chamber sealing and dewatering for short-duration rainfall exceedances; check side-drain capacity and erosion resistance.
- Recalculate room heat balance using higher ambient design temperatures; confirm motor and Variable Frequency Drive (VFD) derating and Motor Control Centre (MCC) ventilation.
- Specify dust-resistant enclosures and surge/lightning protection consistent with convective activity; verify filter capacity and change-out intervals.

S1 – Floodplain to Base Pump Station (km 0.5–14.9)

Assets considered

- Buried trunk main and appurtenances: pipe barrel and joints and gaskets, anchor and thrust blocks, air-release valves at crests, scour and washout valves at low points, line isolation valves, valve chambers.
- Crossings and drainage: road, track and culvert crossings; side drains and soakaways.
- Base Pump Station: pumps, Variable Frequency Drives (VFDs), Motor Control Centre (MCC), switchgear, surge vessel or relief, manifolds and strainers, Heating, Ventilation and Air Conditioning (HVAC), Supervisory Control and Data Acquisition (SCADA), site drainage.

Pluvial flooding (short-duration rainfall)

Heavy rainfall can surcharge side drains and soakaways at the Base Pump Station, causing water to enter valve chambers and platform depressions. On the rising main, concentrated flows at sag points and crossings may undermine bedding or erode outfalls.

Same period, scenario comparison increases in short-duration design rainfall are larger in SSP5–8.5, so exceedance of drainage capacity and chamber inundations are higher than in SSP2–4.5.

Period comparison, same scenario: intensities and exceedance frequency rise from 2020–2039 to 2040–2059, elevating the number of isolation and dewatering events.

Heat stress

High ambient temperatures challenge room cooling at the Base Pump Station. Motors and Variable Frequency Drives (VFDs) approach thermal derating limits more frequently; elastomers and cables age faster.

Same period, scenario comparison: SSP5–8.5 shows more very hot days and longer clusters than SSP2–4.5, so overheating and temporary capacity loss are more likely.

Period comparison, same scenario: 2040–2059 brings more frequent and longer hot spells than 2020–2039, reducing thermal headroom unless room cooling is verified.

Strong winds and dust storms

Dust ingress raises enclosure temperatures and failure rates in outdoor cabinets. Gusts load lightweight structures on site. Convective storms may produce lightning-related trips on controls and communications.

Same period, scenario comparison: higher windy and dusty day counts in SSP5–8.5; more lightning days than SSP2–4.5.

Period comparison, same scenario: moderate increase from 2020–2039 to 2040–2059, suggesting shorter preventive maintenance intervals.

Design-check implications for S1

- Confirm side-drain and soakaway capacity at the Base Pump Station; ensure chamber sealing and dewatering are effective.
- Check bedding, backfill and outfall protection at sag points and crossings for higher peak flows and velocities.
- Re-run room heat balance using higher ambient design temperatures; verify Motor Control Centre (MCC) ventilation and Variable Frequency Drive (VFD) derating.
- Specify enclosure ingress protection and surge protection for increased dusty and stormy day frequencies.

S2 – Northern Kalahari Plains (km 15–95)

Assets considered

- Trunk pipeline in Kalahari sands with anchor blocks, bedding and backfill suitable for sandy soils.
- High and low points: frequent air-valve assemblies and washouts; valve chambers with sealed covers and sump pumps.
- Crossings and access: culvert and track crossings; scour protection at outfalls; patrol and access tracks.
- Booster 1 Pump Station: pumps, Variable Frequency Drives (VFDs), Motor Control Centre (MCC), surge vessel or relief, manifolds, Heating, Ventilation and Air Conditioning (HVAC), Supervisory Control and Data Acquisition (SCADA), telemetry mast.

Pluvial ponding and local flooding

Flat terrain promotes ponding at low points. Heavy rainfall can lead to chamber inflow, saturation of backfill, and local erosion at outfalls and crossings. Access along tracks can be temporarily interrupted.

Same period, scenario comparison: SSP5–8.5 exhibits larger increases in short-duration intensities than SSP2–4.5, leading to more frequent exceedance of chamber and drain capacity and more incidents of local erosion.

Period comparison, same scenario: increased intensities and wet-spell persistence in 2040–2059 elevate the number of ponding events relative to 2020–2039.

Strong winds and dust storms

Dust affects outdoor enclosures and can lead to higher operating temperatures; gusts load small structures such as masts and shelters.

Same period, scenario comparison: SSP5–8.5 shows more windy and dusty days than SSP2–4.5; convective activity can also be stronger.

Period comparison, same scenario: a gradual increase from near-term to long-term, requiring attention to filtration capacity and inspection frequencies.

Heat stress

Ambient heat mainly affects Booster 1 electrical rooms and polymeric components in exposed appurtenances. Room cooling requirements increase in hot spells, and motor and Variable Frequency Drive (VFD) derating may be necessary more often.

Same period, scenario comparison: SSP5–8.5 produces more very hot days and longer sequences of hot days than SSP2–4.5.

Period comparison, same scenario: 2040–2059 shows higher hot-day thresholds and longer warm seasons than 2020–2039.

Wildfire

Vegetated servitudes can carry fire. Damage risk is highest for surface appurtenances and access restrictions during fire-weather days. Smoke and ash may affect chamber filters but usually for short periods.

Scenario and period contrasts: similar between scenarios in the near term, with a slight increase under SSP5–8.5 in the long term; an overall small increase when moving from 2020–2039 to 2040–2059.

Design-check implications for S2

- Confirm chamber sealing, dewatering capacity and drain sizing at low points; check outfall protection for higher short-duration flows.
- Verify Booster 1 room heat balance against higher ambient design temperatures and confirm Variable Frequency Drive (VFD) derating allowances.
- Specify filtration and pressurization levels for enclosures consistent with dusty-day frequencies, check mast and shelter loadings.
- Plan access and inspection frequencies for high fire-weather seasons; check material choices for exposed appurtenances.

S3 – Central Kalahari (km 95–175)

Assets considered

- Trunk pipeline with multiple ephemeral channel crossings; isolation valves, air valves at grade breaks, scour valves at low points.
- Ephemeral crossings: culverts and low-level crossings; invert protection and energy dissipation; bed and bank armouring.
- Booster 2 Pump Station: pumps, Variable Frequency Drives (VFDs), Motor Control Centre (MCC), surge vessel or relief, manifolds, Heating, Ventilation and Air Conditioning (HVAC), Supervisory Control and Data Acquisition (SCADA), backup communications.

Pluvial flooding at ephemeral crossings

Intense local storms generate energetic flows in dry channels. Protection can be scoured, bedding washed out, and access tracks cut. Repairs often require temporary isolation of a pipeline reach.

Same period, scenario comparison: higher short-duration intensities and peak unit discharges in SSP5–8.5 lead to greater scour risk than in SSP2–4.5.

Period comparison, same scenario: the 2040–2059 period shows more frequent damaging events than 2020–2039, raising the need for robust protection details and access planning.

Strong winds, dust and convective storms

Dust and gusts stress outdoor enclosures, masts and shelters; convective storms add lightning and power quality issues that can trip controls and communications at Booster 2.

Same period, scenario comparison: SSP5–8.5 has more and stronger convective episodes than SSP2–4.5.

Period comparison, same scenario: a modest increase in storm frequency and dusty-day counts by 2040–2059 relative to 2020–2039.

Heat stress

The principal sensitivity is in station rooms and polymeric components at exposed appurtenances; derating of motors and Variable Frequency Drives (VFDs) becomes more common during hot spells.

Scenario and period comparisons follow the same pattern: SSP5–8.5 higher than SSP2–4.5, and 2040–2059 higher than 2020–2039.

Wildfire

Wildfire can restrict access and damage surface appurtenances near crossings and station perimeters; impacts on the buried pipeline are limited unless combined with erosion and exposure.

Scenario and period comparisons: slight increases with SSP5–8.5 and towards 2040–2059, respectively.

Design-check implications for S3

- Re-check protection at ephemeral crossings for higher peak flows and scour potential based on updated rainfall design; verify isolation and access strategies for rapid repair.
- Confirm enclosure filtration and surge protection levels, review mast and shelter loadings under gusts.
- Verify Booster 2 room heat balance and equipment derating allowances under higher ambient design temperatures.

S4 – Transition to Otavi Highlands (km 175–245)

Assets considered

- Pipeline on undulating ground: pipe, joints and restraint systems; anchor and thrust blocks at steeper grades and bends; trench stabilisation with geotextile or geogrid where needed.
- Drainage and erosion control: side drains and lined outfalls; erosion and scour control at vulnerable slopes (for example, reno mattresses or geocells).
- Crossings: road and culvert protections; gabions and riprap where velocities exceed permissible.
- Booster 3 Pump Station: pumps, Variable Frequency Drives (VFDs), Motor Control Centre (MCC), surge control, manifolds, Heating, Ventilation and Air Conditioning (HVAC), Supervisory Control and Data Acquisition (SCADA).

Slope instability and erosion

Undulations and steeper spot slopes make this reach sensitive to rilling, gullyng and trench wall sloughing during intense rainfall. Loss of cover can expose pipe; thrust blocks may be displaced if drainage concentrates on steep sections. Sediment delivery to crossings increases when outfalls are undersized or unlined.

Same period, scenario comparison: the increase in short-duration rainfall in SSP5–8.5 produces more frequent triggering of erosion processes than in SSP2–4.5.

Period comparison, same scenario: more severe and frequent short-duration storms in 2040–2059 than in 2020–2039, raising the expected number of repairs and the length of affected reaches.

Pluvial flooding

Short-duration storms can exceed side-drain capacity on steeper sections and erode outfalls and embankments, leading to local access constraints and occasional temporary isolation for repairs.

Scenario and period contrasts: SSP5–8.5 worse than SSP2–4.5 for a given period; 2040–2059 worse than 2020–2039 for a given scenario.

Strong winds and dust; heat stress

Gusts load small structures and outdoor enclosures. Heat affects Booster 3 rooms and polymeric components as in earlier segments, with SSP5–8.5 and the long-term period producing higher stress than SSP2–4.5 and the near term.

Design-check implications for S4

- Confirm trench stability assumptions and restraint/anchor sizing on steeper grades; verify side-drain capacity and outfall protection details under updated rainfall design.
- Check erosion control measures at vulnerable slopes and crossings for the more frequent high-intensity storms indicated by the climate scenarios.
- Re-check Booster 3 room heat balance and enclosure protections for dust and gust loads.

S5 – ENWC/Uitzicht Interface (km 245–276.7)

Assets considered

- Interface works: control and measurement chamber (flow meters; pressure control or pressure reducing valves), energy dissipation or break structures, surge relief tank or valve, tie-in spools and isolation valves, bypass, thrust blocks, chamber sealing and dewatering, instrumentation linked to Supervisory Control and Data Acquisition (SCADA).
- Integration items: telemetry link to the Eastern National Water Carrier (ENWC) control, sampling and quality points, access hardening and drainage.

Pluvial flooding

Short-duration rainfall can flood the interface chamber and hardstand. Ingress requires temporary isolation for dewatering and inspection; repeated events stress electrical and monitoring equipment and reduce availability.

Same period, scenario comparison: chamber flooding frequency is higher under SSP5–8.5 than under SSP2–4.5. Period comparison, same scenario: 2040–2059 shows more exceedances and longer dewatering times than 2020–2039.

Heat stress

High temperatures increase the cooling demand of interface control rooms and can reduce component life of electronics and seals if heat gains exceed cooling capacity.

Scenario and period contrasts: SSP5–8.5 produces more frequent and more intense hot spells than SSP2–4.5; 2040–2059 is more challenging than 2020–2039.

Strong winds and dust storms

Dust ingress can elevate enclosure temperatures and cause premature failure of instrumentation; gusts load small structures around the chamber.

The same contrasts apply: SSP5–8.5 worse than SSP2–4.5 for a given period, and 2040–2059 worse than 2020–2039 for a given scenario.

Design-check implications for S5

- Verify chamber sealing and dewatering; confirm drainage capacity at the interface hardstand for updated short-duration rainfall.
- Re-check control room cooling capacity against hot-day design values; confirm protection levels for instrumentation in dusty and gusty conditions.
- Coordinate operational logic and telemetry with the Eastern National Water Carrier (ENWC) to manage temporary isolation with minimal service effects.

7.4 Rural Projects within 100Km radius of Rundu preliminary climate risk screening

This section provides a preliminary, screening-level climate risk assessment for the proposed rural water-supply extensions within approximately 100 km of Rundu. The objective is to identify hazard-specific hotspots for key climate hazards (drought, heat stress, pluvial and fluvial flooding, storms and wildfires) and to outline implications for the siting, design and operation of the planned infrastructure. The screening combines the conceptual pipeline corridors and service nodes with individual hazard maps, highlighting stretches where High, Very High or Extreme hazard levels occur in the vicinity of the proposed works. In this context, the hotspots refer to locations where one or more hazards reach High+ classes in space and/or time; they do not require all hazards to peak simultaneously. Results are presented for three future time horizons (2020–2039, 2040–2059 and 2060–2079) and two emissions pathways (SSP2-4.5 and SSP5-8.5), using the same datasets as the basin-wide assessment. These findings provide a basis for refining the routing of the extensions and for defining protection standards at critical nodes.

7.4.1 Project site context

The Rundu 100-km rural water-supply extensions aim to improve access to safe and reliable water supply for dispersed rural communities surrounding Rundu. The current project concept foresees a piping distribution system including:

- Extension and reinforcement of bulk conveyance from the existing Rundu abstraction and treatment facilities towards rural areas within a radius of roughly 100 km from the new water treatment plant.
- Construction and/or upgrading of storage reservoirs, distribution pipelines and reticulation networks to serve scattered settlements and village clusters.
- Associated ancillary works (valve chambers, break-pressure tanks, river and drainage crossings, access roads and control facilities).

The current Rundu Water Treatment Plant has an installed capacity of 36,000 m³/day, with provision to double this capacity in the future. The estimated average annual daily demand (AADD) for Rundu town was 19,073 m³/day, with a projected AADD of 35,321 m³/day for 2037 (NOD, 2022).

Upon completion of the new Rundu Water Treatment Plant, expected in early 2026, there will therefore be surplus capacity relative to the projected demand for Rundu town. This surplus has been intentionally sized to enable the supply of potable water to communities located within a 100-km radius of the plant. These additional demands were explicitly considered in the design of the plant and are already embedded in the installed capacity.

