Exploring The Sustainable Transformation Tools on Climate Change-Water-Health Nexus Scenarios in a Dry Region of South Africa: The Case of Vhembe District Municipality (VDM), Limpopo, South Africa

Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

Rationale

Transformative adaptation in the water sector aims to ensure access to clean, safe water for sanitation and hygiene, as well as livelihood support. This study presents an assessment of gaps and opportunities for transformation and resilience building towards anticipated Day Zero planning under uncertainty in the Venda District Municipality (VDM), Limpopo Province. The study serves as a baseline for transformative adaptation for the anticipated Day Zero scenarios, at the community level, while also informing policy on context-specific resilient pathways.

In this study, transformation towards ensuring minimum access to water for hygiene, sanitation (considered part of health), and livelihoods, under various Day-Zero scenarios, is considered as part of Water, Health and Sanitation (WAHSH) innovation. The study conceptualised transformative innovation pathways as ideas and practices, governance trajectories, and policies that ensure minimum water access beyond mere survival, as well as a dignified life (access to a toilet, pursuit of desired livelihood activities, food production and utilization), which will facilitate escape from water crises, triggered by poverty traps. The study operationalised system dynamics through nexus lenses on climate change-water-health (CWH) and multidisciplinary participatory processes that unpacked cognitive dissonances associated with chain impacts of climate change on sanitation and hygiene outcomes, at the community level. Balancing competing societal objectives implies a focus on justice and equity dimensions as integral lenses in climate-resilient development (CRD) pathways. Transformative adaptation planning, as well as effective participation, is critical in such endeavours. This research, therefore, provides a building block to innovation, collaborative learning, and co-production of no-regret planning for the understudied yet critical CWH nexus pathways. Ultimately, the results could inform institutional, policy, and governance transformation towards no regret adaptation, in general, and the CWH nexus.

Objectives

The primary objective of this study was to explore an innovative scenario building for no regret adaptation along the CWH nexus and inform policy and institutional transformation, at local and national levels. Specifically, the study aimed to:

- To identify institutional, policy, and governance gaps in transformation for CRD in the water sector;
- To undertake a multi-stakeholder consultative process that addresses anticipatory planning in the drylands of South Africa with respect to the CWH nexus
- To map stakeholders in the CWH nexus and model the link between climate change and health; and
- To initiate innovation for collaborative learning and co-production, on no-regret adaptation planning, on the CWH nexus.

Methodology

The study employed mixed methods, grounded in the Theory of Change (ToC) and cybernetics, to examine societal choices and actions related to water security, as a health-risk driver under a

changing climate. Desktop and narrative reviews, policy and institutional assessments were conducted to identify gaps in the transformation of CRD in the water sector. Multi-stakeholder consultative processes were undertaken to identify adaptation pathways and assumptions underlying them. This was undertaken through 1 expert and 3 community participants through face-to-face ToC workshops. Descriptive statistics were used to analyse any innovations and practices identified by the community and experts. These were backed up by key informant interviews and findings from focus-group discussions (FGDs). The CWH nexus modelling used historical and future climate data (rainfall, relative humidity, and maximum temperature) to project future cases of malaria, bilharzia, and diarrhoea in VDM. The WAHSH Day-Zero scenarios informed the conceptualisation of innovative collaborative mechanisms for learning, from the perspective of policy-design principles.

Results and Discussion

The contexts of CWH and Day Zero water scenarios

All the FDGs unanimously (100%) agree on the likelihood of increased vulnerability to waterborne diseases and water insecurity if the current water situation is not addressed, under the changing climate risks and uncertainty. This was followed by increased pathogen pollution at 80%, increased morbidity and mortality from waterborne diseases at about 47%, and increased water-related conflicts at the household and community level. A 20% decrease in the water table was the least projected under the business-as-usual (BAU) scenario if transformative planning approaches are not adopted. At 64%, increased vulnerability to food and nutrition risks emerged as a major uncertainty to be considered in planning for Day-Zero scenarios. This is closely followed by limited knowledge on water-related conflicts, morbidity, and mortality from water-borne diseases, hospitalisation, as well as pathogen pollution, respectively, at about 57% each. Currently, smart agriculture and nature-based approaches dominate household-level adaptation pathways. Water and sanitation, and smart-water technologies, at 62% and 60%, respectively, were the preferred future adaptation strategies at the household level. Climate services and risk messages accounted for about 54%, with urban planning, indigenous knowledge, and institutional and governance reforms, at about 48%. There was unanimous agreement across various communities and expert groups that conveyance losses, inadequate water access, poor governance, and unsafe drinking water are major issues in water development planning for the Day-Zero scenario. In general, imaginaries of future scenarios were shaped by knowledge and context specific experiences that are livelihood related.

Institutional, policy, and governance framework in the CWH nexus

The institutional, policy, and governance systems give insight into social practices, biophysical and social drivers of vulnerability, and root causes of risks, past path dependencies, and historical triggers of adaptation and/or transformation needs. The study's findings suggested a multifaceted interdependence and complex relationships among CWH, that concurrently intersect directly and indirectly with rural and urban planning, land use, food security, and behavioral dynamics. Health, as a crucial facet of this nexus, is intricately linked to the availability and quality of water, food security, nutrition, and ultimately climate dynamics. The policy and multi-governance framework in the CWH nexus is generally characterised by legal and

institutional pluralism, which in turn introduces additional complexity, breeds constitutionally-anchored mandate conflicts, organisational and investment fragmentation that undermine effectiveness in the medium and long term. This, in turn, contributes to implementation inertia and paralysis

Despite strategic-level recognition of the nexus, various policy actors at the implementation level continue to operate in silos, failing to account for the complex linkages between resource systems and sectors. The ensuing pursuit of narrow sectoral specific goals within a telecoupled system undermines synergies, resulting in significant knowledge gaps in addressing interdependent disaster risk drivers, as most of the current policy and research agenda focuses on single hazards and solutions. The study highlights gaps and opportunities and underscores the importance of integrated multihazard evaluation into CRD, thereby establishing a holistic planning framework for WAHSH. This can serve as a basis for an actionable perspective in the design and steering of fit-for-purpose grassroots transformation of CRD water development, for a nuanced and structured approach to CWH transformation. This will provide the means and an end to orchestrating governance pathways for transformation with its potential cascading effects across social and cultural structures.

Deep uncertainty is unavoidable when assessing a community's vulnerability to climate change. The uncertainty is interlinked with water development, land-use planning, and urbanization patterns, which impact water demand and supply dynamics in a changing climate over several decades. The study's findings indicate that participatory planning is well recognised in legal and institutional frameworks, including the National Water Act of 1998, the Municipal Systems Act No. 32 of 2000, the Constitution, and the Disaster Management Act. However, it does not explain how the narrative of participation can be carried out. Accordingly, a nexus framework, essentially a polycentric governance approach, emerged as an appropriate analytical lens for overcoming silo-planning pitfalls. Effective participation is inherently integral to governance and transformative imperatives. From the analysis, it is apparent that decision-making and empowerment are context specific; hence, they should inform transformative planning, while the distribution of knowledge, networks, and trust is not context-specific and can, therefore, be adapted to context.

Modelling the link between climate change and health

The lagged correlation analysis of rainfall and malaria indicated a weak but statistically significant positive correlation ($\rho = 0.28$, $p = 0.019$), suggesting that mosquito breeding habitats are created immediately after rainfall events. The malaria cases further weakened and became non-significant with lags 2 and 3 (months 2 and 3), respectively, indicating a diminishing influence of rainfall on malaria incidence, beyond two months. Relative humidity had a modest, temporally short influence on malaria transmission in the VDM, with the strongest association occurring within the same month and progressively weaker, non-significant relationships at longer lags. Maximum temperature (Tmax) showed a weak positive but statistically non-significant relationship with malaria incidence ($\rho = 0.19$, $p = 0.118$), suggesting that contemporaneous temperature conditions alone do not strongly explain variations in malaria cases. Rainfall had a

moderate but temporally limited negative influence on bilharzia transmission, with the strongest effects occurring within the same month and persisting for approximately 2 months. Tmax played a substantial, temporally persistent inhibitory role in bilharzia transmission in the Vhembe District, with consistently negative relationships across all lags. This highlighted the sensitivity of bilharzia transmission dynamics to thermal conditions, with the strongest effects occurring within one to two months following elevated temperature conditions. Rainfall and Tmax played a limited, indirect role in shaping diarrhoeal disease incidence, with consistently weak, non-significant relationships across all lags. This implied that diarrhoeal transmission is likely influenced more strongly by non-climatic factors, such as water supply reliability, water quality, sanitation infrastructure, hygiene practices, and contamination pathways.

Multi-variate negative binomial regression results indicate that climatic variables were significantly associated with malaria, while they were not statistically significant predictors of bilharzia and diarrhoea. There was poor predictive performance for malaria, which may be partly influenced by the limited data (2020-2025) used. The future projections indicate persistence of pronounced peaks under SSP5-8.5, highlighting the potential for episodic surges for all diseases. The model for bilharzia demonstrated the lowest error metrics. For diarrhoea, substantial overlap was observed between SSP2-4.5 and SSP5-8.5 projections, suggesting that future diarrhoeal risk may be governed more by threshold exceedance and infrastructure vulnerability than by emissions pathway alone.

Proposed innovation for collaborative learning and co-production, on no regret adaptation planning, on the CWH nexus

The main output from this main activity is the "how" of the innovation process, mainly mechanism for collaborative learning and WAHSH innovations in general, and particularly the orchestration of innovation through community innovation platforms. Contexts are critical in transformative planning. This suggests the need for Innovation platforms, at the community level. The trajectories are not only complementary in terms of envisioned scope, depth, and speed of change, but are also nonexclusive subcategories of transformation, suggesting the need to consider inherent synergies and trade-offs, within and between them. The three nonexclusive pathways/governance trajectories in transformative adaptation for climate resilient water systems are:

- Big wins pathways - in-depth and systematic public service reforms, technological projects, large-scale infrastructural investments, and land-use planning that can be adapted, adopted, and implemented;
- Small wins pathways - rapid and systemwide/in-depth small steps to system-wide-grassroot initiatives/ experiments/ startups with possibility for replication, accumulation, and ultimately system-wide amplification (transformation /scaling) of the whole system; and
- Rules change pathways - Includes rapid and systemwide rule change to in-depth change, by means of enacting new regulations, economic incentives, minor changes of existing

schemes, as well as actor-behavioural change (risk communication and communication for development approaches) over time.

Big win (in-depth and systematic public service reforms, technological projects, large-scale infrastructural investments, and land use planning) trajectories are the most favoured. The low preference for small wins could be attributed to poor or nonexistent community-based disaster risk reduction (CBDRR) initiatives and governance structures in the study area. Essentially, water-related issues and adaptation go beyond water-sector specific lenses on demand and supply, suggesting that multidisciplinary planning is a must for resilient Day-Zero scenario planning. Such multidisciplinary processes could be critical in exploring synergies, developing compromises for difficult conflicts of interest, and facilitating good dialogue within the nexus adaptation framework, and ultimately, constructive dialogue. Such an approach has the potential for co-creation of knowledge and establishment of joint understanding and consensus building on complex, transformative nexus needs. This research contributes to innovation in collaborative learning and co-production of no-regret planning for the understudied, yet critical CWH nexus pathways. Ultimately, it informs institutional, policy, and governance transformation towards no regret adaptation, in general and the CWH nexus in particular.

Proposed policy, governance, and institutional framework for resilience building, in adaptation planning and resilient Day-Zero scenarios

Adopting the principle of indivisibility, such as the landscape approach in nexus planning and implementation, requires integrated approaches rather than a focus on siloed knowledge and policymaking in climate action and development decision processes towards sustainability, extensively, at the local scale. The study has proposed a community-centric policy, governance, and institutional framework for supporting adaptive planning and transformation of the CWH nexus and no-regret adaptation and Day-Zero water scenarios. A multi-level learning (MLL) approach that can concurrently address the inherent policy and learning gaps could be handy. This is would be especially appropriate in addressing the fragmented programming of nexus issues and past legacies in planning. An integrated community-based Disaster Risk Reduction Innovation Platform (CBDRR-IP), in essence, what is proposed, is a self-organisation at the local level of implementation as an innovative collaborative learning innovation for zero-day water scenarios. The proposed framework can broadly guide:

I. The design of a responsive multi-level learning and policy platform in transformative adaptation planning;
II. A framework for resilience planning with potential for supporting policy learning, coherent MLL and MLG systems for transformative adaptation; and
III. A cross-sector partnership in the transformation of WAHSH.

Use of anticipatory adaptation planning frameworks is likely to guarantee wider actor engagement in exploring innovative CRD pathways. Co-produced actions under the proposed framework and by multiple actors are likely to capture divergent worldviews, knowledge and values on CWH and assist in the construction of context-specific no-regret adaptation pathways. Focus can then be placed on how governance decisions have shaped development pathways and

how power dynamics could support innovations for addressing inequitable and maladaptive outcomes that may arise in anticipatory Day Zero no regret planning, on the CWH nexus.

Short summary of results (Key findings)

The key findings of the study are as follows:

- Co-developing socially robust solutions for sustainable futures on CWH is a necessity for future learning, co-creation of knowledge, and collaborative action;
- Use of animations agreed upon *a priori* to facilitate the participatory planning processes;
- Backcasting is a promising methodology for understanding the nexus between past policy, governance, institutional systems and planning for resilient water systems and sustainability under climate change uncertainties;
- An innovative use and adaptation of TSP tools to context has the potential to support cross-sectoral collaboration and social-technical innovation; and
- That although TSP tools have endless possibilities for informing transformation in adaptation planning and pursuit of Climate Resilient Development (CRD) objectives, it is resource-intensive in terms of finances, time and human resource requirements.