At this stage, the project remains at a conceptual planning level. Detailed geo-referenced alignments and final locations for all rural extensions are not yet available. For this reason, the present assessment focuses on:

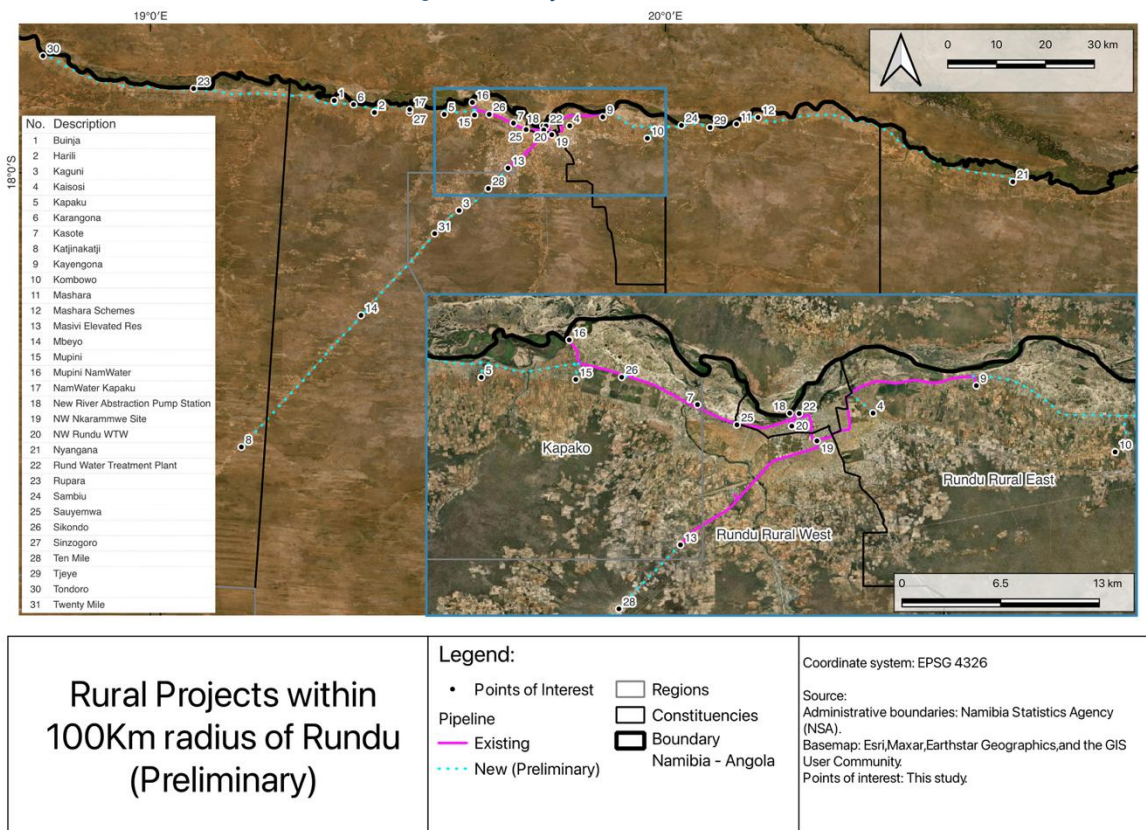
- Characterising the spatial pattern of climate and flood hazards within the 100-km area of interest (AOI); and
- Identifying sub-areas where planned infrastructure is likely to intersect hazard-specific hotspots, defined as areas classified as High, Very High or Extreme in the relevant hazard maps.

The results should therefore be considered as a screening-level input, to be refined and localised once NamWater develops detailed designs and alignments. To enable this preliminary climate risk screening in the absence of a final layout, the team has used its technical expertise and contextual knowledge to sketch an indicative alignment of potential bulk supply routes within the 100-km AOI. This indicative alignment is provided solely to illustrate the potential extent and reach of the scheme and **does not** represent a definitive route, nor does it imply that the system will ultimately extend to the full 100-km radius to the west, east and south.

The figure below shows the rural areas that are expected to be supplied with potable water from the newly constructed Rundu Water Treatment Plant, together with this indicative alignment, which is used here only to support the preliminary assessment of exposure to climate and flood risks.

For the purposes of this preliminary assessment, the consultant has prepared a shapefile and developed informed estimates of the potential locations of the new infrastructure, based on technical judgement and existing NamWater schemes. The schematic figure below provides an overview of the indicative infrastructure layout, including the potential areas that could be supplied with potable water from the newly constructed Rundu Water Treatment Plant. Infrastructure that is already part of the confirmed project is shown with **solid lines**. In contrast, **dashed lines** represent indicative alignments for potential future extensions to rural areas that could be supplied within approximately 100 km to the west, east and south of Rundu. These dashed sections are not part of the current project scope and are included solely to illustrate the potential coverage of the 100-km rural water-supply concept for this preliminary climate risk screening.

Figure 71. Project site locations around Rundu.



7.4.2 Identified rural areas

The table provides a list of the areas that are planned to be included in the water supply project, as provided by NamWater. It also indicates the direction from the new Rundu WTP, the GPS coordinates of each node, and the preliminary water demand, including the planning horizon and data source.

Kayengona, Masivi and Sikondo/Mupini form part of the closest water supply areas to the new Rundu Water Treatment Plant and are part of the NWSISP (phase one) extension project. Their water supply infrastructure is under construction, with some sections already completed and awaiting commissioning once the new WTP becomes operational.

The rows highlighted in grey were not part of the original list provided by NamWater; however, they have been included here as they still fall within the 100-km radius and are currently served by NamWater schemes.

Table 38. Water projects 100 Km radius Rundu. Summary table with locations and estimated water demand. Source: NamWater additional information from the author.

Node No	Area to be provided with Water Supply from Rundu WTP	Direction from Rundu WTP and Distance	GPS Coordinates		Estimated Waer Demand (AADD) and Horizon	Source
			South	East		
1.1	Kiasosi	East 7.7 km	17.9033°	19.8142°	TBD	Unknown
1.2	Kayengona	East 12.8 km	17.8922°	19.8786°	494 m ³ /d 2037	NoD, 2022
1.3	Kombowo	East 22.7 km	17.9333°	19.9648°	38.16 m ³ /d 2036	CMB, 2021
1.4	Tjeye	East 35.6 km	17.9124°	20.0867°	TBD	Unknown
1.5	Mashara	East 46.3 km	17.9056°	20.138°	475 m ³ /d 2037	NoD, 2022
1.6	Mashara Schemes	East 49.7 km	17.8929°	20.1799°	Seem to be included in above	NA
1.7	Nyanagana	East 96 km	18.0177	20.6747	TBD	NA
2.1	Sauyemwa	West (Near Rundu)	17.9164°	19.7295°	TBD	Unknown
2.2	Satotua	West (Near Rundu)	nd	nd	TBD	Unknown
2.3	Kasote	West (4.7 km)	17.9038°	19.7026°	TBD	Unknown
2.4	Siyandaya	West	nd	nd	TBD	Unknown
2.5	Nakazaza	West	nd	nd	TBD	Unknown
2.6	Sikondo	West (13 km)	17.8868°	19.6578°	TBD	Unknown
2.7	Mupini	West (13.6 km)	17.8886°	19.6219°	143 m ³ /d 2037	NoD, 2022
2.8	NamWater Scheme (Mupini)	West (15.5 km)	17.8641°	19.6259°	Seem to be included in above	NA
2.9	Matenda	West (16.7 km)	nd	nd	TBD	Unknown
2.10	Kapako	West (22.6 km)	17.8869°	19.5705°	176 m ³ /d 2037	NoD, 2022
2.11	Sinzogoro	West (29.8 km)	17.8828°	19.5032°	TBD	Unknown
2.12	NamWater Scheme (Kapako)	West (30.8 km)	17.8774°	19.5035°	Seem to be included in 2.10	NA
2.13	Sia School	West (33.9 km)	nd	nd	TBD	Unknown
2.14	Harili	West (37.1 km)	17.8820°	19.4369°	TBD	Unknown
2.15	Karangona	West (40.8 km)	17.8718°	19.4095°	TBD	Unknown
2.16	Buinja	West (46.3 km)	17.8671°	19.3633°	327 m ³ /d 2037	NoD, 2022
2.17	Rupara	West	17.8369°	19.0839°	TBD	NA

Node No	Area to be provided with Water Supply from Rundu WTP	Direction from Rundu WTP and Distance	GPS Coordinates		Estimated Waer Demand (AADD) and Horizon	Source
			South	East		
		(74 km)				
2.18	Tondoro	West (105 km)	17.8369	19.0839	TBD	NA
3.1	Masivi	South (7.7 km)	18.6120°	19.6868°	99 m ³ /d 2037	NoD, 2022
3.2	Ten Mile	South (14 km)	18.0308°	19.6561°	TBD	Unknown
3.3	Kaguni	South (18.5 km)	18.0734°	19.5994°	TBD	Unknown
3.4	Twenty Mile	South (27.5 km)	18.1181°	19.5519°	TBD	Unknown
3.5	Thirty Mile	South (40 km)	nd	nd	TBD	Unknown
3.6	Mbeyo	South (52 km)	18.2768°	19.4090°	TBD	Unknown
3.7	Epingiro	South (58.2 km)	nd	nd	TBD	Unknown
3.8	Mayongora	South (73.5 km)	nd	nd	TBD	Unknown
3.9	Katjinakatji	South (90 km)	18.5437	19.1652	332 m ³ /d 2037	NoD, 2022
The above AADD does not include for any losses.						

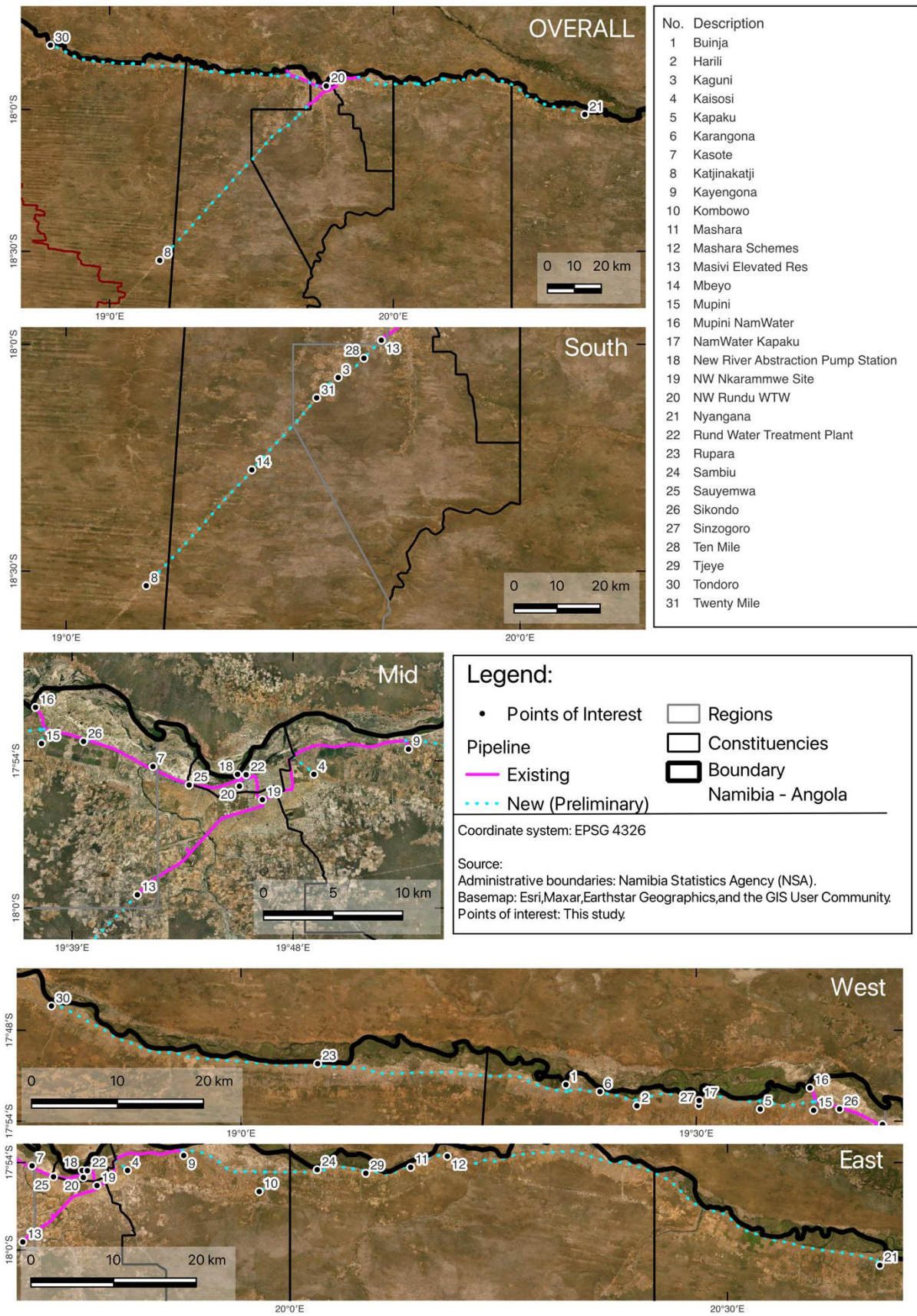
7.4.3 Planned infrastructure

This project is in the initial planning stage, as understood from NamWater, and no detailed information on the planned infrastructure is available at this point. However, the overall concept has been adopted and broadly entails the following:

- Pressure / booster pump stations at the Rundu WTP to pump water in the different directions towards the identified supply areas.
- Trunk pressure pipelines, one in each of the three directions. These will most likely operate as constant-pressure mains, with pipe diameters decreasing as downstream demand reduces. In this area, pipelines are typically uPVC or oPVC and are installed underground.
- Offtakes to each supply area, including elevated reservoirs to provide both pressure and storage. NamWater's standard storage requirement is 48 hours of the AADD. Elevated reservoirs are normally constructed using galvanised steel support structures with tanks manufactured from sectional galvanised plates or LLDPE tanks mounted on the structure.
- Disinfection facilities at storage sites to ensure that the required free chlorine levels are achieved, in line with the Department of Water Affairs' Water Resources Management Regulations (DWA, 2023). Disinfection is typically provided by one of the following methods: chlorine gas, sodium hypochlorite dosing, or calcium hypochlorite tablets.
- Given the distances to be covered, additional booster pump stations along the pipeline routes will likely be required, depending on the final hydraulic design.
- Water meter installations at customer connections.
- Electrical power supplies to pump stations and disinfection facilities.
- SCADA and telemetry systems for remote monitoring and control of key infrastructure.

At present, no detailed project information is available regarding the exact locations of stations, pipe diameters, pipe lengths, pipeline routes, reservoir capacities, pump duties, power requirements, or other design parameters.

Figure 72. 100 Km around Rundu Project preliminary locations by section: South, West and East. Source: the Author.