In the context of climate change modelling, future diarrhoeal risk may be governed by threshold exceedance and infrastructure vulnerability. Future malaria risk is likely to be characterised by heightened climate-driven variability and occasional extreme transmission periods, rather than uniform increases in disease burden. Bilharzia risk remains strongly governed by water availability, ecological persistence of snail habitats, and human water-contact behaviour, with climate acting as an indirect enabling factor. This shows the influence of the CWH in exacerbating disease dynamics.

Conclusions and recommendations for further research

The following recommendations are made based on the results of the study:

- Need to strengthen MLL planning approaches for nexus challenges in CWH;
- Strong focus should be placed on CBDRR-IPS for monitoring, learning, and collaboration;
- There should be community engagement and establishment of a protocol for co-designing transformative adaptation action in general, and navigating climate-related water crisis, from a multi-level governance and systems approach
- A need for a holistic socio-political innovation lens that concurrently addresses scope, speed (planning horizon) and depth of transformative needs, and resolution to silo-planning cycles;
- Upscaling of governance recommendations and best scenario for water-sensitive sanitation and hygiene innovations, from experiments and niches to regime levels; and
- Future adaptation planning should consider the CWH nexus, while developing preventative actions and adaptation strategies for combating and managing disease outbreaks.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY ..... **iii**
ACKNOWLEDGEMENTS ..... **ix**
CHAPTER 1: INTRODUCTION **1**
1.1 Background and motivation 1
1.2 Objectives 5
CHAPTER 2: LITERATURE REVIEW **6**
2.1 Introduction 6
2.2 Purpose and scope of the literature review 6
2.3 Impacts of climate change on human health 7
2.4 Projecting/predicting impacts of climate change on human health 19
2.5 Climate adaptation policies/strategies and the health sector 23
2.6 Climate Resilient Development (CRD) 27
2.7 No regret adaptation 29
2.8 Theory-based sustainable transformation tools (STP) 30
2.9 Theory of change (ToC) 35
2.10 Summary 37
CHAPTER 3: METHODOLOGY **39**
3.1 Introduction 39
3.2 Research methods 39
3.3 Climate change-water–health nexus modelling 45
3.4 Approach to AP process 46
3.5 Participatory planning workshops 48
3.6 Scenario planning 54
3.7 Ethical considerations 56
CHAPTER 4: ASSESSMENT OF CURRENT POLICY, GOVERNANCE, AND INSTITUTIONAL SYSTEMS IN THE TRANSFORMATION FOR CRD IN THE WATER SECTOR **57**
4.1 Introduction 57
4.2 Concepts and tools for exploring institutional governance and policy systems in transformative adaptation planning 57
4.3 Structures, institutions, and processes in CWH Nexus governance and adaptation planning 62
4.4. Methodology 74
4.5. Results and discussion 76
4.6. Main findings of this chapter 93
4.7. Summary 95
CHAPTER 5: MULTI-STAKEHOLDER PLANNING PROCESSES TO ADDRESS ANTICIPATORY FUTURE PLANNING ON CWH NEXUS **98**
5.1 Introduction 98
5.2 Definition of concepts used in participatory planning processes 98
5.3 Transformation planning tools 103
5.4 Methodology 106

5.5 Results and discussion 125
5.6 Summarised main findings from TSP tool in participatory planning 138
5.7 Summary 139
CHAPTER 6: MODELLING OF THE CWH NEXUS 141
6.1 Introduction 141
6.2 Understanding the CWH nexus 141
6.3 South African case studies on the impacts of climate change on human health 144
6.4 CWH modelling methodology 149
6.5 Results on the influence of climatic factors on infectious diseases incidence, within the CWH nexus 156
CHAPTER 7: INNOVATIONS, COLLABORATIVE LEARNING AND CO-PRODUCTION OF NO REGRET ADAPTATION STRATEGIES AND CRD IN THE WATER SECTOR 191
7.1 Introduction 191
7.2 Overview of innovations theory and practice 191
7.3 Concepts and tools for exploring pathways for innovation in transformative adaptation planning 192
7.4 Analytical approach 195
7.5 Data analysis 197
7.6 Assumptions 200
7.7 Results and discussion **..... 204**
7.8 Innovations for collaborative learning and co-production 220
CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS 223
8.1 Conclusion 223
8.2 Recommendations and gaps for future research 226
REFERENCES 229
APPENDICES 263

LIST OF FIGURES

Figure 2.1: Pathways of climate change impacts on health, highlights on human infectious diseases (Cissé, 2019) 7
Figure 2.2: Climate change-related infectious diseases 8
Figure 2.3: Projected heat-related deaths in South Africa (WHO, 2015) 11
Figure 2.4: Direct and indirect impacts of heat waves (DoH, 2020) 11
Figure 2.5: Impact of climate change on health (Myers and Rother, 2012) 13
Figure 2.6: Predicting health impacts due to climate change (Haines et al., 2006) 20
Figure 2.7: The QST cycle 35
Figure 3.1: Methodological approach for the study 40
Figure 3.2: Map of the study area 42
Figure 3.3: The adaptation thinking process adopted for the study 47
Figure 4.1: Summary of evaluation criteria (OECD, 2021) 76
Figure 4.2: Multi-governance response to climate change impacts (Petrie et al., 2019) 77
Figure 4.3: Vertical and horizontal coordination of the multi-government approach (Petrie et al., 2019) 77
Figure 5.1: Summarised methodological approaches of the study. The broken line indicates that scenario planning is not a stand-alone phase but rather integral in the iterative processes during modelling, ToC, and community planning workshops 108
Figure 5.2: Components of the ToC 111
Figure 5.3: Generic logical framework 111
Figure 5.4: Iceberg metaphor illustration 115
Figure 5.5: Google map metaphor illustration 116
Figure 5.6: Location of the 3 villages where the community workshops were conducted 119
Figure 5.7: Expert level ToC workshop 120
Figure 5.8: Community level TSP processes 121
Figure 5.9: Community FGDs during TSP processes 122
Figure 5.10 : Overview photo of the participants 123
Figure 5.11: Validation workshop participants 124
Figure 5.12: (a) Number of respondents from each village and (b) gender of participants 125
Figure 5.13: Concerns about water quantity, water quality, health/disease, environment and food, at different planning horizons 126
Figure 5. 14: Perceptions on changes in water security, water colour, water taste, food-borne diseases, skin diseases and dental discoloration 127
Figure 5.15: (a) Baseline, (b) BAU, and (c) best scenarios contexts on CWH at the household level 128
Figure 5.16: Visual display of baseline, BAU and best scenarios by expert level FGDs 130
Figure 5. 17: Visual display of baseline, BAU and best scenarios by Tiyani community FGDs 131
Figure 5.18: Visual display of baseline, BAU and best scenarios by Dopeni community FGDs 132
Figure 5.19: Currently used adaptation strategies 133
Figure 5.20: Suggested future adaptation strategies 133
Figure 5.21: Impact of TSP on trust, degree of empowerment, networking, knowledge, policy and decision-making, within the CWH nexus 135

Figure 6.1: The pathways through which climate is a driving force impacting water and health 144
Figure 6.2: Illustrations of climate change and extreme weather events and their health impacts, around South Africa 145
Figure 6.3: Projected population at risk of malaria in South Africa (WHO, 2015) 146
Figure 6.4: SSPs and associated challenges to mitigation and adaptation..... 153
Figure 6.5: Change in mean annual rainfall 157
Figure 6.6: Mean Rx1day rainfall 158
Figure 6.7: Tmax mean anomalies 158
Figure 6.8: Malaria, bilharzia, and diarrhoea cases in VDM 160
Figure 6.9: Scatter plots of monthly malaria cases against rainfall totals at lags 0–3 months in VDM (2020–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line indicates the fitted regression with a 95% confidence interval (blue shading) 161
Figure 6.10: Scatter plots of monthly malaria cases against relative humidity at lags 0–3 months in VDM (2020–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line indicates the fitted regression with a 95% confidence interval (Blue shading)..... 163
Figure 6.11: Scatter plots of monthly malaria cases against maximum temperature at lags 0–3 months in VDM (2020–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading) 164
Figure 6.12: Scatter plots of monthly Bilharzia cases against rainfall at lags 0–3 months in VDM (2017–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading) 166
Figure 6.13: Scatter plots of monthly bilharzia cases against Relative humidity at lags 0–3 months in VDM (2017–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading). 167
Figure 6.14: Scatter plots of monthly bilharzia cases against Tmax at lags 0–3 months in VDM (2017–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading) 169
Figure 6.15: Scatter plots of monthly diarrhoea cases against maximum rainfall at lags 0–3 months in VDM (2004–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading) 170
Figure 6.16: Scatter plots of monthly diarrhoea cases against relative humidity at lags 0–3 months in VDM (2004–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading). 172
Figure 6.17: Scatter plots of monthly Diarrhoea cases against Tmax at lags 0–3 months in VDM (2004–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading). 174

Figure 6.18: Observed and XGBoost-predicted monthly malaria cases for the present-day period 178
Figure 6.19: SHAP summary plot illustrating the contribution of climatic predictors to XGBoost model predictions of present-day malaria incidence 179
Figure 6.20: Observed and XGBoost-predicted monthly bilharzia cases for the present-day period 180
Figure 6.21: SHAP summary plot showing the contribution of climatic predictors to XGBoost model predictions of bilharzia incidences 180
Figure 6.22: Observed and XGBoost-predicted monthly diarrhoea cases for the present-day period 182
Figure 6.23: SHAP summary plot illustrating the contribution of climatic predictors to XGBoost model predictions of diarhoea incidences 182
Figure 6.24: XGBoost-Projected mean monthly malaria incidence under SSP2-4.5 and SSP5-8.5 scenarios for the near-term period (2021–2040) 185
Figure 6.25: XGBoost-projected mean monthly malaria incidences under SSP2-4.5 and SSP5-8.5 scenarios for the mid-term period (2041–2060) 186
Figure 6.26: XGBoost-projected mean monthly malaria incidences under SSP2-4.5 and SSP5-8.5 scenarios for the long-term period (2081–2100) 186
Figure 6.27: XGBoost-projected mean monthly bilharzia incidences under SSP2-4.5 and SSP5-8.5 scenarios for the near-term period (2021–2040) 187
Figure 6.28: XGBoost-projected mean monthly bilharzia incidences under SSP2-4.5 and SSP5-8.5 scenarios for the mid-term period (2041–2060) 188
Figure 6.29: XGBoost-projected mean monthly bilharzia incidences under SSP2-4.5 and SSP5-8.5 scenarios for the long-term period (2081–2100) 188
Figure 6.30: XGBoost-projected mean monthly diarhoea incidences under SSP2-4.5 and SSP5-8.5 scenarios for the mid-term period (2041–2060) 189
Figure 6.31: XGBoost-projected mean monthly diarrhoea incidences under SSP2-4.5 and SSP5-8.5 scenarios for the near-term period (2081–2100) 190

LIST OF TABLES

Table 2.1: Classification of water related diseases 9
Table 2.2: National, provincial and local climate adaptation policies/strategies 25
Table 3.1: Dominant and alternative narrative assessment guide on CWH nexus 45
Table 3.2: Desktop review of data and secondary literature 45
Table 4.1: Governance system analysis matrix guide 60
Table 4.2: Summary metrics of policy field assessment in adaptation planning 74
Table 4.3: Criteria and guiding questions used in the assessment (adapted from OECD, 2021). 75
Table 4.4: Government departments and institutions playing a role in climate change response in South Africa 78
Table 4.5: National, provincial and local policies/strategies within the CWH nexus 82
Table 4.6: Assessment of the policies and strategies 85
Table 4.7: Assessment of policies/strategies on the sustainability criterion 86

Table 4.8: Summary policy field on CWH adaptation planning in South Africa 89
Table 4.9: Level of policy integration on CWH nexus in South Africa and VDM 91
Table 4.10: Remarks from the validation process and discussions 137
Table 5.1: Matrix for pathway planning and underlying assumptions 117
Table 5.2: Schedule of participatory workshops and attendance 119
Table 5.3: Uncertainty and risks to Best Scenarios on CWH 134
Table 5.4: Influence of context on TSP outcomes 136
Table 6.1: Details of the selected 10 Global Climate Models in CMIP6 153
Table 6.2: Negative binomial regression coefficients (log scale) for malaria incidence in VDM 175
Table 6.3: Incidence Rate Ratios (IRRs) from Negative Binomial regression for malaria incidence 175
Table 6.4: Negative binomial regression coefficients (log scale) for Bilharzia incidence..... 176
Table 6.5: Incidence Rate Ratios (IRRs) from Negative Binomial regression for Bilharzia incidence 176
Table 6.6: Negative binomial regression coefficients (log scale) for Diarrhoea incidence 177
Table 6.7: Incidence Rate Ratios (IRRs) from negative binomial regression for diarrhoea incidence 177
Table 6.8: Performance metrics of XGBoost models for predicting present-day infectious diseases' incidences 183
Table 7.1: Summary of governance pathways for innovation transition in WAHSH by municipality..... 212
Table 7.2: Evidence on the CWH nexus in South Africa and lessons for no regret adaptation governance..... 218