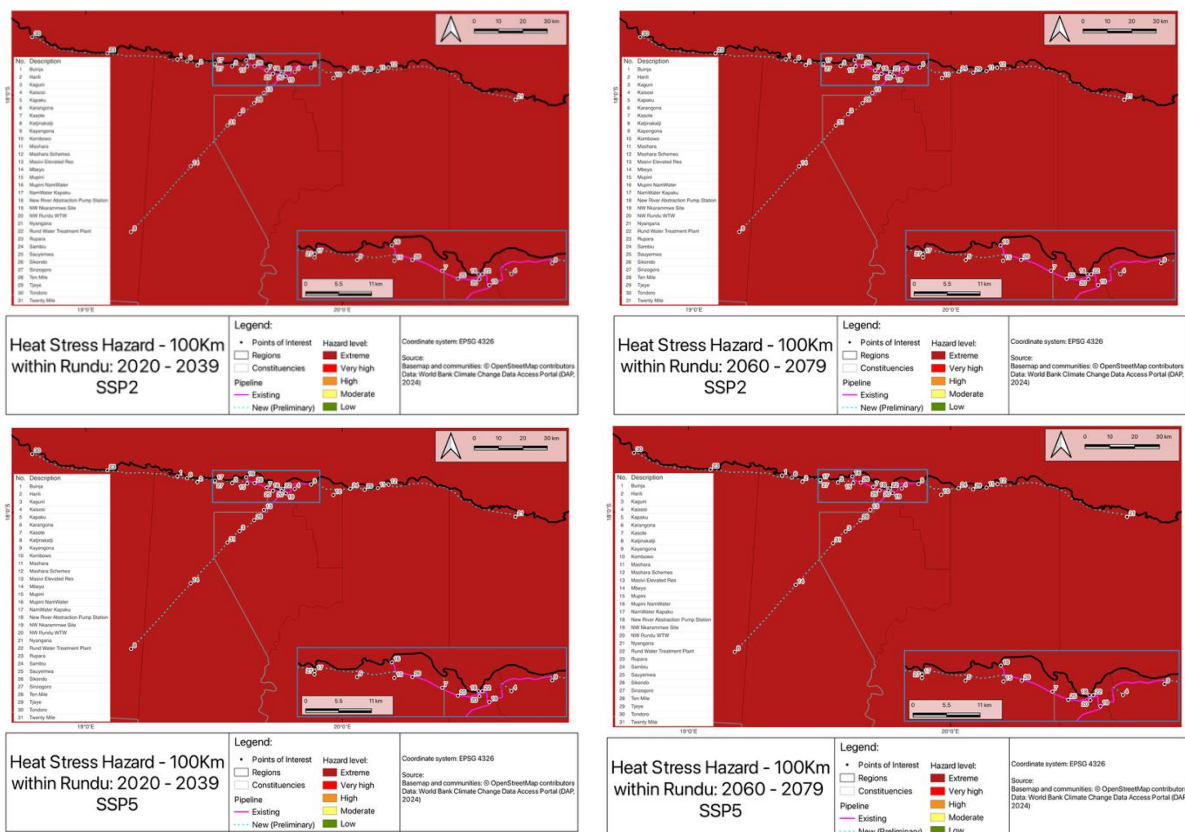
7.4.4 Climate hazard profile and hazard specific hotspots.

7.4.4.1 Heat stress hazard

Heat-stress hazard across the 100 km radius around Rundu emerges as one of the most uniform and intense hazards. In the near-term period (2020–2039), both SSP2-4.5 and SSP5-8.5 already classify the entire region as high to extreme, with minimal spatial variability. This early saturation of hazard levels reflects high baseline temperatures, limited evaporative buffering and the rapid intensification of heatwaves driven by regional warming trends. Even communities close to the river show no significant reduction in hazard, highlighting the dominance of atmospheric drivers over microclimatic effects.

By the long-term horizon (2060–2079), the region is fully classified as extreme hazard under both SSP2 and SSP5. The absence of scenario divergence suggests that extreme heat is unavoidable in this landscape and will become a defining stressor for water-supply operations. For the Rundu rural water-supply concept, this means that heat-adaptive design, thermal protection for equipment, cooling strategies for personnel, and robust contingency plans for heatwave-induced power stress will be vital. Heat stress is not only an environmental hazard but a direct operational challenge that will shape the resilience requirements of the entire system. This trend signals profound implications for construction schedules, maintenance work, energy demand for pumping, and occupational safety, particularly for staff involved in field operations and repairs.

Figure 73. Heat Stress Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPs 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.

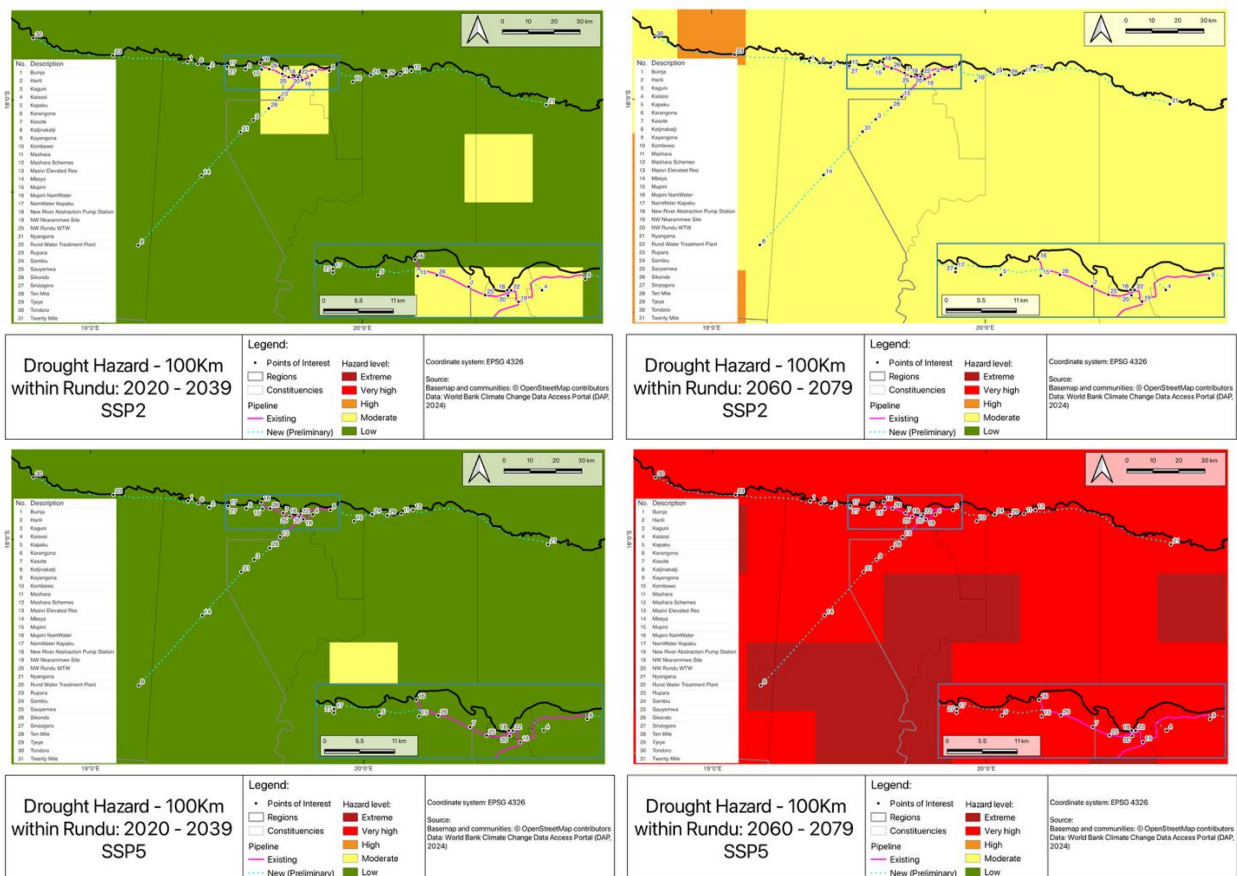


7.4.4.2 Drought hazard

Drought conditions across the 100 km radius around Rundu intensify progressively over time and across scenarios. In the near-term (2020–2039), both SSP2-4.5 and SSP5-8.5 reflect predominantly low drought hazard across most of the corridor, with only small pockets of moderate exposure emerging around specific inland zones away from the river. These early patterns suggest that, in the short term, surface and shallow groundwater resources remain relatively resilient, although some communities could already experience localised stress in drier years.

The long-term horizon (2060–2079) reveals a much stronger escalation. Under SSP2-4.5, nearly the entire 100 km buffer reaches at least moderate drought hazard, while under SSP5-8.5 vast regions are classified as high, very high or even extreme. This implies more frequent and persistent seasons with rainfall deficits, lower baseflows and a reduced capacity of ecosystems and aquifers to buffer inter-annual variability. For the Rundu rural water-supply concept, these patterns highlight a growing dependence on robust storage, conjunctive use of surface and groundwater, and flexible operational rules. The strong divergence between SSP2-4.5 and SSP5-8.5 in later decades underscores the sensitivity of the scheme to long-term warming and drying, and the importance of aligning design choices with ambitious climate-mitigation pathways.

Figure 74. Drought Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPs 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.

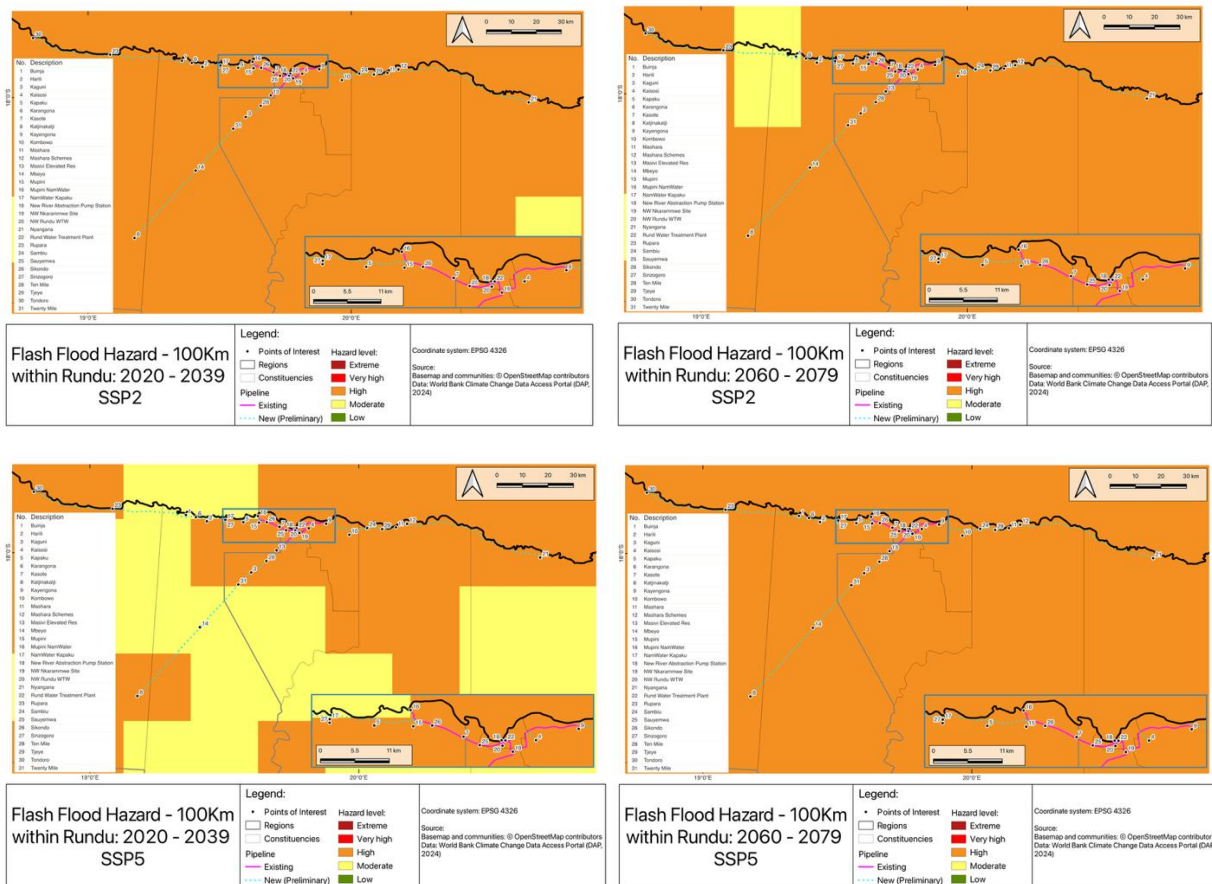


7.4.4.3 Flash Floods Hazard

Flash-flood hazard around Rundu follows a different trajectory compared to drought and remains high throughout all time slices. In the near-term horizon (2020–2039), the 100 km corridor is predominantly affected by high flash-flood susceptibility, driven by short-duration convective storms, intense local runoff and the rapid response of small catchments. Under SSP2-4.5, this high hazard band extends almost continuously across the study area, while SSP5-8.5 introduces slightly more spatial variability, with some clusters of moderate hazards emerging inland. Nevertheless, the overall signal is one of consistently high exposure to short-lived but intense flood events.

In the long-term period (2060–2079), the region continues to be overwhelmingly characterised by high flash-flood hazard under both SSP2-4.5 and SSP5-8.5. Scenario divergence is smaller than for drought, indicating that intense rainfall events and associated rapid runoff remain a stable, long-lasting driver of risk regardless of the emissions pathway. For the Rundu rural water-supply concept, this persistence of high flash-flood hazard implies that climate-robust design must prioritise conservative drainage standards, erosion-resistant protection at crossings and platforms, and reliable access arrangements for operation and maintenance. Even if long-term drying increases, the system will still need to withstand recurrent short-duration storm events capable of punctually damage infrastructure.

Figure 75. Flash Floods Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPs 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.



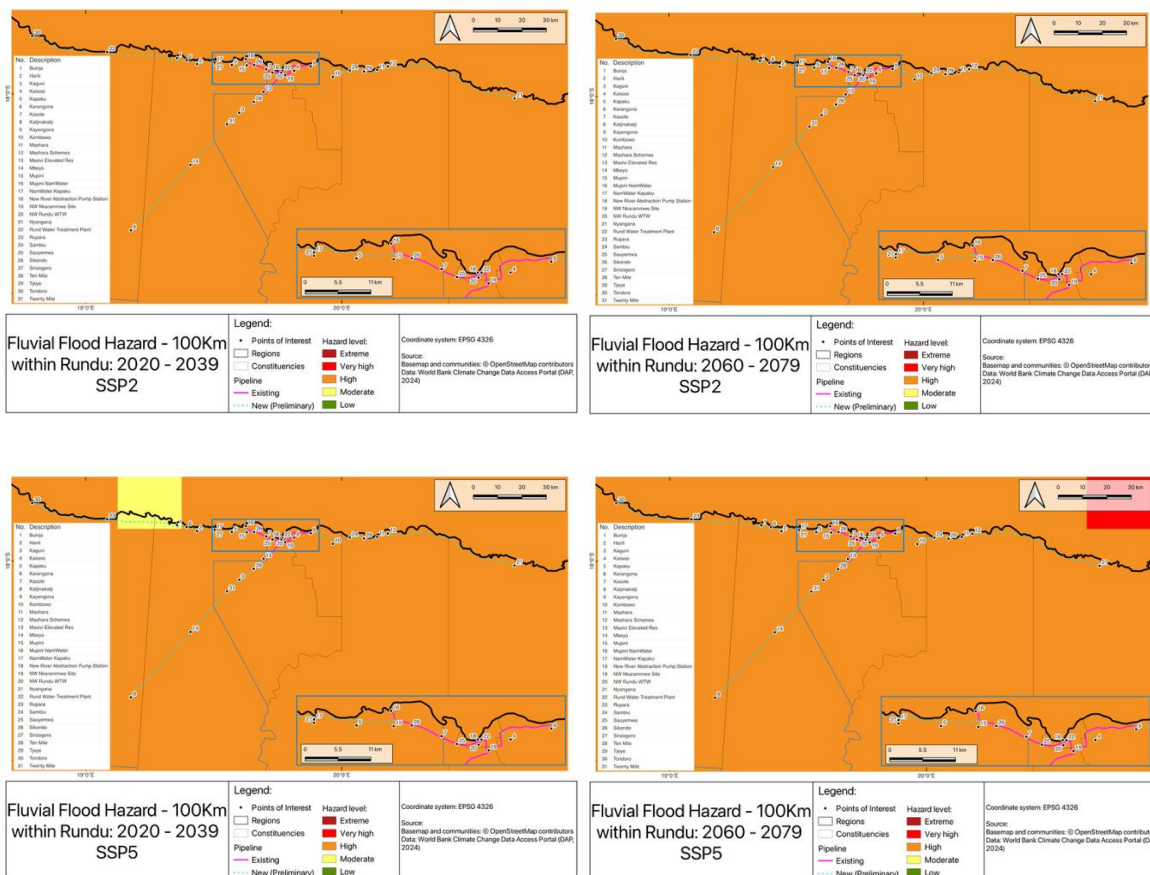


7.4.4.4 Fluvial Floods Hazard

Fluvial flooding along the 100 km radius around Rundu shows a pattern strongly shaped by the Kavango River and its adjacent low-lying floodplains. In the near-term period (2020–2039), both SSP2-4.5 and SSP5-8.5 indicate consistently high fluvial-flood hazard along the river corridor, with inland areas showing much lower susceptibility. Under SSP2-4.5, the high-hazard band is relatively continuous, while SSP5-8.5 introduces small pockets of moderate or low hazard inland, although the riverine belt remains uniformly high. These early patterns suggest that even in the short term, any infrastructure positioned near the river or crossing seasonal channels could face recurrent inundation pressure linked to river overflow, backwater effects and saturation of adjacent soils. The dominant structure remains that fluvial flooding is overwhelmingly concentrated along the riverine spine. This reinforces the need to design the intake, treatment plant, and initial pipeline segments with strong protection against prolonged inundation, lateral erosion and disruptions linked to seasonal river dynamics.

Towards the long-term horizon (2060–2079), the river corridor continues to exhibit high to very high fluvial-flood hazard in both scenarios. Scenario divergence appears mainly in the inland blocks, where SSP5-8.5 introduces smaller patches of moderate hazard due to broader climatic shifts influencing catchment wetness and rainfall concentration. However, the primary risk zone remains unchanged: the infrastructure built near or upstream of Rundu might face high fluvial-flood risk regardless of the emissions pathway. For the 100 km rural water-supply concept, this stability in hazard across decades implies that flood-resilient siting, elevated platforms, reinforced crossings, and protection against lateral erosion will be required throughout the project life.

Figure 76. Fluvial Floods Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSP2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.

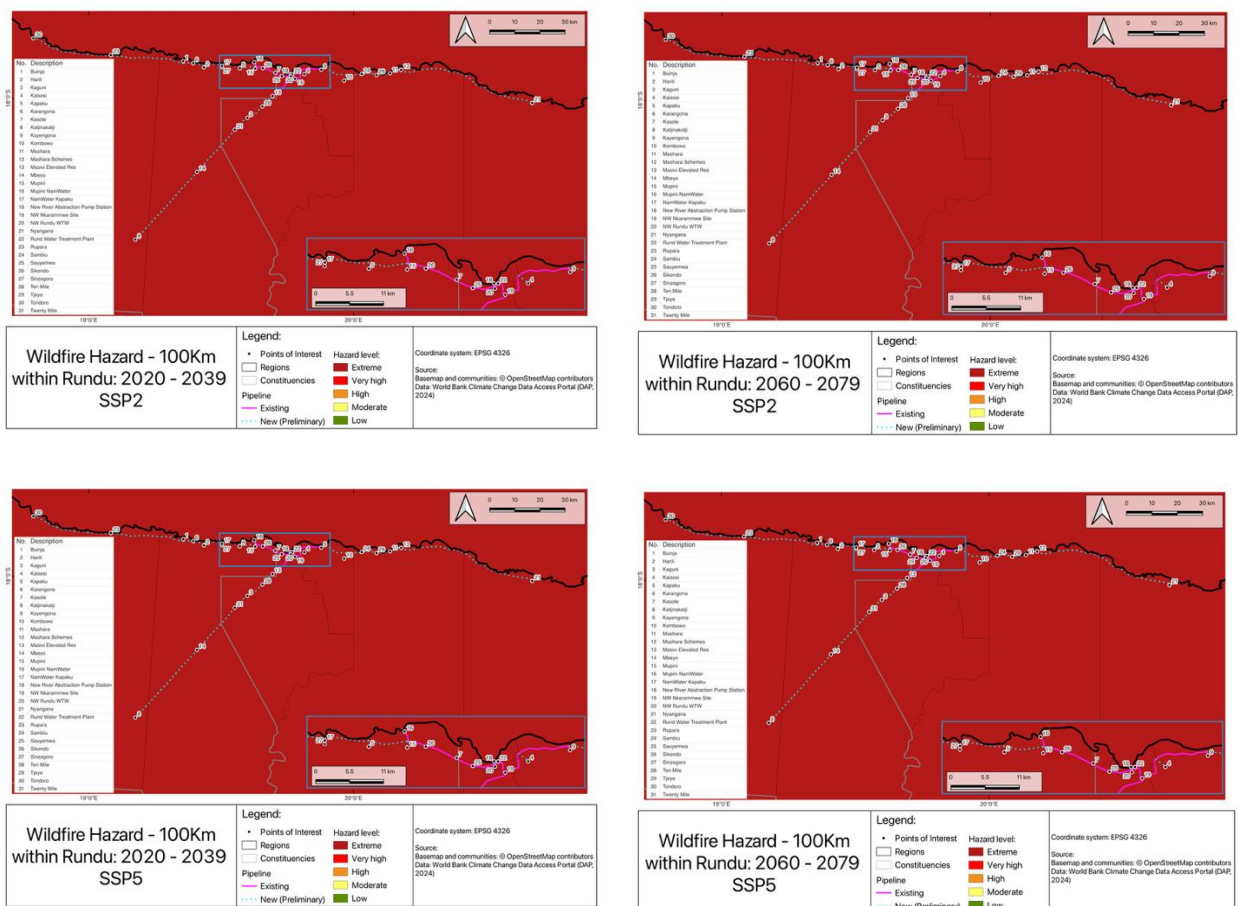


7.4.4.5 Wildfire Hazard

Wildfire hazard within the 100 km Rundu radius emerges as one of the most consistently severe hazards across all time slices and scenarios. In the near-term period (2020–2039), both SSP2-4.5 and SSP5-8.5 classify almost the entire corridor as extreme hazard, with only minimal spatial variation. This reflects the combined influence of high baseline temperatures, widespread flammable vegetation types, and recurrent dry seasons that promote ignition and rapid spread. Even areas adjacent to the river show no meaningful reduction in risk, suggesting that fluvial systems provide limited natural buffering against wildfire propagation.

By the long-term horizon (2060–2079), SSP2-4.5 continues to show fully saturated extreme hazard conditions, while SSP5-8.5 reinforces and intensifies the same pattern. Scenario divergence is negligible, confirming that wildfire risk is among the least sensitive hazards to mitigation pathways. For the Rundu rural water-supply concept, this persistent extreme wildfire hazard implies that infrastructure must be planned with fire-resistant materials, protected corridors, and operational protocols capable of maintaining service during fire events. Access routes may be compromised, aboveground components may face direct thermal exposure, and communities themselves may experience simultaneous water demand spikes during fire outbreaks. Wildfire resilience therefore becomes an essential pillar of the system’s long-term climate robustness.

Figure 77. Wildfire Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPs 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.

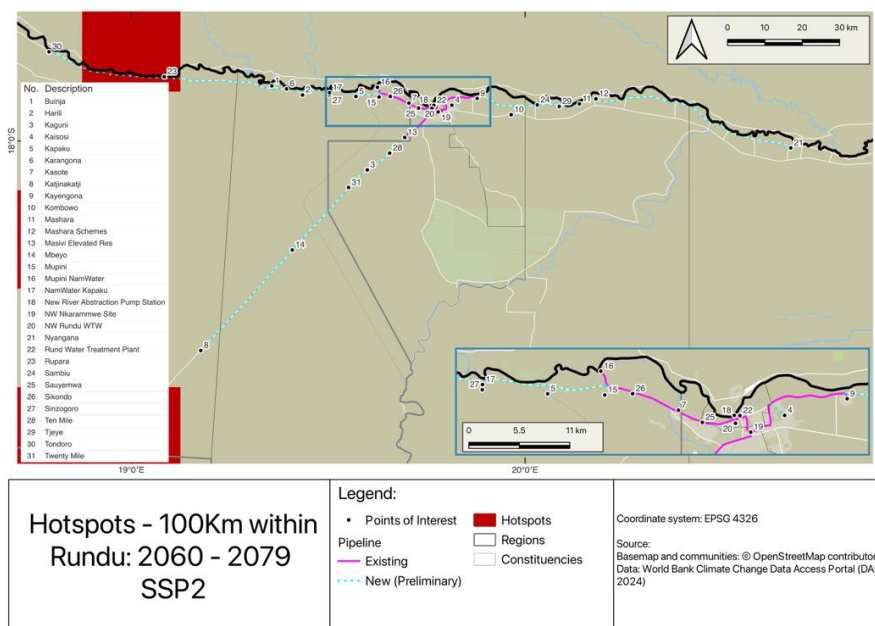


7.4.4.6 Multihazard Hotspots for the 100 Km Rundu Water Projects.

After examining each hazard individually, the multihazard hotspot analysis provides an integrated understanding of where multiple climate stressors converge within the 100 km radius around Rundu. These hotspots represent areas where high, very high or extreme levels of drought, flash flooding and fluvial flooding overlap spatially across long-term horizons. The importance of identifying these areas lies in the fact that even if hazards do not occur simultaneously, the cumulative or sequential nature of impacts can significantly amplify vulnerability, reduce system reliability and heighten lifecycle risk for water-supply infrastructure. Zones repeatedly exposed to back-to-back climate shocks tend to experience accelerated degradation of assets, disrupted access for maintenance crews and reduced resilience of both natural and built systems.

For long-distance water supply schemes (such as the envisaged Rundu rural supply concept) multihazard hotspots are therefore a critical layer of analysis. They allow to screen alignment sections, identify potentially unsuitable zones for locating critical nodes (pump stations, river abstractions, elevated tanks) and preemptively integrate design safeguards. Areas showing consistent multihazard stress may still accommodate linear infrastructure but will require enhanced protection measures, conservative hydraulic and structural design margins, and contingency planning for service continuity. Overall, this chapter provides a consolidated view of the climate-risk landscape, highlighting zones where cumulative exposure could compromise system performance if not adequately accounted for in the prefeasibility and later design stages.

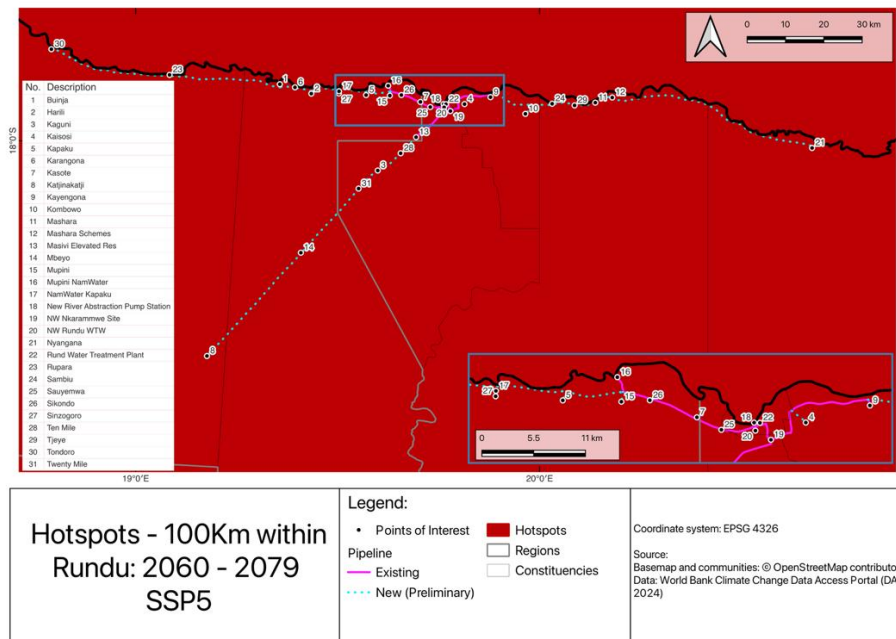
Figure 78. SSP2-4.5 Multihazard Hotspots. 100 Km around Rundu Water Supply Project. Projections to 2060-2079 Source: the author.



Under SSP2-4.5, multihazard hotspots are limited but strategically important.

The hotspot cluster is located along the main river corridor along the western preliminary branch of the scheme, near rural settlement of Rupara, where high drought hazard combines with significant flash-flood exposure in small catchments. In that cluster the co-occurrence of hazards increases the likelihood of service interruptions, higher maintenance needs and faster degradation of embankments, river intakes and access roads. This segment should therefore be prioritised for reinforced design standards, redundant conveyance options and clear emergency-response protocols before confirming final alignments.

Figure 79. SSP5-8.5 Multihazard Hotspots. 100 Km around Rundu Water Supply Project. Projections to 2060-2079 Source: the author.



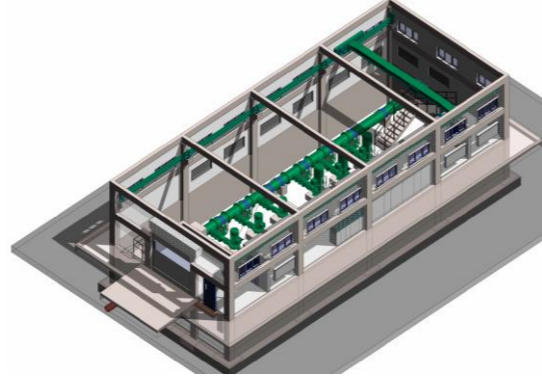
Under SSP5-8.5, the multihazard footprint expands substantially and the 100 km corridor around Rundu becomes almost entirely classified as a hotspot. High to extreme drought conditions extend across most inland areas, while intense flash-flood and fluvial-flood hazard remain widespread along the river corridor and many tributary catchments. As a result, both existing and preliminary pipeline alignments traverse long stretches where infrastructure would be exposed to overlapping stressors rather than isolated events. In this scenario, the concept of “hotspot” evolves from discrete avoidance zones to a systemic design need: robust flood-protection and drainage, flexible intake and storage options, and adaptive operation and maintenance planning will be required along most of the scheme. For strategic planning, this reinforces the need to test the project under SSP5-type assumptions, even if actual emissions pathways move closer to SSP2-4.5, to ensure that the rural water-supply concept remains viable under high-impact climate futures.