LIST OF APPENDICES

Appendix 1: Stakeholder identification and assessment in climate- water- health nexus, VDM 263
Appendix 2: Theory of Change Interview guide 265
Appendix 3: Participatory planning workshops 265
Appendix 4: Scenario planning 266
Appendix 5: Household questionnaire 267
Appendix 6: Workshop evaluation and learning 271
Appendix 7: Pathways assumptions 272
Appendix 8 : Animations illustration CWH scenarios and pathways..... 273
Appendix 9: Observed changes in components of CWH at household level 284
Appendix 10: Effect of TSP tool on various dimensions of CWH...**Error! Bookmark not defined.**

LIST OF ABBREVIATIONS

ADWIM	Assets Drivers Well-being Interaction Matrix
ARIMA	Autoregressive Integrated Moving Average
AIDS	Acquired Immunodeficiency Syndrome
APs	Adaptation Pathways
ARIMA	Autoregressive Integrated Moving Average
BAU	Business as Usual
CCA	Climate Change Adaptation
CCIA	Climate Change Institutional Assessment
CMAs	Catchment Management Agencies
CRD	Climate Resilient Development
CWH	Climate Water Health
CBDRR	Community-based Disaster Risk Reduction
CBDRR-IPs	Community-based Disaster Risk Reduction-Innovation Platforms
CRM	Comprehensive Risk Management
DAPP	Dynamic Adaptive Policy Pathway
DEA	Department of Environmental Affairs
DRR	Disaster Risk Reduction
DoE	Department of Education
DoH	Department of Health
DWS	Department of Water and Sanitation
FGDs	Focus Group Discussions
GWP	Global Water Partnership
GBV	Gender Based Violence
HIV	Human immunodeficiency Virus
IO	Institutional Order
IDP	Integrated Development Plans
IPCC	Intergovernmental Panel on Climate Change
KIIs	Key Informant Interviews
LEDET	Limpopo Department of Economic, Development, Environment and Tourism
LTAS	Long-Term Adaptation Scenarios
MCA	Multi-criteria Analysis
MLL	Multi-level learning
MLG	Multi-level Governance
NAP	National Adaptation Plan
NBA	Nature-based Approaches
NCCAP	National Climate Change Action Plan
NCCRP	National Climate Change Response Policy
NCCAS	National Climate Change Adaptation Strategy
NDP	National Development Plan
NGOs	Non-governmental Organisations
NWRS	National Water Resource Strategy
PCSD	Policy Coherence for Sustainable Development

PEM	Pragmatic Enlightened Model
PESTEL	Political, Ecological, Socio-cultural, Technological, Economic, and Legal
PRA	Participatory Rural Appraisal
PCC	Presidential Climate Commission
PCSD	Policy Coherence for Sustainable Development
RCP	Representative Concentration Pathway
RDM	Robust Decision Making
PA	Paris Agreement
PSI	Participatory Systemic Inquiry
QST	Quantitative Story Telling
SA	Substantive Authority
SARIMA	Seasonal auto-regressive integrated moving average
SDBIP	Service Delivery and Budget Implementation Plan
SDGs	Sustainable Development Goals
SE	Substantive expertise
SES	Socio Ecological System
SFDRR	Sendai Framework for Disaster Reduction
SSPs	Shared Socioeconomic Pathways
STP	Sustainable Transformation Tools
SWOT	Strengths, Weaknesses, Opportunities and Threats
ToC	Theory of Change
TSP	Transformative Scenario Planning
VDM	Vhembe District Municipality
WAHSH	Water, Health and Sanitation-Hygiene
WMA	Water Management Area
WUAs	Water Users Association
WSAs	Water Service Authorities
WHO	World Health Organization
WRC	Water Research Commission

CHAPTER 1: INTRODUCTION

1.1 Background and motivation

Climate change has caused substantial damage, and increasingly irreversible losses, in terrestrial, freshwater, coastal, and open ocean marine ecosystems (Intergovernmental Panel on Climate Change (IPCC), 2022). The negative impacts on human health are expected to increase, especially in water stressed countries such as South Africa. Climate change directly impacts the physical availability and quality of water resources, which are the main propellers of health outcomes. This calls for no regret adaptation and mitigation measures, in line with Climate Resilient Development (CRD) principles and Transformative Scenario Planning (TSP) tools. Participatory and citizen science, which has focused on the nature of CRD and TSP, facilitated holistic planning and ensured no one is left behind, has transformed communities, institutions, and governance systems, in adaptation planning. In particular, CRD ensures that mitigation and adaptation measures support sustainable development initiatives (IPCC, 2022; Stringer et al., 2022).

Telecoupling is the underlying logic in CRD transitions that address adaptation, mitigation, and development needs. These include the integrated processes, for addressing urgent livelihood needs and sustainable development goals for adaptation planning and policies (Stringer et al., 2021). Inadvertently, it includes the analysis of messy bricolage around political, economic, financial, socio-cultural, and knowledge space in decision making that impacts on the sustainability and/or resilience (IPCC, 2014; Stringer et al., 2022). The CRD integrates adaptation, mitigation, and development to drive societal transformation. The ensuing societal transformation negotiates the diversity of complex tradeoffs that operate at the temporal and social scale (Butler et al., 2016).

Intuitively, CRD principles, Theory of Change (ToC) and TSP could inform no regret planning, for more aggressive climate mitigation and adaptation strategies to prevent future Day-Zero droughts in dry areas in South Africa. Day Zero terminology is associated with the 2017-2018 unprecedented drought-related water crisis in Cape Town, South Africa. This was an occurrence

that served as a wake-up call for resilient water systems amidst increasing climate related risks and uncertainties. Day Zero scenarios increase the urgency for transformative adaptation planning, as well as the need for a systems approach through the integration of biophysical- social lenses into planning and decision making. The systemic nature of current and predicted future climate related shocks and impacts, such as waterborne disease outbreaks, further underscores the need for transformative interventions, that address the underlying drivers.

Scenario building for anticipated changes in water security dimensions, such as availability, access, and cost, as well as quality (Stringer et al., 2022), are critical health risk propellers under climate change and can inform water and health managers and policy makers, on plausible future adaptation needs. Such strategies could contribute towards transformative adaptation policies for the water sector and also feed into present and future water resource management planning.

While technological considerations are necessary in a transformative agenda, effective science-policy-societal interfaces, require keen attention to governance models, as well as alternative narratives in framing the problem and identifying potential solutions to complex societal challenges, such as climate change (Béné, 2022). Governance, policy, and institutions play a critical role in the planning cycles and processes. Governance refers to a myriad of institutional and actor relationships, in service delivery (Huitema et al., 2009). This includes multiple possible modes of policy and decision-making structures, including networks and stakeholder fora, across government bureaucracy, policy, and community of practice. Governance is broadly defined by formal institutions, such as laws, official policies, and organizational structures, and informal institutions, such as the power relations, practices, and operational rules as well as a whole range of structures, discourses, rules, and norms that bear on a project's planning cycle, as well as embedded transparency and accountability mechanisms (Folke et al., 2005).

Normative discourses consider transformation as a deliberative process aimed at improving relationships among interrelated actors and associated outcomes (Béné, 2022). Governance dimensions are especially critical in targeting and including social segments that are highly exposed and likely to incur adverse impacts from climate change. These factors include, barriers

to implementation of adaptation projects, overcoming adaptation mitigation-adaptation dualism and biases, and associated adverse third party social costs (Ziervogel et al., 2017; Newell et al., 2021), as well as increased risk of marginalisation and exclusion (Savvidou et al., 2021). In line with CRD principles, planning processes are expected to account for power differences among development actors and their knowledge cultures in the design of participatory planning processes at the community level, as well as in the identification of interventions with immediate, medium, and future time horizons (Butler et al., 2016). Such interventions should also be sufficiently flexible, given the complexity and uncertain nature of social-ecological challenges (Munene et al., 2018; Roy et al., 2021).

Governance, policy, and institutions play critical roles in the planning cycles and processes. Governance, as mentioned earlier, refers to a whole range of institutions and relationships involved in the process of governing. These include both formal institutions, such as laws, official policies, and organisational structures, and informal institutions such as power relations, practices, and operational rules. Planning processes must encourage participants, especially end-users at the community level, to conceive proximate, medium and future time horizons, while taking into account and addressing asymmetries associated with the involvement of higher-level actors and their knowledge cultures (Butler et al., 2016; Werners et al., 2021a). Governance dimensions are especially critical in targeting the most vulnerable social segments to climate change. There is a need, therefore, to focus, for instance, on barriers to implementation of adaptation projects, as well as overcoming mitigation-adaptation dualism that tends to prioritise mitigation over adaptation (Newell et al., 2021; Ziervogel et al., 2017). Adaptation-mitigation dualism, in turn, increases the risk of excluding key actors for a specific sector, such as marginalized small-scale farmers in the agriculture sector (Savvidou et al., 2021).

Chapter 9 of the National Water Strategy, revitalisation strategy 2 (DWA, 2013) recognises that water management operates within a social, economic and ecological environment, and for effective and integrated management of water resources, top-down consultation should be replaced by citizens' participation. The knowledge of higher level stakeholders and science experts is necessary to collectively identify systemic and long-term issues, as well as related

transformative strategies, however, it risks disempowering community members (Butler et al., 2015). The TSP tool proposed herein addresses such risks and thus has the potential to contribute to a transformative adaptation agenda, in the climate change-water-health (CWH) nexus, in local communities in Limpopo and South Africa, at large. With the increasing need to address historical injustices in access to water, as well the need for transformative and planned no regret adaptation planning, it is necessary to inform planners and empower communities; however, little research literature exists on the use of TSP tools on the CWH nexus in South Africa, in general. The adaptive thinking approach will guide the participatory research processes and scenario planning exercises (Haasnoot et al., 2012; 2013; Vervoort et al., 2014; Colloff et al., 2016; Kwakkel et al., 2016; Brown et al., 2020; Sadr et al., 2020).

As value-based aspirations, desirable futures are premised on the understanding of contextual earth system dynamics to enhance the likelihood of successful societal adjustment, herein referred to as "no regret adaptation" to crisis, such as climate change (Bai et al., 2016). A better understanding of the nexus pressures that underpin pathways is key to planning amidst knowledge gaps on future climate dynamics and their impacts (Leal Filho et al., 2021). Little research literature, however, exists on the use of TSP tools on the CWH nexus in South Africa.

No regret adaptation planning takes cognisance of both proximate and underlying factors to ensure intended goods, services and benefits from an intervention are realised, even when risk occurs (Hallegatte, 2009; Omore et al., 2019; Werners et al., 2021a). Scenarios can be used to represent plausible development outcomes, in which strategies are considered to be no regrets if they do not carry the risk of negative externalities under all scenarios (Butler et al., 2016). Backcasting is one of the scenario planning tools that examines a suite of explorative decision pathways (Vervoort et al., 2014). The current study aims at contributing to policy and decision-making processes that will support the mainstreaming of future uncertainty into the CWH nexus, through a multi-stakeholder planning process that addresses climate change risks on water and its impact chain in dryland ecosystems of South Africa. This, it is anticipated, will contribute to adaptive planning and transformative capacity building that considers citizen science for no-

regret water planning scenarios and more aggressive climate mitigation and adaptation strategies that prevent future Day-Zero droughts, in dry areas in South Africa.

South Africa is one of the most water-stressed countries, with an urgent need to undertake transformative no-regret adaptation measures in most areas impacted by climate change. Coupled with underlying past injustices, poverty, and unemployment, there is a need for CRD strategies through participatory planning strategies and citizen science. Exploring TSP, as well as cybernetics in relation to societal choices and actions within the water sector, could inform policymakers and water managers on more aggressive climate mitigation and adaptation strategies that can prevent future Day Zero droughts, in dry areas and water planning, in general. The research contributed to institutional, policy and governance transformation towards no-regret adaptation in general and the CWH nexus and enhanced innovation in collaborative learning and co-production of no-regret planning, for the understudied yet critical CWH nexus pathways.

1.2 Objectives

The primary objective of this study was to explore an innovative scenario building for no regret adaptation, along the CWH nexus, as well as inform policy and institutional transformation at local and national levels. Specifically, the study aims to:

- To identify institutional, policy, and governance gaps in transformation for CRD in the water sector;
- To undertake multi-stakeholder consultative processes that address anticipatory planning in drylands of South Africa, with respect to the CWH nexus
- To map stakeholders in the CWH nexus and model the link between climate change and health; and
- To initiate innovation for collaborative learning and co-production on no regret adaptation planning, on the CWH nexus.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The review presented in this chapter examined the existing body of knowledge on the CWH nexus through the lens of transformative adaptation planning. The literature review focused on the global and context-specific state of knowledge of the CWH nexus, policy and governance dimensions of the CWH nexus, as well as innovation for cross-sectoral collaborative learning, in climate-resilient development pathways.

2.2 Purpose and scope of the literature review

The purpose of the literature review was to provide an understanding of TSP in the context of the CWH nexus, assess how well this knowledge is established, and identify where future research might be best directed. The literature review, hence, provided a foundation of knowledge on the CWH nexus and transformative adaptation planning, so as to:

i. Identify areas of prior scholarship, thereby preventing duplication and giving credit to other researchers;
ii. Identify inconsistencies, gaps in research, conflicts in previous studies, and open questions left by other researchers;
iii. Identify the need for additional research, hence, justify the current research;
iv. Identify relationships among the literature, in the context of their contribution to the current research topic and to other works; and
v. Place the current research within the context of existing literature, making a case for why further study is needed.