The semi-detailed hazard and hotspot maps explicitly overlay High, Very High and Extreme hazard bands with the indicative bulk-supply alignments and rural nodes, allowing early identification of hazard-specific hotspots along the envisaged 100-km extensions.




7.4.5 Implications for siting, design and operations.



The preceding hazard-specific and multihazard-hotspot analysis defines the envelope of climate and flood stresses within which the preliminary 100-km Rundu rural water-supply concept will operate. Heat stress and wildfire emerge as pervasive background constraints, while drought, fluvial floods and flash floods concentrate along the Okavango River corridor and key branches of the indicative alignment, with a discrete multihazard hotspot near Rupara under SSP2-4.5 and an almost continuous hotspot corridor under SSP5-8.5. Building on these findings, Table 39 summarises the main assets foreseen for the scheme, outlines their indicative climate-change vulnerabilities in relation to the mapped hazards and hotspots, and proposes preliminary siting, design and operational measures to reduce risk. The table is intended as a screening tool to flag sections where critical nodes should be avoided or hardened, and to inform the scope of more detailed prefeasibility and engineering studies.

Table 39. 100Km around Rundu project. Description of the assets part of the 100 Km Rundu project extension (preliminary), its vulnerability to climate change and current or proposed mitigation. Source: the author.

No	Description	Image of Existing or an Example of the Infrastructure	Comments	Vulnerability to climate change	Current or Proposed Mitigation
1	River abstraction pump station. Pump station abstraction water from the Ogavango and pump water to the new Rundu WTP		This infrastructure is not included in the scope of this project, as it is currently being constructed under an existing NamWater initiative: the Rundu Purification Plant Extension	<p>The intake area falls within the high fluvial-flood corridor and, under SSP5-8.5, within the multihazard hotspot belt, where drought, fluvial floods and flash floods can occur sequentially. This increases the likelihood of repeated inundation of civil works, access roads and power supply, alternating with periods of low river levels and high sediment loads. Main vulnerabilities:</p> <ul style="list-style-type: none"> • Water source from Angola (drought / low river level). • Fluctuation in river level (flooding of pump station / low submergence at pump intake). 	<ul style="list-style-type: none"> • Install intake as low as possible / feasible • Select equipment to be submerged (even if installed dry) if below flood line such as dry installed submersible pumps and motors
2	New Rundu Water Treatment Plant (WTP). Conventional water treatment plant to treat river water.		This infrastructure is not included in the scope of this project, as it is currently being constructed under an existing NamWater initiative: the Rundu Purification Plant Extension	The plant is located close to the Okavango River corridor, where fluvial-flood hazard remains High to Very High across all horizons, and under SSP5-8.5 it is embedded in the multihazard hotspot corridor. This implies recurrent exposure to bank erosion, access disruption that may affect treatment performance.	During the field mission the WTP works were visited, and the mitigation measures have been considered: setting critical process units and electrical rooms on flood-protected platforms, fire protections and options to manage low-flow and turbidity events.
3	Pressure / base pump station/ss at the Rundu WTP. Pump station/s convey water to the different areas identified above.		No information is available on these pump stations. Size and pressure to be confirmed once water demand and hydraulic design have been completed.	<ul style="list-style-type: none"> • Flooding if pumps are installed below ground level • Motor failure due to high ambient temperature • Failure of electrical and electronic equipment due to excessive ambient temperatures • Power outages (no power no pumping) / loss in production due extreme weather conditions affecting power supply • Extreme working condition due to high ambient conditions during maintenance operations 	<ul style="list-style-type: none"> • Install early warning (level sensor) for flooding indication • Select equipment to be submerged (even if installed dry) if below ground level such as dry installed submersible pumps and motors • Depending on the size of the motors and variable speed drives (VSDs) install water cooled equipment. The water being pumped can be used as a cooling source. • Use synchronous reluctance motors (SynRM) for reduced heat load. • Ensure building is well naturally ventilated. Ventilation calculation should be based on future higher ambient condition • Provide HVAC equipment for electrical and mechanical equipment. Heat load estimates should be based on future higher ambient condition. • Select well insulated building material. • Provide 48 storage at end uses to allow for power outages. • Install surge protection in MCC.
4	Main Pressure pipeline/s from the Rundu WTP to the to the different areas identified above. This is normally oPVC or uPVC piping.		No information is available on the pressure pipelines. Size and pressure class to be confirmed once water demand and hydraulic design have been completed. Pipe diameters will in all probability range from OD 110 mm to OD 355 mm.	<p>Along the western branch towards Rupara and other rural stretches, trunk mains traverse areas identified as multihazard hotspots, where High to Extreme drought coincides with persistent flash flood and fluvial-flood hazard. Sequential drying and flooding can accelerate ground movement, embankment instability and scour at river and drainage crossings. Main vulnerabilities:</p> <ul style="list-style-type: none"> • Damage to pipe material during construction due to high temperature when pipe material is stored on site. The recommended maximum storage temperature for oPVC is 45°C. For uPVC this is higher at 55°C. 	<p>For hotspot segments (e.g. the western branch near Rupara), consider local rerouting to avoid the most exposed polygons, deeper burial with trench stabilisation, and upgraded protection at crossings (culverts, encasement, thrust blocks and rock armouring). Main considerations:</p> <ul style="list-style-type: none"> • Ensure piping are not stored directly in the sun and when covered there should be natural ventilation to avoid high storage temperatures. • When PVC pipelines are installed, pipes must be underground.

No	Description	Image of Existing or an Example of the Infrastructure	Comments	Vulnerability to climate change	Current or Proposed Mitigation
				<ul style="list-style-type: none"> Flash flooding could cause damaged to installed pipes. 	<ul style="list-style-type: none"> Where pipeline pass through rivers ensures sufficient cover or encase pipeline in concrete to avoid damage during flash flooding. Select different material for above ground pipeline such as steel or ductile cast iron.
5	Ground / elevated sectional steel reservoirs tanks for water storage at each scheme or areas identified above. To provide 48-hour storage of AADD.		No information is available on the reservoir capacities and elevated height currently. Sizes and height to be confirmed once water demand and hydraulic design have been completed.	<p>Storage sites located close to the river corridor or within depressions are exposed to High to Very High fluvial- and flash-flood hazard, while inland reservoirs fall under increasing drought and Extreme wildfire hazard across all horizons. In hotspot areas, repeated cycles of drought, high temperatures and intense storm runoff can stress foundations, access roads and power supply simultaneously.</p> <ul style="list-style-type: none"> Leaks could occur due to excessive expansion and contraction due to higher daily seasonal temperature ranges (unlikely). 	<p>Prioritise siting of new reservoirs outside mapped multihazard hotspots where feasible; where this is not possible, elevate tanks above design flood levels, harden access and drainage, and maintain cleared, fire-resistant buffer zones around structures. Main considerations:</p> <ul style="list-style-type: none"> Ensure reservoirs have a sufficient water level to prevent excessive expansion and contraction. If the reservoir is sized for 48 hours the level of water in the reservoir will remain constant except in the event of an emergency
6	Disinfection facilities such as chlorine gas disinfection, Sodium Hypochlorite dosing, or Calcium Hypochlorite tablets	 <p>Cl₂ Gass Installation</p>  <p>Sodium Hypochlorite</p>	No information is available on the dosing requirements. Capacities and type to be confirmed once water demand and hydraulic design have been completed and the final water quality is known.	<p>In hotspot locations, disinfection facilities may be affected by concurrent stresses: power interruptions from storms and wildfires, access constraints during flash- or fluvial-flood events, and higher chlorine demand driven by warmer water and increased organic loads after drought-breaking storms. Main considerations:</p> <ul style="list-style-type: none"> Pressure builds up in chlorine gas cylinders if stored at temperatures above 55°C. Decomposition of Sodium Hypochlorite and Calcium Hypochlorite tables disinfection at high temperatures. 	<ul style="list-style-type: none"> Provide backup power and sufficient on-site chemical storage at hotspot reservoirs and design flexible dosing capacity to cope with sharp post-storm turbidity and organic spikes. Provide plantroom for disinfection equipment. Ensure building is well naturally ventilated. Ventilation calculation should be based on future higher ambient condition Select well insulated building material

No	Description	Image of Existing or an Example of the Infrastructure	Comments	Vulnerability to climate change	Current or Proposed Mitigation
7	Booster pumps to elevate water to elevated reservoirs and along the pipeline for additional pressure boosting if the hydraulic design require these.		No information is available on these pump stations. Size, location and pressure to be confirmed once water demand and hydraulic design have been completed.	<p>Booster stations located along the western branch near Rupara, and other low-lying crossings fall within multihazard hotspots, where overlapping drought, flash flood and fluvial-flood hazards can trigger frequent access cuts, scour around foundations and repeated electrical outages. Main considerations:</p> <ul style="list-style-type: none"> • Flooding if pumps are installed below ground level (normally installed above ground level) • Motor failure due to high ambient temperature • Failure of electrical and electronic equipment due to excessive ambient temperatures • Power outages (no power no pumping) / loss in production due extreme weather conditions affecting power supply • Extreme working condition due to high ambient conditions during maintenance operations 	<ul style="list-style-type: none"> • Install early warning (level sensor) for flooding indication • Select equipment to be submerged (even if installed dry) if below ground level such as dry installed submersible pumps and motors • Depending on the size of the motors and variable speed drives (VSDs) install water cooled equipment. The water being pumped can be used as a cooling source. • Use synchronous reluctance motor (SynRM) for reduced heat load. • Ensure building is well naturally ventilated. Ventilation calculation should be based on future higher ambient condition • Provide HVAC equipment for electrical and mechanical equipment. Heat load estimates should be based on future higher ambient condition. • Select well insulated building material. • Provide 48 storage at end uses to allow for power outages. • Allow mobile standby generator to be connected to system in the event of a power failure. • Design to consider standalone PV installation, including battery energy storage system (BESS) to provide electrical power. • Install surge protection in MCC.
8	Water meter installations to measure production and sales	 	<p>Mechanical Water Meter Manifold</p> <p>Electromagnetic Production Flow Meters</p> <p>No information is available on demand. Size and location pressure to be confirmed once water demand and hydraulic design have been completed.</p>	<ul style="list-style-type: none"> • Failure of water meters due to very high ambient conditions (unlikely) • Damage to electromagnetic water meters due to flooding. 	<ul style="list-style-type: none"> • Protect water meters form direct sunlight. • Where water meters are installed below ground level specify equipment that can be submerged.

No	Description	Image of Existing or an Example of the Infrastructure	Comments	Vulnerability to climate change	Current or Proposed Mitigation
9	Electrical power supply to pump station and other infrastructure that require electrical power. Medium voltage (MV) power lines.		No information currently available on the electrical load therefore size and availability of electrical power should be determined during concept / preliminary design stage to finalise this.	<p>Overhead MV lines traverse areas of High to Extreme storm and wildfire hazard. Strong winds, lightning and bushfires can damage poles and conductors, particularly along the rural branches, leading to repeated power outages for pumps and treatment facilities. Main considerations:</p> <ul style="list-style-type: none"> • Reduced power capacity (de-rating) increased physical sagging of overhead lines, and accelerated degradation of insulation due to high ambient conditions. • Lighting strikes due to severe weather. 	<p>In hotspot segments, consider improved pole foundations, fire-resistant pole materials where feasible, increased lightning protection.</p> <ul style="list-style-type: none"> • Specify conductor material to accommodate the future ambient temperatures. • Provide sufficient protection (switchgear) for especially lightning.
10	SCADA and telemetry system to stations		The extend of the system would only be known once the design of the entire system is completed.	<p>Because SCADA and telemetry depend on the same MV lines and towers that cross multihazard hotspots, their functionality is sensitive to concurrent storm-related outages, heat-induced equipment stress and wildfire-related damage. Loss of communications during compound events could delay fault detection and recovery along the 100-km corridor. Main considerations:</p> <ul style="list-style-type: none"> • Failure of electronic equipment due to excessive ambient temperatures. • Power outages loss in communication due extreme weather conditions affecting power supply. 	<p>Provide redundant communication paths (e.g. dual power supplies, radio / GSM back-up) for key nodes within hotspot areas and ensure that local control modes allow safe operation during temporary loss of telemetry. Main considerations:</p> <ul style="list-style-type: none"> • Provide HVAC equipment for electrical and mechanical equipment. Heat load estimates should be based on future higher ambient condition. • Select well insulated building material. • Provide backup (batteries) power for electronic control equipment • Provide secure design of antennas for severe weather conditions. • Provide lightning protection.

PART VIII : CONCLUSIONS

This Climate Risk and Vulnerability Assessment (CRVA) deliver a comprehensive evaluation of climate-related hazards and their implications for Namibia's water sector, focusing on the Kunene and Kavango basins where NWSISP II investments will be concentrated. The analysis combines climate hazard projections, multi-hazard hotspot mapping, exposure assessments of WASH assets, and a preliminary site-level evaluation of planned infrastructure. Together, these components provide a robust evidence base to guide strategic investment planning, ensuring that water-sector interventions are resilient to the evolving climate dynamics that will shape Namibia's future.

The findings underscore the urgency of integrating climate risk considerations into water infrastructure design and operational planning. By identifying where hazards intensify, where infrastructure is most exposed, and how planned investments intersect with climate pressures, this assessment enables targeted adaptation measures and informed sequencing of investments. It also lays the groundwork for mobilizing adaptation finance and strengthening institutional preparedness to safeguard water security objectives under changing climatic conditions.

At the **hazard level**, the Kunene Basin is characterized by a hazard profile dominated by drought, extreme heat, and strong wind events, all projected to intensify throughout the century. These hazards have direct implications for water availability, asset longevity, and operational reliability. Hotspot analysis reveals that the central and eastern sections of the basin represent priority zones where these hazards converge at the highest intensity. These areas will require climate-resilient design standards and contingency planning to maintain service continuity under prolonged dry spells and heat stress.

In contrast, the Kavango Basin faces a markedly different hazard profile. Here, fluvial flooding, pluvial flash floods and rising temperature extremes are the most significant threats. River-adjacent areas and low-lying floodplains, including the lower Okavango corridor between Nkurenkuru and Rundu, are expected to experience increasingly severe and frequent flood-related impacts, particularly under high-emission scenarios. Multi-hazard hotspots cluster along this corridor and around the main urban centres, where fluvial and pluvial hazards compound with high heat and drought stress and threaten both current WASH systems and priority bulk-water investments. This pattern is directly relevant for the Kavango Link transfer and for the conceptual 100-km rural water-supply extensions around Rundu, underscoring the need for robust flood-proofing and multi-hazard-resilient engineering solutions wherever alignments and facilities intersect these hotspot belts.

At the **exposure level**, the assessment demonstrates that the Kavango East and Kavango West regions hold the highest concentration of WASH assets located within future high-hazard zones. Pipelines, boreholes and pumping stations in these constituencies are highly exposed under both SSP2-4.5 and SSP5-8.5 scenarios, indicating that flood-related pressures will remain a persistent challenge even under moderate emissions pathways. Within this pattern, the urban and peri-urban belt around Rundu and the surrounding rural constituencies that fall within the 100-km concept area emerge as a priority exposure cluster where existing and planned water-supply assets intersect the multi-hazard hotspot corridor along the lower Okavango. In the Kunene Region, exposure is driven primarily by drought severity and extreme heat, with rural water points, boreholes and conveyance assets intersecting zones of projected hydrological stress. Constituencies dependent on the Calueque–Oshakati system show consistent exposure across scenarios due to reduced rainfall reliability and increased evapotranspiration, reinforcing the need for redundancy and climate-informed operational protocols.

At the **vulnerability and risk levels**, the CRVA integrates asset sensitivity, operational fragility and institutional capacity into basin-level indices for WASH systems and into segment-level indices for the Kavango Link. For WASH systems in both basins, drought and heat generally drive High or Very High risk where they coincide with high dependence on single surface-water sources and limited redundancy, while flood-related risks peak in constituencies with dense infrastructure on floodplains and weak protection standards. For the Kavango Link segments, risk is highest where intakes, pump stations and major conveyance corridors traverse the multi-hazard hotspot belt along the lower Okavango; the same hotspot corridor also frames the preliminary risk screening for the Rundu 100-km rural water-supply extensions, confirming the need to avoid, where feasible,

siting critical assets in these polygons or to compensate exposure with robust protection, redundancy and emergency-operation protocols.

The asset-level assessment of the **Kavango Link** provides a practical example of how climate risk screening can be embedded into project design and implementation planning. The alignment intersects several hazard zones, particularly those associated with fluvial flooding, pluvial flash flows and extreme heat, and crosses the multi-hazard hotspot belt identified along the lower Okavango between Nkurenkuru and Rundu. Climate exposure varies along the route, with segments S0–S2 near the river and across the northern Kalahari showing higher exposure to floods, flash floods and erosion, while southern segments are dominated by heat, drought and wind-/dust-related stresses. Recommended adaptation measures include reinforced anchoring, elevated and flood-hardened structures, conservative drainage and scour-protection standards, and material specifications capable of withstanding thermal and hydrological stressors, combined with operational redundancy and contingency storage. The same design principles apply to the future **100-km rural water-supply extensions around Rundu**, where conceptual corridors should, as far as practicable, avoid the core multi-hazard polygons and, where they cannot, adopt equivalent or higher protection standards. These differentiated design responses will be critical to ensuring the long-term resilience of both the Kavango Link and associated rural supply schemes.

Finally, the CRVA provides a strategic foundation for the forthcoming **Adaptation Options Report**. By pinpointing hazard hotspots, exposure concentrations, and asset-level vulnerabilities, this assessment enables targeted interventions such as climate-resilient engineering designs, strengthened operation and maintenance protocols, improved monitoring and early warning systems, redundancy and network diversification, watershed and ecosystem protection, and climate-informed investment sequencing. This evidence base will support the Government of Namibia, AfDB, GCA, and implementation partners in aligning NWSISP II investments with the realities of a changing climate, ensuring that water security objectives can be met sustainably and equitably.

BIBLIOGRAPHY

- [1] ISO 14091:2021. Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment. International Organization for Standardization.
- [2] ISO 14090:2019. Adaptation to climate change – Principles, requirements and guidelines. International Organization for Standardization.
- [3] ISO 31000:2018. Risk management – Guidelines. International Organization for Standardization.
- [4] ISO 31010:2019. Risk management – Risk assessment techniques. International Organization for Standardization.
- [5] ISO 24510:2007. Activities relating to drinking water and wastewater services – Guidelines for the assessment and for the improvement of the service to users. ISO.
- [6] ISO 24511:2007. Activities relating to drinking water and wastewater services – Guidelines for the management of wastewater utilities and for the assessment of wastewater services. ISO.
- [7] ISO 24512:2007. Activities relating to drinking water and wastewater services – Guidelines for the management of drinking water utilities and for the assessment of drinking water services. ISO.
- [8] ISO 24516-1:2016. Guidelines for the management of assets of water supply and wastewater systems – Part 1: Drinking water distribution networks. ISO.
- [9] ISO 24518:2015. Activities relating to drinking water and wastewater services – Crisis management of water utilities. ISO.
- [10] IPCC AR6 WG1 Chapter 11. Weather and Climate Extreme Events in a Changing Climate. Intergovernmental Panel on Climate Change, 2021.
- [11] IPCC AR6 WG1 Annex VI. Climatic Impact-Driver and Extreme Indices. Intergovernmental Panel on Climate Change, 2021.
- [12] WMO/ETCCDI. Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation. WMO-TD No. 1500, 2009.
- [13] Zhang X, et al. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Clim Change*. 2011;2(6):851–870.
- [14] World Bank Group. Climate Risk Country Profile: Namibia. Washington, DC: World Bank; 2021.
- [15] GFDRR. ThinkHazard: Namibia – Overview and hazard modules. Washington, DC: World Bank/GFDRR; 2020.
- [16] UNDRR & CIMA Research Foundation. Disaster Risk Profile: Namibia. Geneva/Nairobi: UNDRR; 2019.
- [17] Republic of Namibia. Fourth National Communication (NC4) to the UNFCCC. Windhoek: Government of Namibia; 2020.
- [18] African Development Bank. Climate Safeguards System (CSS): Guidance Materials. Abidjan: AfDB; [undated].
- [19] African Development Bank. Borrower Guidance Note for the Updated Integrated Safeguards System (ISS). Abidjan: AfDB; 2024.
- [20] Hersbach H, et al. The ERA5 global reanalysis. *QJR Meteorol Soc*. 2020;146(730):1999–2049.
- [21] Giorgi F, Gutowski WJ. Regional Dynamical Downscaling and the CORDEX Initiative. *Annu Rev Environ Resour*. 2015; 40:467–490.
- [22] Iturbide M, et al. An update of IPCC “Atlas”. *Earth Syst Sci Data*. 2021;13:665–685.
- [23] Vicente-Serrano SM, et al. A multiscalar drought index sensitive to global warming: the SPEI. *J Climate*. 2010;23:1696–1718.
- [24] McKee TB, Doesken NJ, Kleist J. The relationship of drought frequency and duration to time scales. *Proc. 8th Conf. on Applied Climatology*, 1993:179–184.

- [25] African Union Commission. Agenda 2063: The Africa We Want. Addis Ababa: AUC; 2015.
- [26] Windhoek Observer. (2024, Oct 31). Plans to draw water from Okavango intensify.
- [27] Namibia Water Corporation (NamWater). (2024 - 2025). ESIA/ESMP Bid SC/RP/NW-009/2025: Okavango Link to Secure Water Supply to CAN. Procurement pages.
- [28] NBC Online. (2024). NamWater explores Kavango Link to supply water to central area.
- [29] The Brief Namibia. (2024, May 8). NamWater plans N\$7bn Okavango extraction to mitigate CAN water crisis.
- [30] New Era. (2024, Jul 3). Rundu to get N\$665m water purification plant.
- [31] NamWater. (2022). Rundu Purification Plant Upgrade (project summary/ESIA BID).
- [32] Xinhua. (2024, Jul 2). Chinese firm to expand Rundu water treatment plant.
- [33] Informanté. (2024, Jul 2). N\$665m project to enhance water supply in Rundu.
- [34] Windhoek Observer. (2024, Feb 16). Upgrade for Rundu purification plant.
- [35] EIS Namibia Library. (2023). EMP: Grootfontein - Omatako Canal Water Supply Scheme (ENWC).
- [36] Windhoek Observer. (2025, Aug 1). Water supply capacity to increase by 2030 (incl. ENWC canal restoration).
- [37] EIS Namibia Library. (2019). EMP: Continuation of the Waterberg - Okakarara Water Supply Scheme & infrastructure maintenance.
- [38] Windhoek Observer. (2024). Ohangwena - Oshikoto water supply issues addressed [26] (Ohangwena II scheme facts).
- [39] The Namibian. (2024, Jul 2). Govt kick-starts N\$250m water supply project (Omundaungilo - Omutsegwonime).
- [40] Smart Water Magazine. (2025, May 23). Namibia secures €75 million loan. Omundaungilo – Omutsegwonime Bulk Pipeline Scheme.
- [41] Reuters. (2024, Jun 27). Namibia to build second desalination plant in January 2025.
- [42] New Era. (2024, Apr 16). Second desalination plant coming (NamWater–Swakop Uranium JV; 20 Mm³/yr).
- [43] Lund Consulting Engineers (LCE). (n.d.). Projects: Oshivelo - Omutsegwonime - Okankolo Water Supply Project.
- [44] NBC Online. (2024). Ondangwa–Omutsegwonime water project to resolve supply challenges (phase budgets & schedule).
- [45] Confidante Namibia. (2025, May 2). NamWater reports progress on 110-km pipeline project (Ondangwa-Omuthiya - Omutsegwonime).
- [46] BGR/DWA. (2005). Groundwater Investigations in the Oshivelo Region – Main Hydrogeological Report.
- [47] Mendelsohn, J., Jarvis, A., Roberts, C., & Robertson, T. (2009). Atlas of Namibia: A portrait of the land and its people (2nd ed.). Sunbird Publishers.
- [48] Intergovernmental Panel on Climate Change (IPCC). (2021). Sixth Assessment Report (AR6): Climate Change 2021 – The Physical Science Basis. Cambridge University Press.
- [49] Namibia Ministry of Agriculture, Water and Land Reform (MAWLR). (2013). Water Resources Management Act No. 11 of 2013. Government of Namibia.
- [50] Global Center on Adaptation (GCA). (2025). Climate Risk and Vulnerability Assessment for Namibia Water Sector Infrastructure Program (NWSIP II). GCA-PR-23-323.
- [51] World Bank Group. (2021). Climate Risk Profile: Namibia. Climate Knowledge Portal, World Bank.
- [52] Government of the Republic of Namibia (2023). Updated Nationally Determined Contribution (NDC). UNFCCC registry.
- [53] Office of the Prime Minister (1997). National Drought Policy & Strategy. Government of Namibia.

[54] WHO/UNICEF JMP (2023). Progress on household drinking water, sanitation and hygiene (country data: Namibia).

[55] NamWater (2024). Integrated Annual Report 2023/24 (includes Ruacana/Kunene flow variability).

TABLES AND FIGURES

Tables

Table 1. Climate indices used in the study.	18
Table 2. Hazard level matrix to assess Heat stress.	21
Table 3. Hazard level matrix to assess droughts.	22
Table 4. Hazard level matrix to assess pluvial flash floods.....	23
Table 5. Hazard level matrix to assess fluvial floods.	24
Table 6. Hazard level matrix to assess Storms.	25
Table 7. Hazard level matrix to assess Wildfires.	26
Table 8. Risk Assessment Criteria Tables.	33
Table 9. Overview on relevant climate hazards in the water and sanitation sector.	55
Table 10. Heat Stress Indicators - Anomalies vs. Reference Period (1995–2014). Source: CCKP, World Bank... 57	57
Table 11. Drought Indicators - CDD vs. Reference Period (1995–2014). Source: CCKP, World Bank.	59
Table 12. Pluvial Flash Floods - Reference Period (1995–2014). Source: CCKP, World Bank.	60
Table 13. Fluvial Floods - Reference Period (1995–2014). Source: CCKP, World Bank.	61
Table 14. Wildfires - Reference Period (1995–2014). Source: CCKP, World Bank.	63
Table 15. Heat Stress indicators anomalies. Reference Period (1995–2014). Source: CCKP, World Bank.	65
Table 16. Drought indicators. Reference Period (1995–2014). Source: CCKP, World Bank.	66
Table 17. Pluvial Flash Floods indicators. Reference Period (1995–2014). Source: CCKP, World Bank.	67
Table 18. Fluvial Floods indicators. Reference Period (1995–2014). Source: CCKP, World Bank.	69
Table 19. Wildfires proxy indicators. Reference Period (1995–2014). Source: CCKP, World Bank.....	70
Table 20. Hazard levels in the Kunene River Basin for SSP2-4.5 and SSP5-8.5 scenarios and 2020-2039, 2040-2059 2060-2079 and 2080-2099 time slices.	77
Table 21. Hazard levels in the Okavango River Basin for SSP2-4.5 and SSP5-8.5 scenarios and 2020-2039, 2040-2059 2060-2079 and 2080-2099 time slices.	78
Table 22. Percentage of WASH infrastructure exposed to Hotspots by constituency in Kunene and Kavango regions.....	101
Table 23. Percentage of WASH infrastructure exposed to Hotspots by constituency in Kunene and Kavango regions (SSP2-4.5 and SSP5-8.5 scenarios and 2060-2079 period). Source: The Water Supply Points, NSA 2022. Ministry of Agriculture, Water & Land Reform. Urban Areas, Ministry of Urban and Rural Development 2022. .	102
Table 24. Vulnerability Index reporting classes. Source: the author.	103
Table 25. Assignment rationale for Heat Stress by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.	104
Table 26. Vulnerability index results for heat stress hazard (Typology-based calculation).	105
Table 27. Vulnerability index results for drought hazard (Typology-based calculation).	106
Table 28. Vulnerability index results for fluvial flash floods hazard (Typology-based calculation).	106
Table 29. Vulnerability index results for pluvial flash floods hazard (Typology-based calculation).	107
Table 30. Vulnerability index results for wildfires hazard (Typology-based calculation).	108
Table 31. Estimated CAN water demand.	116
Table 32. CAN-Okavango Link Pump station and termination location.	117
Table 33. Climate hazard summary and rationale.....	125
Table 34. Components for risk assessment 129	129
Table 35. Proposed Segmentation for the analysis (S0–S5) for CRA Scoring and Works Packaging..... 132	132
Table 36. Impact Criteria and rating scale..... 140	140
Table 37. Okavango Link. Summary Climate Risk Evaluation Table by segment (2020-2039- and 2040-2059 for SSP2 and SSP5).	143
Table 38. Water projects 100 Km radius Rundu. Summary table with locations and estimated water demand. Source: NamWater additional information from the author.	155
Table 39. 100Km around Rundu project. Description of the assets part of the 100 Km Rundu project extension (preliminary), its vulnerability to climate change and current or proposed mitigation. Source: the author.	166
Table 38. Assignment rationale for Heat Stress by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.	180
Table 39. Assignment rationale Drought by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.	181