The scope of the review was limited to:

- CWH nexus in the context of CRD principles;
- coordination responses across multiple decision-making levels, influencing climate resilience development of water resources;
- No regret strategies that prevent future Day-Zero droughts in the dry region of South Africa, in general, and the Limpopo Vhembe District Municipality (VDM) in particular;

- Propositions for mainstreaming participatory future uncertainty into decision-making at the community, local, and national levels; and
- Innovations for mainstreaming stakeholder perspectives on CRD for water resources and no-regret adaptation plans into development processes.

2.3 Impacts of climate change on human health

Climate change is altering weather patterns, resulting in extreme events, such as heat waves, floods, and droughts. Heat waves and drought events also result in reduced water availability, with implications for diseases that become widespread due to the lack of water and poor hygiene. Flood events also destroy water supply infrastructure and contaminate water sources, with implications for human health. This shows the linkage between climate change, water, and health, hence the CWH nexus. It is crucial to understand this interlinkage to address climate change impacts on human health. Figure 2.1 illustrates the pathways through which climate change impacts health in relation to infectious diseases. Figure 2.2 indicates examples of infectious diseases related to climate change.

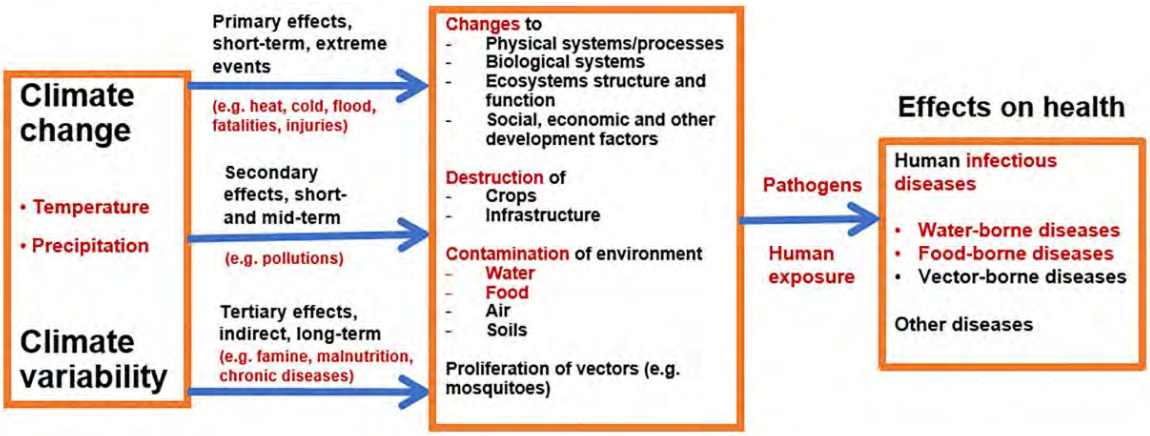


Figure 2.1: Pathways of climate change impacts on health, highlights on human infectious diseases (Cissé, 2019)

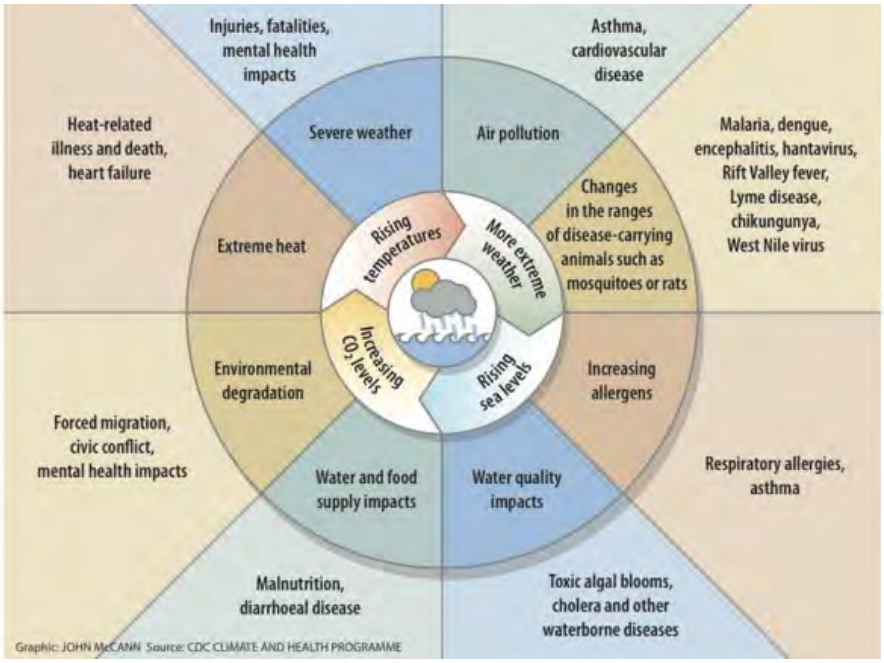


Figure 2.2: Climate change-related infectious diseases

The status of water availability (too little or too abundant) influences the prevalence of certain water-related diseases in an area. Water-related diseases include illnesses related to water shortage or water contamination during adverse climate events, such as floods and droughts, diseases related to vectors with part of their life cycle in water habitats, and diseases related to inhalation of contaminated water aerosols (Stanwell-Smith, 2009). Increased flooding may contaminate water supplies, increasing the spread of waterborne diseases, such as cholera and dysentery, while droughts will lead to water scarcity that will compromise public hygiene, thereby increasing the risk of water-washed diseases (Levy et al., 2018). Table 2.1 indicates the classification of water-related diseases based on the root cause. Some of the climate change impacts' pathways are:

- Vector-borne diseases such as malaria, bilharzia, rift valley fever, helminth infestation due to floods and droughts, as well as poor sanitation;
- Avian influenza and its impacts on food security;
- Malnutrition indicators in children under 5, pregnant and lactating mothers, as proxy of weather-related impacts(drought) on food availability and health;
- Occurrence of hunger;
- Induced diseases (physiological impacts) due to utilisation of unsuitable/ poor quality water sources, such as boreholes;

- Skin, dental and eye diseases and/or worm infestation due to sanitation impacts, as proxy for climate impacts on water and health;
- Occurrence and prevalence of trauma and psychological impacts of climate change on health, for example, heat stress and heat rash;
- Climate-induced conflicts and indirect impacts on health;
- Dietary impacts/food security (access and availability) and potential health impacts in the general populace;
- Social impacts, such as suicide and gender-based violence (GBV);
- Respiratory diseases including tuberculosis; and
- Food- borne diseases, such as listeria.

Table 2.1: Classification of water-related diseases

Class	Route Cause	Disease
Water-borne	Drinking contaminated water	Cholera, Amoebic dysentery, Bacillary dysentery (shigellosis), Cryptosporidiosis, Typhoid, Giardiasis, Paratyphoid, Balantidiasis, Salmonellosis, Campylobacter enteritis, Rotavirus diarrhoea, *E. coli* diarrhoea, Hepatitis A, Leptospirosis and Poliomyelitis.
Water-Washed	Lack of clean water for washing.	Scabies, Typhus, Yaws, Relapsing fever, Impetigo, Trachoma, Conjunctivitis and Skin ulcers.
Water-Based	Host organisms that develop to human parasites.	Schistosomiasis, Dracunculiasis, Paragonimiasis and Clonorchiasis.
Insect-Vector	Organisms that need water to breed.	Mosquito-borne diseases; Malaria, Yellow fever, Dengue fever, Filariasis and Fly-borne diseases; Onchocerciasis (river-blindness), Trypanosomiasis (West African sleeping sickness), Leishmaniosis (Kala-azar), Loiasis.

The scale of recent changes in the climate is unprecedented, with significant extremes, such as heatwaves, heavy precipitation, droughts and tropical cyclones. Climate change is a global process, but the effects it has on different populations and parts of the world vary in extent and magnitude (National Institute of Environmental Health Sciences, 2022). It is essential to recognise that the impacts of climate change reach far and wide, affecting both the environment and human health and well-being, with already vulnerable populations feeling these impacts more severely (UK Universities Climate Network, 2022). The impacts of climate change in the short- to medium-term will be determined by the population's vulnerability, its resilience to ongoing climatic variations, and the pace and extent of its adaptation (WHO, 2021; Wright et al., 2021).

The effects of climate change and its variability are very evident and pose significant risks to human life. Some of these risks include heat exposure, water scarcity, frequent flood and drought events, changes in the distribution and prevalence of vector-borne and other infectious diseases, as well as the potential impact on global food security (Wright et al., 2021; Coates and Norton, 2021; Aik et al., 2018). Climate change also increases health hazards through the deterioration of air quality and the increased frequency of extreme weather events, creating environmental conditions that favour the spread of waterborne, foodborne and vector-borne diseases. Diseases such as cholera, malaria, diarrhoea, dengue fever, and many other infectious diseases have been found to be climate-sensitive (Thompson et al., 2012).

Temperature increases in South Africa have been projected to be 2°C higher than the global temperature increase (Wright et al., 2014). Given the high burden of environmental-related diseases already present in South Africa, this temperature increase will further exacerbate the challenges to human health and quality of life. Health impacts associated with temperature increases can be direct, where increased temperatures lead to heat stress, and indirect, where they increase the incidence of diseases due to changes in the environment that favour pathogen survival and distribution (Wright et al., 2014). In some circumstances, the formation of new infectious disease organisms due to the pathogen’s genetic adaptation to changes in the external environment, such as ecological conditions and climate (National Research Council Committee on Climate, 2001). Wright et al. (2019) reported that 3.4% of total deaths

(8.8 million) from 1997 to 2013 were associated with non-optimal temperatures (extreme heat or cold). WHO (2015) indicated that under a high emissions scenario, heat-related deaths in the elderly (65+ years) are projected to increase to about 116 deaths per 100,000 by 2080, compared to the estimated baseline of about 2 deaths per 100,000 annually between 1961 and 1990, in South Africa (Figure 2.3). Extreme heat events can directly impact health, or make other health problems worse, or indirectly impact health through behavioural changes, infections, or impact on health services and infrastructure, as indicated in Figure 2.4 (DoH, 2020)

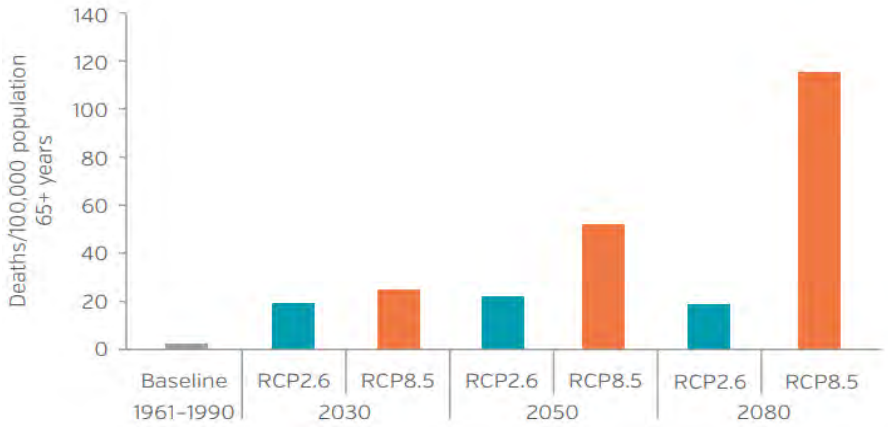


Figure 2.3: Projected heat-related deaths in South Africa (WHO, 2015)

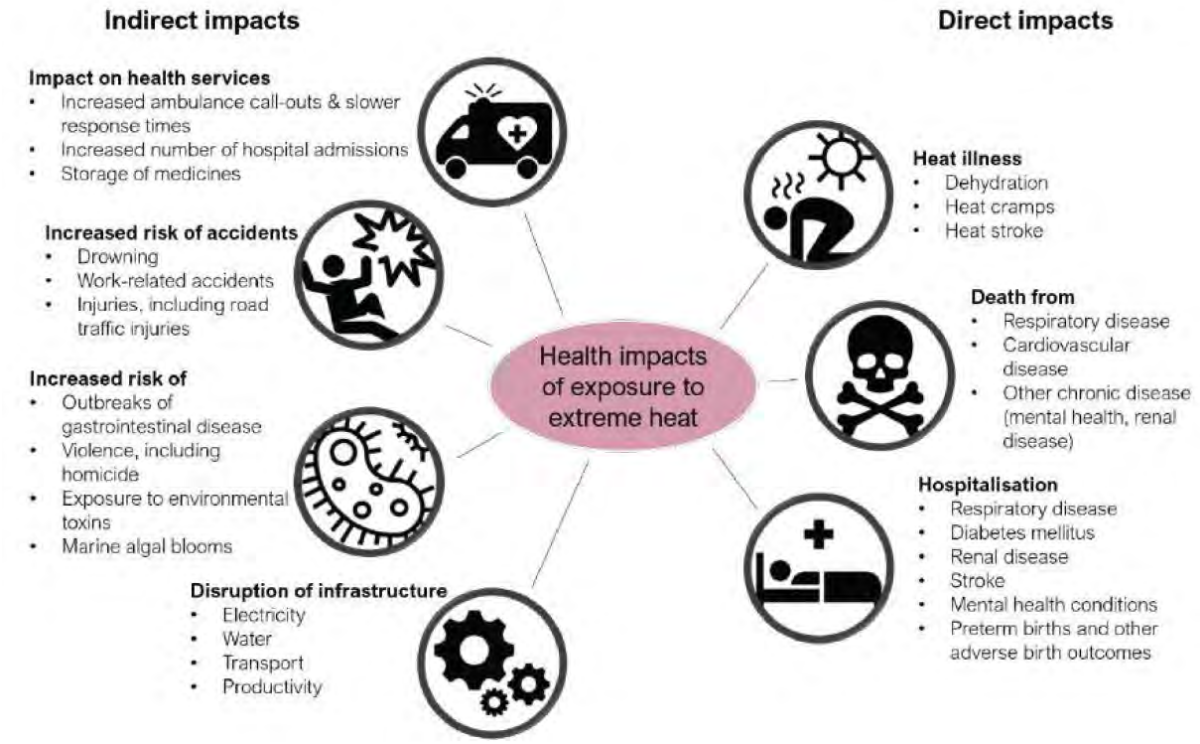


Figure 2.4: Direct and indirect impacts of heat waves (DoH, 2020)

The level of vulnerability of a population to climate-induced health risks is dependent on various factors, including the rate of population growth, demographics, standards of living, access to healthcare, the state and development of healthcare and public health infrastructure (Rose et al., 2000; Wright et al., 2014). Human health-related climate change impacts will be felt more severely in regions already burdened by climate-sensitive diseases (IPCC, 2014). An existing burden of diseases, such as HIV/AIDS, food and water insecurity, poverty, and inadequate access to public health services, further increases the population's vulnerability to climate-related health threats (Wright et al., 2014). Healthcare systems in Africa are already strained as they try to accommodate the rapidly growing populations that depend on them. The impacts of climate change could exacerbate problems for human health and further strain healthcare systems (Coates et al., 2020).

A study conducted by Harper et al. (2020) on the impacts of climate change on human health concluded that, although the amount of literature available on the impacts of climate change on human health has considerably increased in recent years, research on this topic is still in the very early stages in comparison to the rapid progression of climate change. An observational study by Chowdhury et al. (2018) investigated the relationship between temperature, humidity, rainfall, and six common climate-sensitive infectious diseases in Bangladesh. The diseases investigated were malaria, bacterial meningitis, encephalitis, enteric fever, pneumonia, and various diarrheal diseases. Results from the study show that the incidence rates for all diseases increased from 2008 to 2012; furthermore, correlations were observed between disease incidence and different seasons within the year. The cases of malaria, pneumonia, and diarrheal diseases were highest during the rainy seasons, while enteric fever, encephalitis, and bacterial meningitis were highest in autumn. Increased temperature was positively correlated with incidents of malaria, enteric fever, and diarrheal diseases, but was negatively correlated with cases of encephalitis, meningitis, and pneumonia. Higher humidity levels were positively correlated with cases of malaria and diarrheal diseases but were inversely correlated with meningitis and encephalitis. Lower rainfall magnitudes resulted in increased incidents of encephalitis and bacterial meningitis. Malaria, enteric fever, and diarrheal disease cases were more prevalent in higher rainfall conditions.

A study conducted in rural Burkina Faso, West Africa, investigated the relationship between rising ambient heat from climate change and the rising popularity of non-communicable diseases. Results from the study showed that deaths from non-communicable diseases were elevated at significant levels by exposure to moderate or extreme ambient temperatures (Bunker et al., 2017). The health risks that are potentially impacted by climate change in South Africa include food insecurity (hunger and malnutrition); natural disasters (floods and droughts); communicable diseases (specifically HIV/AIDS); non-communicable diseases; injury burden; mental health; and occupational health (Ziervogel et al., 2014; Chersich et al., 2018). Figure 2.5 indicates the connections between climate-related exposures and direct and indirect adverse health outcomes.

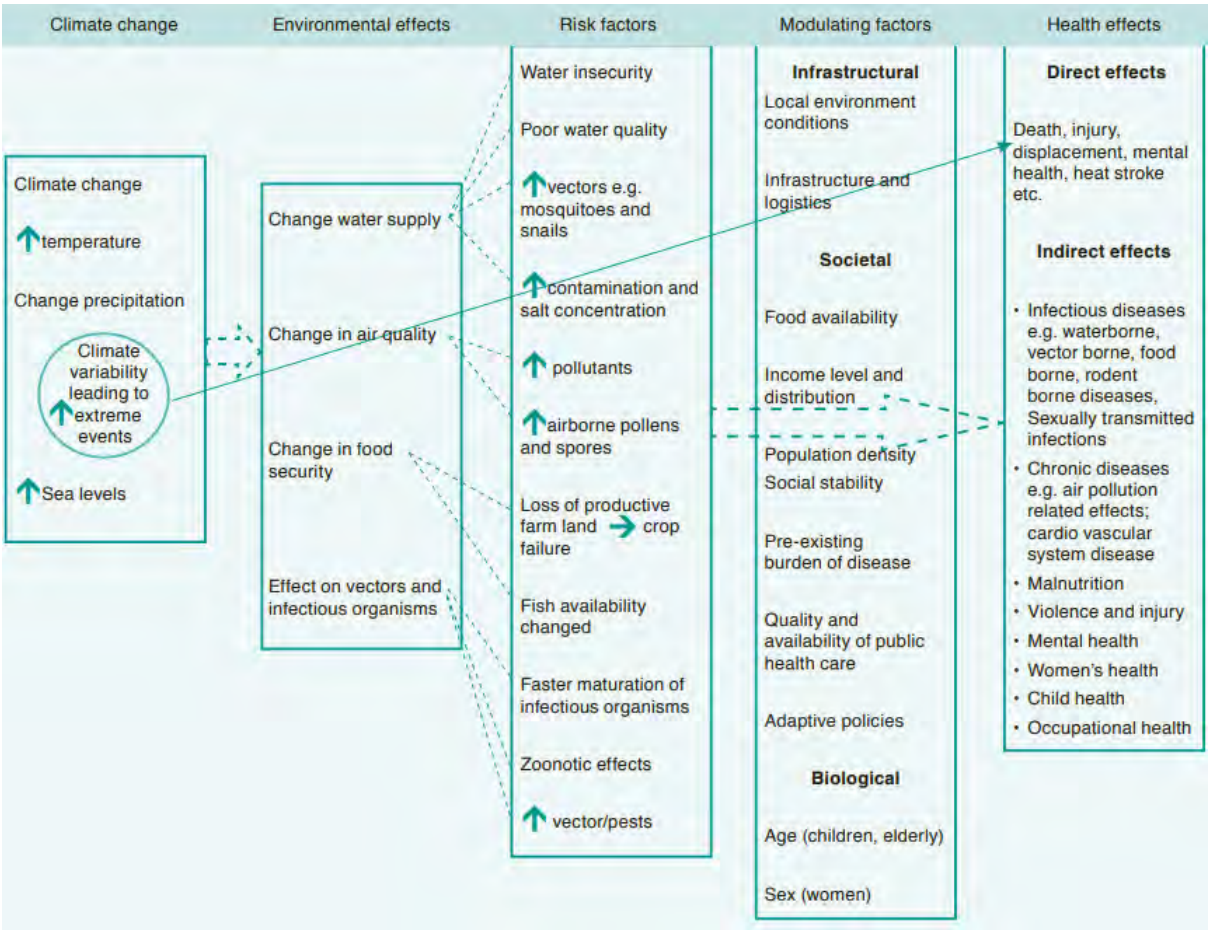


Figure 2.5: Impact of climate change on health (Myers and Rother, 2012)

Cissé (2019) noted that climate change will lengthen the transmission season and expand the geographical range of many diseases. The prevalence and geographical distribution of various diseases are heavily influenced by weather and climate conditions (National Research Council

Committee on Climate, 2001). Infectious diseases take a heavy toll on various communities around the world, and some of the most ubiquitous infections are sensitive to climate conditions (WHO, 2012). A variety of terminologies are used to characterise the presence of a disease in a certain population at a specific point in time. For example, disease "prevalence" refers to the proportion of people with a disease in a specific population, but disease "incidence" reflects the number of new cases arising in a population over a specific period (National Research Council Committee on Climate, 2001). Meteorological parameters, such as temperature, humidity, and rainfall, affect the spread of waterborne, foodborne, and vector-borne diseases. Each of these environmental factors can significantly affect the epidemiology of various diseases (National Research Council Committee on Climate, 2001; WHO, 2012). Tropical diseases, particularly vector-borne diseases, will spread throughout temperate areas as a result of global climate change (Lafferty, 2009). The environmental changes caused by global warming, however, may also result in some illnesses becoming less prominent (Shope, 1991); for instance, the Cryptosporidium parvum cyst's survival decreases with prolonged exposure to warm temperatures because increased metabolism depletes its energy reserves (Lafferty, 2009).

Human pathogens are easily influenced by environmental factors because they can be indirectly carried by insect or rodent vectors that spend significant time outside their hosts (Patz and Olson, 2006). The geographic ranges of many arthropod vectors are restricted by minimum and maximum temperatures, humidity, and the availability of breeding sites (National Research Council Committee on Climate, 2001). Most vector-borne diseases are transmitted by arthropod vectors, such as mosquitoes, flies, ticks, and fleas. Since these insects are cold-blooded, even minor temperature changes can have a major influence on disease transmission (Patz and Olson, 2006). Temperature-sensitive microorganisms that multiply include mosquitoes, flies, ticks, and other cold-blooded arthropods that cause all vector-borne diseases. The time required for microbial reproduction in vector species varies substantially with ambient temperature, and below specific temperature thresholds, pathogen reproduction may cease entirely. Thus, each vector-borne pathogen has a restricted range of conducive climatic conditions in which it can reproduce and survive (Patz and Olson, 2006; National Research Council Committee on Climate, 2001). Malaria, schistosomiasis (bilharzia or snail fever), dengue fever, lymphatic filariasis (elephantiasis), onchocerciasis

(river blindness), African trypanosomiasis (sleeping sickness), leishmaniasis, American trypanosomiasis (Chagas disease), yellow fever, and many other rare arthropod-borne diseases are examples of vector-borne diseases (Lafferty, 2009).

Waterborne diseases are a wide range of diseases transmitted through contaminated water and inadequate sanitation (Levy et al., 2018). Waterborne diseases are transmitted by a wide range of pathogens across various taxa, including viruses, bacteria, helminths, and protozoa. Waterborne diseases have a variety of symptoms, including diarrhoea, flu-like symptoms, fever, neurological disorders, liver damage, and many others (Levy et al., 2018). Cholera is one of the most common diseases in underdeveloped countries, caused by the consumption of polluted and untreated water (Mudau et al., 2017). Cholera has already caused seven pandemics before 1991, spreading from Asia to Europe, Africa, and North America (Shope, 1991). Cases of cholera in South Africa were first identified in Musina in the Limpopo Province. A total of 12,706 cases of cholera were later reported by the National Department of Health between 15 November 2008 and 30 April 2009. During that time, VDM also experienced a cholera outbreak with 720 cases being confirmed (Ismail et al., 2013).

The prevalence of diarrhoea in semi-arid areas is generally linked to the scarcity of water resources, which increases the concentration of contaminants in the limited water sources. Furthermore, changes in climate and water cycles, challenges water availability and increases the populations' exposure to unsafe water as the extreme climatic events increase the cases of diseases and fatalities by adding an oral-faecal contamination pathway that is difficult to manage; this is particularly challenging for developing countries, where outbreaks occur seasonally and are associated with poverty, poor sanitation practices and unsafe water (Funari et al., 2012). Additionally, the potential impacts of climate change on populations reliant on surface water are not well-explored. Alexander et al. (2018) conducted a retrospective analysis, revealing that hydrometeorology and flood-pulse dynamics play a pivotal role in triggering diarrheal disease outbreaks; hence, these factors contribute to heightened vulnerability to climate change in populations dependent on surface water resources.

Exposure to climate shifts is constant and may be indirect or direct, depending on the nature and degree of variation in the climate. The direct exposure to climate change is due to changes in temperature, precipitation, natural disasters, and storms. Indirect exposures arise from increasing pollen production, worsening air pollution, agricultural sector constraints resulting in a shortage of food and malnutrition, a conducive environment for the production and spreading of vector diseases, lack of infrastructure, as well as changes in the ecosystem and biodiversity (Jha and Dev, 2024); thus, both direct and indirect impacts need attention.

2.3.1 Direct and indirect impact of climate change on humans

- **Heat Stress**

The rise in daily temperature, causing heat waves, poses great threats to human health. Heat stress, with its corresponding morbidity and mortality rates, produces increased health risks, such as cardiovascular issues, respiratory problems, kidney disease, complications in pregnancy and life-threatening heat stroke (William et al., 2024). The temperature record, spanning over 50 years, was broken during a severe heat wave in the Northwest Province of South Africa in 2016. About 11 lives were claimed during the extreme heat of 40°C, mainly elderly people. In 2018, another record-breaking heatwave occurred in Gauteng, North-West, Mpumalanga, and KwaZulu-Natal (Wright et al., 2019). Regions also experiencing extreme heat were the Lowveld of Limpopo and Mpumalanga, the northern and coastal part of KwaZulu-Natal and the Northern Cape. Studies on extreme health impact on human health, however, are still lagging in South Africa. The perception is that sleep is affected when exposed to hot weather, hence causing mental problems and irritability and aggression toward members of the family (Wright et al., 2019). The risk resulting from the rising health problems is both a public health and occupational health concern and must be investigated.