Table 40. Assignment rationale Pluvial flash floods by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.	182
Table 41. Assignment rationale Fluvial flash floods by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.	183
Table 42. Assignment rationale Wildfire by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.	184

Figures

Figure 1. Illustration of Climate risk assessment process. Source: the author.	32
Figure 2: Topography, perennial and ephemeral rivers and water bodies in Namibia.	34
Figure 3. Mean daily temperature for the reference period (on the left) and absolute changes (with respect to the reference period) of the mean daily temperature recorded for the SPSS 2-4.5 and SPSS 5-8.5 future scenarios (2060-2079), central and right side, respectively.	35
Figure 4. Projected timeseries of average mean daily temperature from the historical reference period (1950-2014) and SPSS 2-4.5 and SPSS 5-8.5 future scenarios. Dots represent the median values, shaded areas the 10th-90th percentile's range.	36
Figure 5. Projected change of average means daily temperature for 2020-2039, 2040-2059 and 2060-2079 time periods. Multi-Model Ensemble (reference period 1995-2014) for SPSS 2-4.5 on the left and for SPSS 5-8.5 on the right.	36
Figure 6. Mean total annual precipitation for the reference period (on the left) and absolute changes (with respect to the reference period) of the mean total annual precipitation recorded for the SPSS 2-4.5 and SPSS 5-8.5 future scenarios (2060-2079), central and right side, respectively.	37
Figure 7. Projected timeseries of precipitation from the historical reference period (1950-2014) and SPSS 2-4.5 and SPSS 5-8.5 future scenarios. Dots represent the median values, shaded areas the 10th-90th percentile's range.	38
Figure 8. Change in the mean total annual precipitation from the reference period (1995-2014) to the historical period (1991-2020, in black) and SPSS 2-4.5 and SPSS 5-8.5 future scenarios (left side). Dots represent the median values, shaded areas the 10th-90th percentile's range.	38
Figure 9. Kunene river basin. Change in Maximum of Daily Max-Temperature Percentile 90 (TXx P90) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	39
Figure 10. Kunene river basin. Change in the warm spell duration index from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	40
Figure 11. Kunene river basin. Change in Mean Maximum 1-day precipitation (Rx1day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	41
Figure 12. Kunene river basin. Change in Mean Maximum 5-day precipitation (Rx5 day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	41
Figure 13. Kunene river basin. Change in the Number of days with precipitation ≥ 20 mm (R20mm) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	43
Figure 14. Kunene river basin. Change in the Number of days with precipitation ≥ 50 mm (R50mm) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	43
Figure 15. Kunene river basin. Change of the Drought index (SPEI) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	44
Figure 16. Kunene river basin. Change in Maximum number of Consecutive Dry Days (CDD) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	44
Figure 17. Okavango river basin. Change in Maximum of Daily Max-Temperature Percentile 90 (TXx P90) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	45

Figure 18. Okavango river basin. Change in the warm spell duration index from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	46
Figure 19. Okavango river basin. Change in Mean Maximum 1-day precipitation (Rx1day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	47
Figure 20. Okavango river basin. Change in Mean Maximum 5-day precipitation (Rx5 day) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	47
Figure 21. Okavango river basin. Change in the Number of days with precipitation ≥ 20 mm (R20mm) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	48
Figure 22. Okavango river basin. Change in the Number of days with precipitation ≥ 50 mm (R50mm) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	49
Figure 23. Okavango river basin. Change of the Okavango River (SPEI) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	50
Figure 24. Okavango river basin. Change in Maximum number of Consecutive Dry Days (CDD) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: CCKP, World Bank.	50
Figure 25. Kunene and Kavango transboundary river Basins. Source: the author.	54
Figure 26. Kunene river basin. Heat Stress Hazard) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	58
Figure 27. Kunene river basin. Drought Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	59
Figure 28. Kunene river basin. Pluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	60
Figure 29. Kunene river basin. Fluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	62
Figure 30. Kunene river basin. Wildfire Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	63
Figure 31. Okavango river basin. Heat Stress Hazard) from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	65
Figure 32. Okavango river basin. Drought Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	66
Figure 33. Okavango river basin. Pluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	68
Figure 34. Okavango river basin. Fluvial Flash Floods Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	69
Figure 35. Okavango river basin. Wildfire Hazard from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	71
Figure 36. Kunene river basin. Multi-hazard hotspots combining drought, pluvial flash floods and fluvial floods for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots correspond to grid cells where all three hazards simultaneously fall within the High, Very High or Extreme classes (“High+”). Source: the author.	74
Figure 37. Okavango River Basin. Multi-hazard hotspots combining drought, pluvial flash floods and fluvial floods for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots correspond to grid cells where all three hazards simultaneously fall within the High, Very High or Extreme classes (“High+”). Source: the author.	75
Figure 38. Kunene Region-North. WASH assets exposure to drought from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	82
Figure 39. Kunene Region-South. WASH assets exposure to drought from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	83
Figure 40. Kavango West region. WASH assets exposure to drought from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	84

Figure 41. Kavango East region. WASH assets exposure to drought from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author. .	85
Figure 42 .Kunene Region-North. WASH assets exposure to pluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	87
Figure 43. Kunene Region-South. WASH assets exposure to pluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	88
Figure 44. Kavango West region. WASH assets exposure to pluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	89
Figure 45. Kavango East region. WASH assets exposure to pluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	90
Figure 46 .Kunene Region-North. WASH assets exposure to fluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	92
Figure 47. Kunene Region-South. WASH assets exposure to fluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	93
Figure 48.Kavango West region. WASH assets exposure to fluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	94
Figure 49. Kavango East region. WASH assets exposure to fluvial flash floods from the reference period (1994-2014) to near future (2020-2039), mid-term future (2040-2059) and long-term future (2060-2079). Source: the author.	95
Figure 50 . Kunene Region–North. WASH assets located in multi-hazard hotspots for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classes. Source: the author.	97
Figure 51. Kunene Region–South. WASH assets located in multi-hazard hotspots for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5 Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classe . Source: the author.	98
Figure 52. Kavango West region. WASH assets located in multi-hazard hotspots for long-term (2060–2079) horizon under SSP2-4.5 and SSP5-8.5. Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classes. Source: the author.	99
Figure 53. Kavango East region. WASH assets located in multi-hazard hotspots for the near-term (2020–2039), mid-term (2040–2059) and long-term (2060–2079) horizons under SSP2-4.5 and SSP5-8.5. Hotspots are defined as cells where drought, pluvial flash floods and fluvial floods jointly reach High, Very High or Extreme (High+) classes. Source: the author.	100
Figure 54: CAN Water Supply Project (Rundu – Grootfontein)	115
Figure 55. Heat Stress Hazard. Kavango Link-CAN Water Supply Project 2020-2039.....	119
Figure 56. Heat Stress Hazard. Kavango Link-CAN Water Supply Project 2040-2059.....	120
Figure 57. Flash Flood Hazard. Kavango Link-CAN Water Supply Project 2020-2039:.....	122
Figure 58. Flash Flood Hazard. Kavango Link-CAN Water Supply Project 2040-2059:.....	122
Figure 59. Drought Hazard. Kavango Link-CAN Water Supply Project 2020-2039:.....	124
Figure 60. Drought Hazard. Kavango Link-CAN Water Supply Project 2040-2059:.....	124
Figure 61. Kavango Link. CAN Water Supply Project (Rundu – Grootfontein). Source: Element Consulting Engineers.....	130
Figure 62. Kavango Link. CAN Water Supply Project (Rundu– Grootfontein). Source: Google Earth Pro.	130
Figure 63. Segmentation of the Kavango Link alignment (S0–S5).	134
Figure 64. Longitudinal profile of the Kavango Link-CAN water project. Source: consultant’s elaboration using Google Earth Pro data.	134
Figure 65. Longitudinal profile of the Section n°1 (S1). Kavango Link-CAN water project. Source: consultant’s	135

Figure 66. Longitudinal profile of the Section n°2 (S2). Kavango Link-CAN water project. Source: consultant's	136
Figure 67. Longitudinal profile of the Section n°3 (S3). Kavango Link-CAN water project. Source: consultant's	137
Figure 68. Longitudinal profile of the Section n°4 (S4). Kavango Link-CAN water project. Source: consultant's	137
Figure 69. Longitudinal profile of the Section n° 5 (S5). Kavango Link-CAN water project. Source: consultant's	138
Figure 70. Longitudinal profile of the Section n° 5 (S5). Kavango Link-CAN water project. Source: consultant's	138
Figure 71. Project site locations around Rundu.	154
Figure 72. 100 Km around Rundu Project preliminary locations by section: South, West and East. Source: the Author.	157
Figure 73. Heat Stress Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPS 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.	158
Figure 74. Drought Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPS 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.	159
Figure 75. Flash Floods Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPS 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.	160
Figure 76. Fluvial Floods Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPS 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.	162
Figure 78. Wildfire Hazard. 100 Km around Rundu Water Supply Project. Projections to 2020-2039 (left) and 2060-2079 (right) for SSPS 2-4.5 scenario (Up) and SSP 5-8.5 (down). Source: the author.	163
Figure 79. SSP2-4.5 Multihazard Hotspots. 100 Km around Rundu Water Supply Project. Projections to 2060-2079 Source: the author.	164
Figure 80. SSP5-8.5 Multihazard Hotspots. 100 Km around Rundu Water Supply Project. Projections to 2060-2079 Source: the author.	165

ANNEXES

ANNEX 1. VULNERABILITY RATIONALE BY HAZARD

Purpose and scope. This methodology quantifies the vulnerability of water, sanitation and hygiene assets to climate hazards and reports results per asset type and hazard for each scenario and time slice. Results are aggregated to constituencies and basins. The approach follows widely accepted quality requirements for climate risk work and is reproducible with clear assumptions.

Vulnerability is the expected severity of adverse effects on an exposed asset when a hazard occurs. It is represented by four engineering dimensions that jointly capture intrinsic fragility and service performance. Physical Damage reflects structural or material harm to works and equipment. Operability reflects the ability to run and be accessed during and after the event. Service Life reflects long term degradation and maintenance burden. Productivity or Functionality reflects the ability to deliver the intended output and quality.

Scales and formula. Each dimension is scored on a continuous scale between 0 and 1, where “0” means negligible effect and 1 means severe effect. Scores are combined into a single Vulnerability Index using fixed weights that reflect typical impact pathways in WASH systems.

The formula is $VI(a,h) = 0.35 \times PD(a,h) + 0.30 \times OP(a,h) + 0.15 \times SL(a,h) + 0.20 \times PR(a,h)$.

Where: a = Asset; h= hazard; PD=physical damage; OP=operational; SL= Service Life; PR=Productivity.

Reporting classes are constant across hazards and locations so that results are comparable.

Parameterization. In data rich applications the four scores are derived from measured site attributes such as plinth or threshold elevations relative to mapped flood depths, pump intake margins relative to projected drawdown, elevations and enclosure ratings of electrical equipment, storage autonomy and access vulnerability. In data limited applications the four scores are assigned from typology-based defaults per asset type and hazard and applied uniformly to assets of that type within a constituency. All defaults are listed below and can be updated when field information becomes available.

Assigned values by hazard and asset type. The following tables present the default scores for Physical Damage, Operability, Service Life and Productivity or Functionality, together with the resulting Vulnerability Index computed with the fixed weights. These values reflect the typical failure mechanisms and performance constraints expected under each hazard for the listed asset types.

Table 40. Assignment rationale for Heat Stress by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.

Heat Stress Hazard				
WASH Asset type	PD (0-1) Physical Damage	OP (0-1) Operability	SL (0-1) Service Life	PR (0-1) Productivity/functionality
Borehole	0.20	0.50	0.60	0.50
	Physical harm is limited because key components are underground or submerged; headworks and panels experience moderate heat exposure.	Operability is affected by motor thermal trips, panel derating and operator safety during peak heat.	Heat accelerates insulation ageing, seal wear and lubricant breakdown in motor and headworks.	Output can be constrained during heat waves due to derated motors and higher demand peaks.
Well	0.10	0.40	0.60	0.40
	Structures are simple and mostly passive; physical damage from heat is minor.	Manual or low power operation has moderate sensitivity to heat; access and queuing can limit service.	Inners, ropes and seals age faster with sustained heat and UV exposure.	Throughput falls during peak heat periods; quality excursions are not dominant for heat alone.
Public Tap	0.20	0.40	0.60	0.40

	Kiosk structures can deform or crack at aprons; piping is usually protected.	Operations are constrained by user safety, queuing and lower pressure under heat driven demand.	Gaskets, valves and hose materials age faster at high temperature.	Delivered volumes can drop when upstream sources or pressure are derated.
Water Tanker Service Point	0.30	0.60	0.60	0.50
	Aprons and hoses experience heat related wear; fittings and pavements can degrade.	Operability is sensitive to vehicle and pump overheating and to staff safety limits.	Frequent thermal cycles accelerate wear on hoses, couplings and small pumps.	Throughput is constrained by reduced duty cycles and longer turnaround during heat waves.
Water Pump Station	0.40	0.80	0.70	0.60
	Electrical cabinets, cables and seals are sensitive to high temperature; enclosures can exceed ratings.	Operability is strongly affected by thermal trips, derating of drives and need to limit exposure for staff.	Elevated temperatures accelerate insulation ageing, gasket hardening and bearing wear.	Output is curtailed by derated equipment and protection settings during sustained heat.
Dam	0.10	0.40	0.50	0.70
	Embankments and structures rarely suffer direct heat damage; localized cracking possible at surfaces.	Operations can be constrained by staff safety and by thermal effects on appurtenances.	Liners, seals and exposed appurtenances age faster; evaporative stress increases maintenance.	Available yield and head are reduced through evaporation and temperature induced losses.
Other	0.20	0.50	0.60	0.50
	Heterogeneous small assets with some exposed components; limited structural harm expected.	Operability moderately affected by heat related access and minor equipment derating.	Typical small pumps and fittings age faster under heat and UV exposure.	Service volumes can be reduced under heat driven demand and minor derating.

Table 41. Assignment rationale Drought by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.

Drought Hazard				
WASH Asset type	PD (0-1) Physical Damage	OP (0-1) Operability	SL (0-1) Service Life	PR (0-1) Productivity/functionality
Borehole	0.20	0.70	0.60	0.80
	Casing and headworks face limited structural harm; local subsidence and screen clogging may occur as water levels decline.	Casing and headworks face limited structural harm; local subsidence and screen clogging may occur as water levels decline.	Casing and headworks face limited structural harm; local subsidence and screen clogging may occur as water levels decline.	Casing and headworks face limited structural harm; local subsidence and screen clogging may occur as water levels decline.
Well	0.30	0.70	0.60	0.80
	Shallow linings and platforms can crack under desiccation; minor structural risk otherwise.	Shallow linings and platforms can crack under desiccation; minor structural risk otherwise.	Shallow linings and platforms can crack under desiccation; minor structural risk otherwise.	Shallow linings and platforms can crack under desiccation; minor structural risk otherwise.
Public Tap	0.10	0.60	0.40	0.70
	Appurtenances seldom damaged by drought itself.	Appurtenances seldom damaged by drought itself.	Appurtenances seldom damaged by drought itself.	Appurtenances seldom damaged by drought itself.
Water Tanker Service Point	0.20	0.70	0.50	0.80
	Apron and fittings can deteriorate with heat and traffic; pavement rutting in prolonged dry periods.	Apron and fittings can deteriorate with heat and traffic; pavement rutting in prolonged dry periods.	Apron and fittings can deteriorate with heat and traffic; pavement rutting in prolonged dry periods.	Apron and fittings can deteriorate with heat and traffic; pavement rutting in prolonged dry periods.
Water Pump Station	0.30	0.80	0.60	0.80

	Cavitation and vibration can damage impellers, bearings and seals when suction heads are low.	Cavitation and vibration can damage impellers, bearings and seals when suction heads are low.	Cavitation and vibration can damage impellers, bearings and seals when suction heads are low.	Cavitation and vibration can damage impellers, bearings and seals when suction heads are low.
Dam	0.40	0.60	0.50	0.80
	Embankments develop desiccation cracking and settlement; intake towers exposed.	Embankments develop desiccation cracking and settlement; intake towers exposed.	Embankments develop desiccation cracking and settlement; intake towers exposed.	Embankments develop desiccation cracking and settlement; intake towers exposed.
Other	0.20	0.60	0.50	0.70
	Minor physical effects on small, exposed components.	Minor physical effects on small, exposed components.	Minor physical effects on small, exposed components.	Minor physical effects on small, exposed components.

Table 42. Assignment rationale Pluvial flash floods by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.

Pluvial flash floods				
WASH Asset type	PD (0-1) Physical Damage	OP (0-1) Operability	SL (0-1) Service Life	PR (0-1) Productivity/functionality
Borehole	0.50	0.70	0.30	0.40
	Headworks, fencing and panels can be inundated, surface erosion at apron. Default PD = Medium.	Mud, debris and shorted controls disrupt safe operation, access issues. Default OP = Medium-High.	Wet-dry cycling, grit ingress and lubrication washout increase wear. Default SL = Medium.	Temporary loss of output during and after storm bursts. Default PR = Medium-High.
Well	0.80	0.80	0.40	0.50
	Floodwater can overtop the well mouth and damage lining. Default PD = Medium-High.	Access and water quality constraints limit operation until cleared. Default OP = High.	Contaminant exposure accelerates corrosion of metals and seals. Default SL = Medium-High.	Abstraction suspended until water clears or is disinfected. Default PR = Medium-High.
Public Tap	0.60	0.70	0.40	0.40
	Kiosk and apron can crack or heave under scour and settlement. Default PD = Medium.	Queuing unsafe; low pressure under storm response; intermittent power. Default OP = Medium-High.	Valves and gaskets age faster with silt ingress. Default SL = Medium.	Delivered volumes reduced during storms and clean-up. Default PR = Medium-High.
Water Tanker Service Point	0.60	0.80	0.40	0.30
	Pavements and curbs suffer rutting/scour; bollards impacted. Default PD = Medium-High.	Vehicle movements unsafe; pumps trip on wet electrics. Default OP = Medium-High.	Hoses/couplings see abrasive wear; sumps corrode. Default SL = Medium.	Throughput curtailed by access blockage and safety holds. Default PR = High.
Water Pump Station	0.80	0.90	0.50	0.60
	Electrical cabinets, drives and MCC rooms are sensitive to inundation. Default PD = High.	Trips and lock-out common; manual bypass and safe access required. Default OP = Very High.	Insulation ageing and bearing wear increase after wet exposure. Default SL = Medium-High.	Output curtailed to protect equipment; potential multi-day outage. Default PR = High.
Dam	0.60	0.60	0.50	0.60
	Intense local inflows raise pond levels; localized erosion at spillway/embankment. Default PD = Medium.	Debris loading and sediment pulses constrain operations. Default OP = Medium.	Erosion and wet-dry cycling affect appurtenances. Default SL = Medium-High.	Short-term supply interruptions and quality issues. Default PR = Medium.
Other	0.70	0.80	0.40	0.50

	Small, exposed assets can be undermined or flooded. Default PD = Medium.	Access and minor equipment safety limit use. Default OP = Medium–High.	Repeat wetting/drying accelerates material ageing. Default SL = Medium.	Service curtailed during storm response and clean-up. Default PR = Medium–High.
--	--	--	---	---

Table 43. Assignment rationale Fluvial flash floods by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.

Fluvial flash floods				
WASH Asset type	PD (0-1) Physical Damage	OP (0-1) Operability	SL (0-1) Service Life	PR (0-1) Productivity/functionality
Borehole	0.60	0.80	0.40	0.50
	Riverine inundation can submerge headworks and controls, scour at pads. Default PD = Medium–High.	Extended access loss and electrical safety constraints. Default OP = High.	Prolonged submergence and silt lead to corrosion and wear. Default SL = Medium–High.	Output interrupted for days or weeks; standby supply needed. Default PR = High.
Well	0.90	0.90	0.50	0.60
	Overbank flows can damage superstructure and contaminate the well. Default PD = High.	Operation halted for safety and quality protection. Default OP = Very High.	Lining and covers degrade faster with sediment and debris. Default SL = Medium–High.	Service suspended until waters recede and quality is restored. Default PR = High.
Public Tap	0.70	0.80	0.50	0.50
	Kiosk/apron inundated or undermined; fixtures damaged. Default PD = Medium–High.	Network segments isolated; pressure management disrupted. Default OP = High.	Fittings age with corrosion and silt; repairs recurrent. Default SL = Medium–High.	Delivered volumes curtailed under outage and repair. Default PR = High.
Water Tanker Service Point	0.70	0.90	0.50	0.40
	Pads and pumps flooded; bollards and valves impacted. Default PD = High.	Access roads blocked, unsafe fuelling and loading. Default OP = High.	Frequent replacements of hoses, couplings and electricals. Default SL = Medium–High.	Bulk supply disrupted during flood peaks; long queues after. Default PR = Very High.
Water Pump Station	0.90	0.90	0.60	0.70
	Buildings, cabinets and drives highly sensitive to riverine flooding. Default PD = Very High.	Sustained trips/lockouts; manual intervention limited by access. Default OP = Very High.	Accelerated insulation and bearing degradation post-flood. Default SL = High.	Output loss significant; recovery may require major overhaul. Default PR = Very High.
Dam	0.80	0.70	0.60	0.70
	High river stages stress spillways and embankments; erosion possible. Default PD = Medium–High.	Sediment/debris constrain gate operations, emergency releases. Default OP = High.	Appurtenances age with abrasion and cavitation. Default SL = High.	Downstream supply disturbed; turbidity spikes. Default PR = High.
Other	0.80	0.80	0.50	0.60
	Small, exposed assets in floodplain are easily damaged. Default PD = Medium–High.	Access loss and safety hold limit operation. Default OP = High.	Materials age faster with prolonged wetting and corrosion. Default SL = Medium–High.	Service interruption common through flood season. Default PR = High.

Table 44. Assignment rationale Wildfire by asset type and assigned valued to PD, OP, SL and PR parameters used for vulnerability index calculations. Source: the author.

Wildfire				
WASH Asset type	PD (0-1) Physical Damage	OP (0-1) Operability	SL (0-1) Service Life	PR (0-1) Productivity/functionality
Borehole	0.40	0.50	0.50	0.30
	Headworks, fencing and panels exposed to radiant heat; submersible components safe. Default PD = Low–Medium.	Power outages and staff safety restrict operation during fires. Default OP = Medium.	UV/heat accelerate ageing of exposed plastics and seals. Default SL = Medium.	Throughput reduced under evacuation or power loss. Default PR = Medium–High.
Well	0.50	0.60	0.50	0.30
	Physical harm to lining is minor; above-ground covers can burn. Default PD = Very Low–Low.	Manual operation limited by smoke and access. Default OP = Medium.	Ropes/gaskets age faster with heat/ash exposure. Default SL = Medium.	Abstraction paused during local fire fronts. Default PR = Medium.
Public Tap	0.50	0.60	0.50	0.30
	Plastic fixtures and aprons can deform; kiosks suffer radiant heat. Default PD = Low–Medium.	User safety and low pressure under power cuts constrain use. Default OP = Medium.	Gaskets and meters age faster with heat/ash. Default SL = Medium.	Delivered volumes fall during fire events. Default PR = Medium–High.
Water Tanker Service Point	0.60	0.70	0.50	0.30
	Hoses and rubbers vulnerable to heat; pavements damaged by fire vehicles. Default PD = Medium.	Operations restricted by smoke, visibility and power interruptions. Default OP = Medium–High.	Frequent replacement of hoses and couplings. Default SL = Medium.	High demand and access limits reduce throughput. Default PR = High.
Water Pump Station	0.80	0.80	0.60	0.50
	Cables, cabinets and gaskets vulnerable; buildings exposed. Default PD = High.	Trips/derating due to heat and smoke; staff safety limits attendance. Default OP = Very High.	Insulation ageing, soot contamination and bearing stress. Default SL = Medium–High.	Output curtailed to protect equipment, outages possible. Default PR = High.
Dam	0.30	0.40	0.50	0.20
	Instrumentation and control lines susceptible; scorched surfaces. Default PD = Medium.	Ash and debris inflows constrain outlet works. Default OP = Medium.	Accelerated maintenance from ash/soot contamination. Default SL = Medium.	Yield and water quality affected; operations derated. Default PR = Medium–High.
Other	0.60	0.70	0.50	0.40
	Small exposed components at risk of melting/charring. Default PD = Medium.	Access and minor equipment limitations during fire operations. Default OP = Medium.	Heat/UV accelerate ageing of plastics and elastomers. Default SL = Medium.	Service volumes reduced during fire response. Default PR = Medium–High.

ANNEX 2. VULNERABILITY ASSESSMENT – METHODOLOGY, ASSIGNED VALUES AND MEANING

Purpose and scope. This methodology quantifies the vulnerability of water, sanitation and hygiene assets to climate hazards and reports results per asset type and hazard for each scenario and time slice. Results are aggregated to constituencies and basins. The approach follows widely accepted quality requirements for climate risk work and is reproducible with clear assumptions.

Concept and dimensions. Vulnerability is the expected severity of adverse effects on an exposed asset when a hazard occurs. It is represented by four engineering dimensions that jointly capture intrinsic fragility and service performance. Physical Damage reflects structural or material harm to works and equipment. Operability reflects the ability to run and be accessed during and after the event. Service Life reflects long term degradation and maintenance burden. Productivity or Functionality reflects the ability to deliver the intended output and quality.

Scales and formula. Each dimension is scored on a continuous scale between 0 and 1, where 0 means negligible effect and 1 means severe effect. Scores are combined into a single Vulnerability Index using fixed weights that reflect typical impact pathways in WASH systems. The formula is:

$$VI = 0.35 \times PD + 0.30 \times OP + 0.15 \times SL + 0.20 \times PR.$$

Reporting classes are constant across hazards and locations so that results are comparable.

Parameterization. In data limited applications the four scores are assigned from typology-based defaults per asset type and hazard and applied uniformly to assets of that type within a constituency. All defaults are listed below and can be updated when field information becomes available.

Assigned values by hazard and asset type. The following tables present the default scores for Physical Damage, Operability, Service Life and Productivity or Functionality, together with the resulting Vulnerability Index computed with the fixed weights. These values reflect the typical failure mechanisms and performance constraints expected under each hazard for the listed asset types.

Assets Vulnerability to Drought

Asset type	PD	OP	SL	PR	VI
Borehole	0.10	0.60	0.40	0.90	0.455
Well	0.10	0.70	0.50	0.90	0.500
Public Tap	0.05	0.50	0.30	0.70	0.352
Water Tanker Service Point	0.05	0.40	0.30	0.60	0.302
Water Pump Station	0.10	0.60	0.40	0.70	0.415
Dam	0.10	0.50	0.50	0.90	0.440
Other	0.10	0.60	0.40	0.80	0.435

Assets Vulnerability to Pluvial flash flood

Asset type	PD	OP	SL	PR	VI
Borehole	0.50	0.70	0.30	0.40	0.510
Well	0.80	0.80	0.40	0.50	0.680
Public Tap	0.60	0.70	0.40	0.40	0.560
Water Tanker Service Point	0.60	0.80	0.40	0.30	0.570
Water Pump Station	0.80	0.90	0.50	0.60	0.745
Dam	0.60	0.60	0.50	0.60	0.585

Other	0.70	0.80	0.40	0.50	0.645
-------	------	------	------	------	-------

Assets Vulnerability to Fluvial flood

Asset type	PD	OP	SL	PR	VI
Borehole	0.60	0.80	0.40	0.50	0.610
Well	0.90	0.90	0.50	0.60	0.780
Public Tap	0.70	0.80	0.50	0.50	0.660
Water Tanker Service Point	0.70	0.90	0.50	0.40	0.670
Water Pump Station	0.90	0.90	0.60	0.70	0.815
Dam	0.80	0.70	0.60	0.70	0.720
Other	0.80	0.80	0.50	0.60	0.715

Assets Vulnerability to Heat stress

Asset type	PD	OP	SL	PR	VI
Borehole	0.20	0.50	0.60	0.50	0.410
Well	0.10	0.40	0.60	0.40	0.325
Public Tap	0.20	0.40	0.60	0.40	0.360
Water Tanker Service Point	0.30	0.60	0.60	0.50	0.475
Water Pump Station	0.40	0.80	0.70	0.60	0.605
Dam	0.10	0.40	0.50	0.70	0.370
Other	0.20	0.50	0.60	0.50	0.410

Assets Vulnerability to Wildfire

Asset type	PD	OP	SL	PR	VI
Borehole	0.40	0.50	0.50	0.30	0.425
Well	0.50	0.60	0.50	0.30	0.490
Public Tap	0.50	0.60	0.50	0.30	0.490
Water Tanker Service Point	0.60	0.70	0.50	0.30	0.555
Water Pump Station	0.80	0.80	0.60	0.50	0.710
Dam	0.30	0.40	0.50	0.20	0.340
Other	0.60	0.70	0.50	0.40	0.575

Results meaning and interpretation

The table below explains the reporting classes for the Vulnerability Index and how they should be interpreted when planning upgrades or operations.

Class	VI range	Interpretation and action
Low	0.00–0.24	Limited adverse effects under design conditions. Routine monitoring and standard maintenance are adequate. No immediate upgrades required.
Moderate	0.25–0.49	Noticeable performance constraints during hazard events. Targeted low-cost measures reduce disruption. Prepare operational contingencies.
High	0.50–0.74	Frequent service disruption likely under hazard conditions. Prioritise design upgrades and operational changes. Introduce redundancy and storage autonomy.

Very High	0.75–1.00	Severe impact expected without major adaptation. Implement structural hardening, alternative sources and robust emergency procedures.
-----------	-----------	---