- **Vector diseases**

Vector-borne diseases are among the leading causes of illness and death. Studies have revealed that increases in temperature, rainfall, and occasional humidity patterns can negatively affect the dispersal of vector-borne diseases, such as malaria, dengue fever, Lyme disease, and ticks (IPCC, 2014). Malaria risk is high in certain climatic ranges. Research has shown that little variation in temperature can lead to health risks from malaria. However,

further research is needed to understand the impact of humidity. A shift in climatic conditions can highly impact the life stages and spreading pattern of ticks and tick-borne diseases in South Africa. Warm temperatures may alter tick habitats, boost their survival rates, and extend the tick activity season, potentially increasing the distribution of the diseases (Ogden et al., 2020). Research has shown that Limpopo, Gauteng, Mpumalanga, KwaZulu-Natal, Eastern Cape, and Free State, from September 2020 to November 2022, were concerned provinces on the issue of ticks (Makwarela et al., 2024).

- **Food security, hunger and malnutrition**

Climate change is projected to increase the occurrence, extent, and severity of drought spells, high temperatures, and reduced rainfall in semi-arid regions. Several food systems are affected by climate change, which compromises the availability, accessibility, and utilisation of food, leading to food insecurity. The shift in rainfall distribution has negatively affected production, leading to poor crop yield. This results in food shortages and higher food prices, factors that lead to malnutrition among vulnerable households (Haile et al., 2017). Research gaps need to be addressed regarding how these factors will affect malnutrition in future climate change scenarios.

- **Extreme weather events**

Climatic factors, such as annual rainfall, temperature, and wind speed, as well as non-climatic factors, such as land use patterns and socio-economic status, have a significant influence on natural disasters. Communities with poor water and sanitation services, poor public health infrastructure, and a lack of shelter frequently experience outbreaks of infectious diseases. Extreme weather events, such as droughts, floods, dust storms and wildfires, are also drivers of varying illnesses. The health impacts from floods and storms are: risk of respiratory and diarrhoeal diseases, drowning, injuries, and mental-health illnesses, arising from increased vector abundance, while malnutrition, food shortage, starvation, and infectious diseases may result from drought. Dust can impair visibility and increase exposure to harmful substances such as microorganisms, pollen, and toxic metals (Griffin, 2007). This can trigger or exacerbate respiratory issues, like asthma and pneumonia, cardiovascular diseases such as heart attacks and strokes, and other conditions like conjunctivitis and meningococcal meningitis - leading to increased hospital admissions (Gross et al., 2018; Wright et al., 2021).

- **Air pollution**

Climate change can negatively impact health due to air pollution, as the concentrations of air pollutants are altered by weather and anthropogenic conditions. Ambient air pollution within the country comes from various sources - human activities like traffic, industry, mining, and household solid fuel burning, as well as natural sources, like plant emissions, pollen, dust, biomass burning, and sea salt spray. This is because meteorological factors, including temperature, precipitation, clouds, water vapour, wind speed, and wind direction, influence atmospheric chemical processes. Exposure to high pollution levels is associated with chronic respiratory and cardiovascular illnesses, as well as neurodegenerative diseases, diabetes, adverse perinatal conditions, low birth weight, eye irritation, acute respiratory infection, tuberculosis (TB), and sometimes even death (Zhu et al., 2020).

- **Non-communicable diseases**

Climate change also has a direct impact on non-communicable diseases by increasing temperatures and air pollution concentrations. The indirect impact on non-communicable diseases is demonstrated in poor agricultural yields, leading to food insecurity. These non-communicable diseases, including cardiovascular and respiratory diseases (asthma and bronchitis), are among the leading causes of death in South Africa (Maluleke, 2023).

- **Communicable disease**

Climate change plays a significant role in the distribution of communicable diseases through climatic factors, such as rainfall, wind and temperature. Some of the communicable diseases in South Africa are TB and cholera; these result from a host having direct contact with either an infected person, contaminated foods, beverages or body fluids, or being bitten by an infected animal host (Prabhu, 2023). For cholera, its transmission is linked to rainfall and temperature, which are probably affected by climate change. Non-climatic factors, such as water insecurity, lack of proper sanitation, and population density, also influence cholera transmission.

- **Occupational health**

Common occupational health impacts include heat stress, dehydration, and injuries sustained at work. Temperature is a common climatic factor that affects occupational health (for

example, agricultural labourers' productivity), caused by heat stress and dehydration. Projected future climate scenarios for South Africa predict marked increases in thermal discomfort on many days each year, especially in the summer months (Chersich et al., 2018). This will have serious implications for the productivity of workers in the agriculture and mining sectors.

- **Mental health**

The disruption of social and biophysical support systems due to climate change can cause community displacement, home destruction, and loss of life. This, in turn, could affect mental health and general human well-being. Heat stress and high temperatures can be associated with diminished mental capacity, somatoform disorders, senility, psychological development disorders, as well as other mood disorders (Nicholas et al., 2020).

2.4 Projecting/predicting impacts of climate change on human health

Forecasting future infectious disease incidence under climate change requires jointly modelling changes to future climate and the climate–disease relationship, thereby accounting for uncertainties in both (Metcalf et al., 2017). Climate-based disease forecasting has been proposed as a potential tool in climate change adaptation for the health sector. By integrating climate data into predictive models, this approach offers the potential to foresee changes in disease patterns, enabling proactive and targeted interventions. Such forecasting not only enhances the ability to anticipate disease outbreaks but also empowers health professionals to allocate resources efficiently, minimising the impact on vulnerable populations (Thomson et al., 2018). For these reasons, climate-based disease forecasting stands at the forefront of proactive pathways, bridging the gap between climate science and public health to develop a more resilient and adaptive healthcare system.

Assessing the projected health burden is a step to enable public health agencies to prepare for these impacts. This can be done qualitatively or quantitatively, but quantitative projections may provide more useful information about likely impacts (Hess et al., 2017). Research on the health impacts of climate change focuses on three main topics: current

associations between climate and disease, the effects of recent climate changes, and the evidence base for projecting the future impacts (Figure 2.6) (Haines et al., 2006).

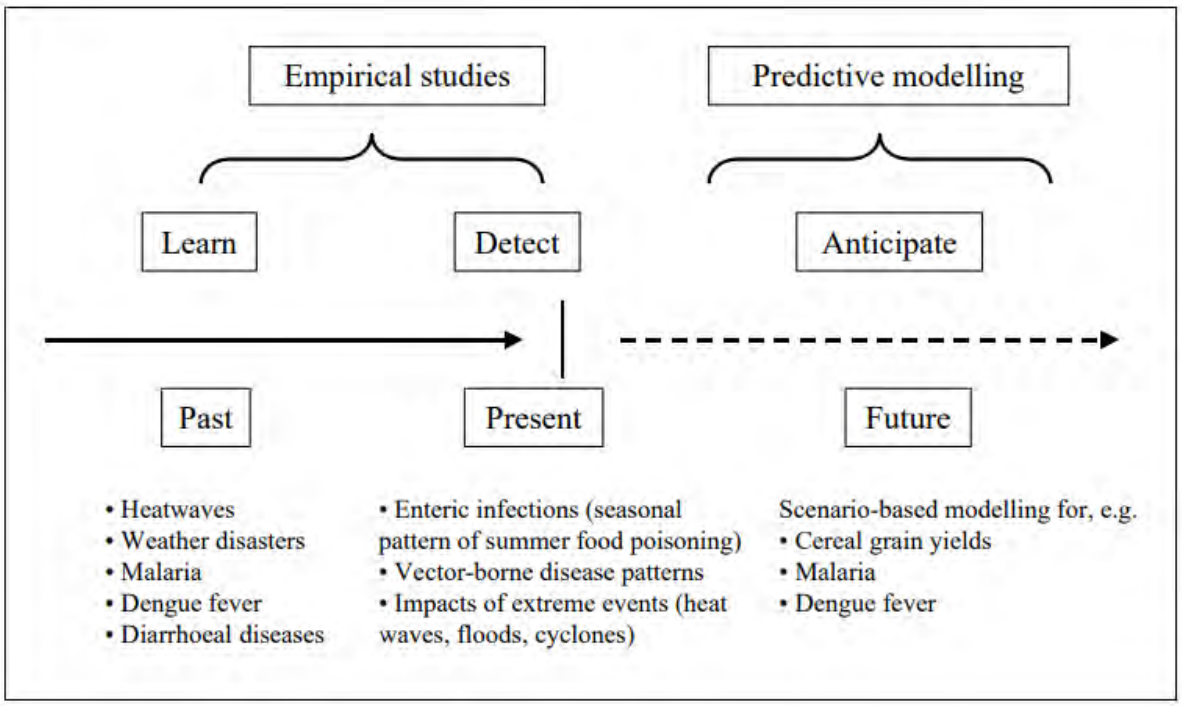


Figure 2.6: Predicting health impacts due to climate change (Haines et al., 2006)

According to Ryan et al. (2023), an ideal tool for predicting climate change impacts on health will:

- incorporate both climate inputs and epidemiological information to produce an output which can serve as a prediction or indicator of disease risk in one package;
- be transparently described and validated;
- be appropriately named (for future searching and versioning); and
- be accessible as published codes, or available on a code repository, or a web platform, or other user interface.

There are various models that can illustrate a correlation between human health and climate change, such as statistical, regression, and artificial intelligence models, but these depend on what is being analysed and how much data is available (Pizzulli et al., 2021). By classifying correlations and patterns in the data, these models can estimate the potential impact of climate change on disease occurrence and its severity. However, it is important to note that statistical models have limitations and uncertainties, as they rely on historical data and assumptions about the relationship between climate and disease. Mathematical models, on the other hand, use mathematical equations to simulate the spread and impact of diseases

under different climate scenarios. These models consider various factors, such as population dynamics, disease transmission mechanisms, and climate variables. They can provide insights into how changes in climate may affect disease dynamics and help inform public health interventions. Computer simulations, often based on complex computational models, are another approach to predicting the impact of climate change on human health sensitive diseases. These simulations integrate data on climate, population, disease transmission, and other relevant factors to simulate the spread and impact of diseases in different climate scenarios. They can help researchers understand the potential consequences of climate change on disease burden and inform policy decisions.

The Poisson model is the most common time-series model for assessing how measured time-varying factors (for example, temperature) explain variation in daily counts of disease occurrence. To determine strong autocorrelations in disease transmission, autoregressive integrated moving average (ARIMA) and wavelet analysis models can be utilised (Imai et al., 2015). A seasonal autoregressive integrated moving average (SARIMA) model was used for time-series analysis between 2000 and 2013 to forecast cholera incidence in Dhaka based on climate variables (rainfall and temperature). Cholera incidence can be forecasted 1 month earlier with the temperature data, which is very promising for preparations, although the multi-variable model (Model B) with a 1-month lag among all combinations of climatic variables and lags showed the best result, since it had the lowest errors (Daisy et al., 2020). Time-series Poisson regression and seasonal autoregressive integrated moving average (SARIMA) models were fitted to examine the potential impact of weather variability on the transmission of cryptosporidiosis. Model assessments indicated that the SARIMA model had better predictive ability than the Poisson regression model (Hu et al., 2007). Patil and Pandya (2021) developed a dengue forecasting model using time-series Poisson multivariate regression that accounted for over-dispersion in the data. Mean weekly predicted cases were estimated through regression on multiple independent variables that included retrospective dengue cases, weekly mean temperature, weekly cumulative rainfall, trend, epidemic cycles and seasonal factors. The forecasting model was developed using three processes:

1) model construction and training using data from 2000–2010;

2) model validation by forecasting cases in 2011–2012; and

3) sensitivity tests on outbreak diagnoses (Hii, et al., 2012).

Predictive models can play a crucial role in early-warning systems, resource allocation, and targeted interventions to mitigate the impact of these diseases. The machine learning model, with its ability to learn from complex data, offers a promising avenue for developing robust and accurate predictive models for water-related diseases. Machine learning is a subset of artificial intelligence that focuses on algorithms and statistical models that allow computers to perform tasks without explicit instructions. By learning from data, these models can make predictions or decisions, making them particularly effective for analysing complex issues like water-related diseases. Various machine learning techniques, such as regression analysis, decision trees, support vector machines, and neural networks, have been utilized to handle vast amounts of public health data, environmental variables, and demographic information (Jordan and Mitchell, 2015).

Abdullahi et al. (2021) undertook several experiments to predict diarrhoea outbreaks in 9 provinces of South Africa. Applications of Support Vector Machines (SVMs), Long-Short Term Memory (LSTM) neural networks and Convolutional Neural Networks (CNNs) in predicting outbreaks based on real-world and synthetic data were evaluated. CNN had the best performance based on real-world data. Precipitation, humidity, evaporation, and temperature were sensitive parameters that contributed to predictive CNN performance. Santosh et al. (2020) applied an LSTM to predict malaria outbreaks using satellite and clinical data in the state of Telangana, India. Rainfall, relative humidity, temperature, and the vegetation index were the environmental variables considered in the study. The study's results indicated that environmental variables play an essential role in enabling the presence and transmission of malaria. The model provided a 12-month seasonal pattern for selected regions in the state.

CNN, transformer, LSTM, and attention-enhanced LSTM (LSTM-ATT) models were compared with traditional machine learning models for forecasting dengue fever in 20 provinces throughout Vietnam by Nguyen et al. (2022). Temperature, humidity, rainfall, evaporation, and sunshine hours were the input data for the models; the findings showed that the LSTM techniques displayed considerable accuracy in forecasting dengue fever.

A statistical and XGBOOST machine learning model were compared to a deep-learning transformer model for predicting malaria using precipitation and temperature in Limpopo Province (Pillay et al., 2023). The transformer model maintained consistent accuracy as more climate variables were included, indicating further potential for this prediction framework to forecast malaria incidence at a daily level using climate data for southern Africa. Discriminant analysis, multi-model and persistence models were used to predict malaria outbreaks in Vhembe and Mopani districts, Limpopo Province, South Africa (Martineau et al., 2022). Machine-learning classification (multi-layer perceptron (ens9), gradient boosting, ADA boost, XG boost, random forest, support vector, k-nearest, Gaussian process, Gaussian naïve Bayes, logistic regression, linear discriminant analysis, multi-model and persistence models) was used to predict malaria outbreaks in Vhembe and Mopani districts, Limpopo Province, South Africa (Martineau et al., 2022). Gridded monthly time series of climate variables, including sea surface temperature, precipitation, surface pressure, minimum and maximum temperatures, 10 m eastward wind and 10 m northward wind, were used in the study. The findings indicated that past information about SST over the western Pacific Ocean offers impressive predictive skill, with approximately 80% accuracy for up to 3 seasons. CNNs, LSTM, and SVM were used to predict daily diarrhoea cases across different South African provinces by incorporating climate information in a study by Abdullahi et al. (2022). Generative Adversarial Networks (GANs) were used to generate synthetic data to augment the available dataset; the results showed that all machine-learning methods were appropriate for predicting daily diarrhoea cases, with respect to the selected climate variables in each South African province. The level of accuracy for each method, however, varied across different experiments, with the deep-learning methods outperforming the SVM method.

2.5 Climate adaptation policies/strategies and the health sector

As health risks associated with climate change are expected to worsen (DoH, 2013), adaptation to these impacts is crucial to reduce and manage the disease burden. In South Africa, adaptation to climate change impacts also supports informed, comprehensive actions to reduce poverty and inequality, as the response strategies include development models (Khine and Langkulsen, 2023). For adaptation to climate change to be meaningful, it must involve a planned and systematic action by the government or private stakeholders (Afinowi, 2020). Thus, it is important to have climate change adaptation policies at national, provincial

and local levels for effective adaptation. Table 2.2 summarises national, provincial (Limpopo Province), and local (VDM) climate adaptation policies relevant to this study. Most of the policies cover adaptation to climate change impacts on human health. However, responsibility for implementing these policies is transferred from the national to provincial and local district levels. At the district level, VDM (2016) indicated that they will include the implementation of strategies in the municipality's Service Delivery and Budget Implementation Plan (SDBIP), although this has not yet been done.

Table 2.2: National, provincial and local climate adaptation policies/strategies

Climate change adaptation policy/strategy	Health related adaptation strategies	Remarks
National Climate Change Response White Paper (DEA, 2011)	Reduce the incidence of respiratory diseases and improve air quality, develop and strengthen existing public awareness campaigns, develop heat-health action plans, improve biosafety, develop a spatial and temporal health data capture system and integrate food security and sound nutritional policies into all adaptation strategies	It was mentioned that the implementation of adaptation strategies will be integrated into the DoH strategic plan. However, the DoH strategic plan 2020/21-2024/25 does not address climate change adaptation.
National Climate Change Adaptation Strategy (NCCAS) (DFFE, 2020)	Each province and municipality should draft and update climate change strategies that include adaptation responses and associated implementation plans to guide climate response in their province. These strategies and associated implementation plans should be reviewed and updated every five years.	The NCCAS, as a national strategy, does not detail how adaptation will occur across sectors affected by climate change.
Just Transition Framework (IPCC, 2022)	The framework focuses on managing the social and economic consequences of climate mitigation and adaptation policies, while putting human development concerns at the centre of decision-making.	The just transition framework is not exhaustive or a detailed implementation plan, but rather a first organising framework to give effect to a just transition in South Africa.
National Climate Change and Health Adaptation Plan (2014-2019) (DoH, 2014)	It provides a broad framework for health sector's action towards climate change adaptation, with objectives focused on describing the economic, environmental and health contexts for the proposals contained in the White Paper, which outlined a broad programme of activities to be undertaken by the South African health sector, timeframes and financial implications.	The DoH will establish, in high-risk areas, a series of model projects for the implementation of adaptation actions with a focus on prevention and intersectoral action. Lessons learned in the model projects may be considered for scaled up implementation in other relevant parts of the country.

Climate change adaptation policy/strategy	Health related adaptation strategies	Remarks
National Heat Health Action Guidelines (DoH, 2020)	Guidelines to ensure that the health sector is prepared to effectively respond to rising temperatures across South Africa.	The guidelines are aimed at supporting Provincial Departments of Health, District Health Services and municipalities to design, implement and improve Heat Health Action Plans to prevent the negative effects caused by increasing temperatures and heatwaves.
Limpopo Provincial Climate Change Response Strategy (LEDET, 2016)	Adaptation measures for the health sector indicate that it should formally join, participate in, and leverage capacity and information from global climate change health networks and knowledge-sharing platforms; secure, dedicate, and allocate substantial funding for better climate-related health surveillance and monitoring in the province and carry out studies within Limpopo on health impacts of climate change; fund and implement a comprehensive public health and climate change awareness and adaptive capacity building programmes, as well as redouble efforts to improve overall socio-economic status and health indices.	Responsibility for implementation would rest with the Department of Health, but in coordination with Limpopo Department of Economic Development, Environment and Tourism (LEDET), DWS, Department of Environmental Affairs (DEA), and the Department of Education (DoE).
Climate change vulnerability assessment and response plan (VDM, 2016)	Identified adaptation actions include managing health impacts from increased storm events, heat stress, waterborne and communicable diseases (typhoid fever, cholera, and hepatitis), and occupational health problems.	The actions should be included in the Service Delivery and Budget Implementation Plan (SDBIP). However, both the SDBIP for 2022/2023 (VDM, 2023a) and for 2023-2024 (VDM, 2023b) contain no aspects of climate change adaptation.

Engelbrecht et al. (2022) noted that there are strong and well-developed policies that can enable adaptation responses to heat risks in the changing climate in South Africa, although there is limited implementation of the policy into actionable climate-health plans on municipal, provincial and national scales. Khine and Langkulsen (2023) noted that although cross-sectoral implementation plans are well demonstrated in the National Climate Change Adaptation Strategy, some institutional challenges and gaps remain, in terms of - climate governance structures, communication issues between different tires of government, the capacity of the human resources, and public–private engagement issues.

Chersich and Wright (2019) indicated that while policy and planning frameworks for climate change at national, provincial and local levels mention health priorities, this sector does not yet appear to be viewed as an essential platform for adaption measures, hence, health concerns appear to be accorded low priority. This latter study, however, noted several significant examples of health-sector involvement in adaptation initiatives within local area government and in occupational settings. This, therefore emphasises and supports development of innovative scenario building for no regret adaptation, along CWH nexus and inform policy and institutional transformation, at local and national levels, as envisaged in this study. This will facilitate the implementation of strategies at local levels and assist in closing institutional and communication gaps.

2.6 Climate Resilient Development (CRD)

Globally, climate-change impacts and hazards disproportionately affect the poorest groups and compromise opportunities for a safe, equitable and sustainable future (Roy et al., 2018). Triggering transformative changes focuses on drivers and outcomes of coupled-systems dynamics that shape pathways at institutional and community levels to achieve positive long-term effects on wellbeing of the poor and vulnerable, amidst risk and uncertainty (Leal Filho et al., 2021). The CRD takes into account diverse options, strategies, coordination initiatives, and implementation as foci for overcoming silo framing traps (Rasmussen, 2018). By facilitating meaningful participatory opportunities, CRD approaches, such as adaptive pathways, enable procedural justice (Wood and Dougill, 2018), address maladaptation (Suckall et al., 2014) and facilitate the integration of diverse world views and knowledge cultures, across multiple scales.

The CRD, thus takes into account aspects of adaptation and mitigation scales while paying attention to inter-generational equity outcomes (Leal Filho et al., 2021). Given that equity and sustainability are inextricably interlinked, CRD is significantly biased towards the social pillar in which poverty, vulnerability and the underlying issues of power, equity, and justice are prioritised. In essence, CRD seeks to decrease the risk of shifting vulnerabilities through systematic and holistic programming systems approach (Buurman and Babovic, 2016; Filho et al., 2021). The objective is to inform the appraisal, prioritization and implementation of responses in adaptation planning (Fazey et al., 2016), as well as guide the resolution of unfavourable socio-economic impacts of climate change (Leal Filho et al., 2021).

The CRD has largely been informed by the need to consider sustainability through integration of adaptation and mitigation measures, in climate change action. In particular, CRD accords prominence to future societal equity outcomes (Schipper et al., 2021). As a subset of CRD, adaptation pathways (APs) set out possible actions that may be implemented over time, depending on possible future economic and societal dynamics (Bosomworth and Gaillard, 2019; Fischer, 2018). The IPCC (2018) elaborates CRD pathways as interventions that - build resilience, tackle the root cause of poverty, reduce welfare gaps, promote a fair and just adjustment as well as explore any opportunity associated with climatic changes – across scale and socio-economic strata. A better understanding of intertwined drivers and outcomes of coupled systems dynamics that shape pathways, hence, is critical in this regard (Leal Filho et al., 2021).

The APs are highly context-specific and grounded in local institutions (Totin et al., 2021). These include, historical, socio- economic, cultural and political contexts (Arkema et al., 2017; Islam et al., 2014). Case studies could extend knowledge and narrow critical science-policy-practice research gaps. In disaster risk-reduction framework, the concept of adaptation is often used in place of “resilience”, whereas in development literature, adaptation is usually replaced by “CRD” (Fankhauser, 2017); however, resilience underpins TSP and CRD framings. Rockström et al. (2023) defined resilience as the capacity to sustain livelihoods, develop, innovate and transform, in the face of crises, such as climate change. Implicitly, transformation, therefore, encompasses resilience and successful adaptation.

2.7 No regret adaptation

Under conditions characterised by variability, uncertainty and change, conventional planning scenarios provide little guidance regarding future needs and conditions (Manocha and Babovic, 2017). Accordingly, there is need for policies that perform effectively under dynamic and uncertain conditions so as to mitigate the risk of them not achieving their intended purpose, and becoming a hindrance to the ability of individuals, communities, and businesses to withstand and adjust to climate change (Manocha and Babovic, 2017; 2018). As climate future cannot be predicted precisely, adaptation policies should reduce potential regrets while taking advantage of presented opportunities (Haasnoot et al., 2013). No-regret or low-regret measures are adaptation strategies that has a high possibility to ensure desirable outcomes and impacts are realisable, even during the occurrence and severity of climate extremes, such as drought. According to IPCC (2014), low-regret climate mitigation and adaptation policies deliver net welfare and/or economic benefits to the target population under current and future change risk scenarios. In a nutshell, development strategies are considered to be no regrets if they do not carry the risk of adverse third party costs on society, under all plausible scenarios (Butler et al., 2016). Implicitly, no regret adaptation planning incorporates proximate and underlying factors to ensure planned goods and services are delivered, the realisation of risks, notwithstanding (Hallegatte, 2009; Omore et al., 2019).

No regret adaptation fundamentally consists of imagining a policy output over a series of decision points, distributed across the planning cycle and beyond, to ensure flexibility, rather than restricting the evaluation metrics and criteria to the present alone (Hallegatte, 2009). Tipping points or thresholds provide a clue that the course of action chosen is no longer adequate for meeting the planned objectives and new measures are required, hence the creation of alternative course(s). Such standalone and/or combined actions are known as "APs" (Werners et al., 2021a). The APs assessment considers diverse individual and community value judgements, hence the vulnerability context across political, institutional, economic, and social contexts (O'Brien et al., 2011). Vulnerability of communities to health risks associated with climate change usually originates from poor water quality, sanitation and hygiene, which are considered in this study. Hinkel (2011) defines vulnerability as

susceptibility to future harm or deterioration in state, such as flooding impacts on health and associated outcomes, such as diarrhoeal diseases.

2.8 Theory-based sustainable transformation tools (STP)

Achieving sustainability and resilience under climate change requires transformative and multi-scale visions to stimulate coherent thinking and action towards radically alternative futures (Steffen et al., 2018; Otto et al., 2020). Research and policy debates, however, continue to base decisions on Business as Usual (BAU) approaches or reactive approaches without regard to future risks, threats and decisive choices (Hölscher et al., 2022). In particular, conventional adaptation planning tools, often fail to integrate power dynamics and other social lenses, such as belief systems, in a systemic way, thereby, creating grounds for maladaptation (Schipper et al., 2021). The myriad of uncertainties in adaptation planning include, lack of adequate and accurate information, cognitive divergence among the diverse stakeholders, as well as poorly-defined outcome (Wise et al., 2014; Butler et al., 2015; Gajjar et al., 2019). Inclusion of communities into predesigned adaptation plans that are rooted in a narrow climate-risk framing is just a form of tokenism, which limits the solution space and biases planning towards dominant imaginaries that fail to account for context-specific socio-economic realities (Quealy and Yates, 2021).

Transformation-oriented approaches use the idea of pathways to frame diverse directions of change across a range of strategic aims and future visions that take into account societal and community individual aspirations in response to large-scale changes in climate and ecosystems. In a systematic review of the literature, performance-based multi-stakeholder-oriented and transformation-oriented clusters on pathway thinking, are identified (Werners et al., 2021b). These include - impact pathways for theory of change (Omore et al., 2019; Dinesh et al., 2021); pathway thinking for sustainability (Butler et al., 2016; Gajjar et al., 2019; Leach et al., 2007) as well as, dynamic processes of change and responses for strategic planning (Colloff et al., 2016). The outcomes of adaptation policy can, in most cases, only be observed in the far future; hence, it has been suggested that process indicators are appropriate metrics for monitoring the adaptation process, for instance, whether a heatwave emergency management plan has been put in place or not (Hinkel, 2011). Although the

pathway clusters are not mutually exclusive, the adapted multi-stakeholder-oriented approach will be adopted in this study.

Operationalising climate resilient-development pathways implicitly requires explicit engagement with the aspirations of actors; working with multiple pathways to embed flexibility, anticipation and learning into planning, as well as the prioritisation of justice and equity lenses (Butler et al., 2022). In their findings, Leal Filho et al. (2021), argued that most methodological approaches fail to critically focus on root causes and the social-political-economic contexts that underpin vulnerability and transformation. In this study, the definition of vulnerability of communities to the health risks-climate change nexus, through water quality, sanitation and hygiene pathways was adopted. The goal of this study is to support climate compatible development in South Africa and Limpopo, particularly in contexts characterised by high poverty, and rapid environmental and social change. The participatory lenses and focus on the marginalised, as well as addressing contextual needs in a sustainable manner, connect CRD and TSP, hence resonating with the main assumptions under TSP.

In sustainability discourses, transformation refers to fundamental changes in the structural, functional, relational, and cognitive aspects of socio-ecological and technological systems that lead to emergent patterns of interactions and outcomes (Patterson et al., 2017). Transformation is underpinned by the realisation that power structures and diversity of values, cultural changes, accepted way of life and practices, form the basis for risk attitude and response at scale, as well as successful adaptation planning (Ng'ang'a and Crane, 2020; Totin et al., 2021; Butler et al., 2022). Accordingly, it is recognised that narrow climate-risk lenses, which drive adaptation planning, are inadequate if underlying causes of vulnerability are to be addressed. It is acknowledged that failure to recognise and challenge the situated and multifaceted drivers of vulnerability among disadvantaged segments of a community in adaptation-development programming will not only reinforce existing power asymmetries but also deepen social inequalities (Quealy and Yates, 2021). In essence, AP embeds multiple pathways in planning for transformative sustainability and refrains from focusing on a single pathway or technological fix that is likely to fail or increase vulnerability (Nightingale et al., 2020; Pearson and Dare, 2021). Adaptive planning further enhances flexibility in decision making (Haasnoot et al., 2013; Wise et al., 2014). Pathway thinking is, thus, underpinned by

the need to integrate the diverse knowledge cultures and test the assumptions underlying their preferences (Wise et al., 2014; Werners et al., 2021a). The following section reviews various tools and approaches in societal transformation, in general, and AP in particular.

2.8.1 Pathway thinking

Adaptation pathways have been proposed as a promising decision-focused approach to incorporate flexibility into decision-making and account for future uncertainties (Haasnoot et al., 2013; Wise et al., 2014; Bosomworth et al., 2017). The basic notion of pathways is that decisions and measures are sequenced in time to achieve future goals (Werners et al., 2014; 2021a; 2021b). Pathways broadly correlate with the outcome of accounting for complexity and long-term change, including the potential need for transformation (Sparkes et al., 2023). Although it is necessary to collectively identify systemic and long-term issues, and related transformative strategies, it risks undermining the participation and capacity of community members in decision-making (Butler et al., 2015). Such approaches risk entrenching already existing social inequality and communities' vulnerability to disasters (Quealy and Yates, 2021). The inclusion of stakeholders with different worldviews in pathways processes is not only fair, but also diversifies the framing optics, enhances the quality of decisions, democratises decision-making space, addresses ambiguity and reduces inequality. In so doing, it addresses both the symptoms and root causes of vulnerability, to facilitate the successful mainstreaming of adaptation plans and policies into broader development planning, thereby enhancing sustainability visions (Sparkes et al., 2023).

The APs are framed in the reviewed literature as sequences of actions that can be implemented sequentially depending on how the future unfolds, on the development of knowledge, as well as stakeholders' preferences (Patterson et al., 2017)**.** The AP has emerged, in part, due to the realisation that technological "fixes" to adaptation problems fail to unpack the structural causes of vulnerability (Nightingale et al., 2020). Focusing on underlying causes of vulnerability could radically unpack interwoven dynamics, integrate technical and social factors that jointly impact vulnerability and inform societal transformation (Faye and Ribot, 2017; Mikulewicz, 2019). Operationally, pathway thinking generally refers to alternative action for addressing a specific adaptation need, for instance, health challenges in a changing climate (Haasnoot et al., 2013; Sadr et al., 2020), as well as adaptation of existing narratives

or framing for broad direction of change and transformation (Wise et al., 2014; Colloff et al., 2016).

Pathway planning enables planners to identify robust actions that can support a targeted system to adapt to complex phenomena, for example, changing climatic, social, environmental, and economic conditions (Haasnoot et al., 2013). As a form of structured, yet flexible decision-making tool, AP planning facilitates the exploration and iterative sequencing of actions, referred to as pathways (Bosomworth and Gaillard, 2019). In this way, AP links climate change and development challenges, facilitates co-production of knowledge, and integrates differing perceptions of future time horizons on climate change and development priorities (Wise et al., 2014; Werners et al., 2021a). The utility of adaptive planning has thus increased in the face of temporal uncertainties (Munene et al., 2018).The need to address systemic drivers of vulnerability (Butler et al., 2016), as well as being used as a tool for the identification of lock-ins (Haasnoot et al., 2013). Pathway approaches basically answer the question “what could be” or is an unfolding scenario in the short, medium, and long term, as well as “what should be” or visions, strategies and responses that address the risk propellers. Unlike the ubiquitous log-frame tool in conventional project planning, which only addresses cause-and-effect and means-end, pathway thinking tests assumptions underlying the visions advanced by the diverse actors (Omore et al., 2019). Specific analytical tools for data gathering, analysis and synthesis in pathway thinking are diverse, through the use of decision trees (Haasnoot et al., 2013).

As an effective planning approach, AP provides an opportunity for flexibility and learning in an evolving context, such as a changing climate (Sparkes et al., 2023; Werners et al., 2021b), hence can act as a learning framework for systematic reflection and framing in diverse adaptation decision-making contexts (Werners et al., 2021b). Such an approach considers the long-term and short-term needs. Pathways may identify projects and programmes that are not path-dependent, hence those that are no- and/or low-regret adaptation, or low risk of maladaptation. In so doing, AP nurtures stakeholders’ capacity for change and enhances transformation, which are critical for successful adaptation (Colloff et al., 2021; Roy et al., 2021), disaster risk reduction, as well as for development planning (Sparkes et al., 2023). Governance of knowledge is one of the most critical societal transition metrics in decision-

making (Butler et al., 2022). Under multi-stakeholder approaches, pathways are often framed as the actions needed to manage trade-offs and risks for achieving mutually agreed-upon societal goals. The acknowledgement of the system's ambiguity and integration of non-expert knowledge promotes co-creation and capacity building. Performance threshold-oriented approaches inform planning by providing alternative sequences of actions in response to projected future scenarios and broadly correlate with the outcome of meeting short- and long-term adaptation needs (Sparkes et al., 2023); however, stakeholder approaches are preferable in contexts of data scarcity. The back-casting approach is critical in identifying context-specific collective actions for adaptation and social learning, thereby progressing towards shared goals through multi-stakeholder discourses and for integrating uncertainty - aligning agreed perspectives on adaptation with desired vision (Bruley et al., 2021).

Adaptive thinking enhances reflective learning, although there is a paucity of information on the utility of such tools and approaches in formal planning practice (Lawrence et al., 2018; Werners et al., 2021a). Problem definition and agenda-setting in contexts thus remains a key gap under the diverse, yet robust adaptation pathway approaches (Werners et al., 2021a). In essence, adaptation thinking is implicitly underpinned by Theory of Change (ToC) principles. This study addresses the CWH impact scenarios in the drylands of South Africa by testing the underlying assumptions that underpin existing (planned) adaptation against community values and expectations. The aim is to improve the adaptive planning process and inform the transformation of institutional and governance systems for no-regret adaptation options in water under a changing climate, with a view to enhancing the adaptive capacity of the target social systems and ensuring the sustainability of adaptation initiatives. Problem trees, which explore cause-and-effect and means-end relationships to address various water scenarios and health-risk drivers under a changing climate, were used to identify no-regret adaptation measures. This is akin to the pragmatic enlightened model (PEM) model (Edenhofer and Kowarsch, 2015).

2.8.2 Quantitative storytelling (QST)

Narratives encompass divergent viewpoints, such as opinions and their interpretations, expert and lay judgments, knowledge authorities, truth claims, and assumptions informed by

a complex combination of cognitive and moral principles, beliefs, values, knowledge, experience, and socio-political factors (Kowarsch et al., 2017). The QST (Figure 2.8) has emerged as a multiscale nexus assessment and biophysically grounded method for assessing dominant stakeholder narratives and expectations and analysis of complex social–ecological system challenges (Di Felice et al., 2021), co-production of knowledge (Saltelli and Giampietro, 2017) as well as checking the coherence of already existing or new narratives (Di Felice et al., 2021). QST is a nexus assessment method that uses both numbers and narratives; it may not be instrumental in directly inducing policy change, but it is a valuable means to initiating discussions on innovations, outside the dominant imaginaries. In essence, the significance of QST lies in its support for citizen science and effective participation, as envisaged under the transformative approaches to planning.



Figure 2.7: The QST cycle

2.9 Theory of change (ToC)

Interlinked global climate change challenges, such as climate change and poverty, make silo approaches untenable, hence the need for integration (Stafford-Smith et al., 2017). The ToC is an evidence- and experience-based process for pursuing a logical set of outcomes (Thornton et al., 2017; Campbell et al., 2018) as well as the development of context-specific approaches

for convergence between practitioners, scientists, and policy-makers, through a coordinated set of efforts that address underlying development change (Thornton et al., 2017; Campbell et al., 2018; Dinesh et al., 2021). Use of ToC can both inform evidence-based policy design (unpack context-specific challenges and identify potential solution space), policy instrumentation, and networking between state and non-state actors, hence promoting participatory assessment and planning (Reed et al., 2022).

The ToC can be applied in scenario planning, impact assessment, or for a complete planning, monitoring, and evaluation process. Mayne and Johnson (2015) listed numerous uses for ToC, in ex-ante and ex-post, designing, implementing, and evaluating project interventions. Co-developing a ToC for integrated landscape management, although it is inherently context-specific, the process and outcomes hold relevance across a range of contexts faced with sustainability challenges (Reed et al., 2022). The ToC cycle embraces the complexity of social change and proposes a model of change that can be tested and improved over time, through a systematic process of analysing the feasibility and plausibility of planned pathways to change (O'Flynn and Sonderskov, 2015). This is in sync with AP thinking. In essence, the ToC process involves developing:

- the change pathway (APs that are context-specific) and
- assumptions (scenarios informed by science and experience) through stakeholder deliberation and reflective thinking.

The data collected through the ToC process includes: climate change context and vulnerability, entry points for interventions (adaptation pathways), main drivers of vulnerability, enabling environment for adaptive capacity and adaptive planning, partnerships, existing projects/ plans/ programmes, focal actors, and specific data related to the selected change areas. A participatory tool, "The Assets Drivers Well-being Interaction Matrix" (ADWIM) (Mayne and Johnson, 2015; Butler et al., 2016(Skewes et al., 2016) was adapted to estimate the interaction of climate change and social pathways, such as population growth and income, on water availability and health. The analysis was guided by the following questions:

- What are the key drivers of change (economic, cultural, technological, institutional and governance, climate and biophysical) at the community level?
- What are the climatic changes in the community?

- How are the climatic changes impacting water and health, and associated scenarios (BAU and optimistic)?
- What have been the responses and challenges, if any?
- What is the extent of effectiveness for the existing and proposed adaptive measures (SWOT/ PESTEL model)?
- What are the short-, medium- and long-term measures for no-regret adaptation, suggested by interested actors and related assumptions?
- Are there better current responses (adaptations) with reference to government, behavioural, informational, governance, and institutional frameworks?
- What are the likely best future practices and the underlying assumptions, based on good practice criteria, such as efficiency, relevance, coherence, and sustainability dimensions?
- What are the visions for no-regret adaptation strategies?

2.10 Summary

A review was conducted on the body of literature on transformative adaptation planning and CRD water systems. The literature review findings also highlighted the need to understand the existing and potential innovations for collaborative learning, as well as responsive adaptation planning policies. Iterative sharing and integration of knowledge across scales, from local communities to national and global actors, are critical in empowering institutions to successfully steer adaptation. Adaptation also requires multidisciplinary knowledge and shared responsibility, coordinated among governmental and non-governmental actors across different policy areas. Knowledge, however, is often held, stored, and perceived differently across levels, resulting from differences in what is perceived as salient, credible, and legitimate knowledge, or in what is perceived as the essential scale or level of the problem.

Apparently, knowledge creates asymmetries in influence and control over policy, orchestration, and shaping of co-production in the process, thereby undermining transformative intent (Turnhout et al., 2020). This challenge in the co-production of knowledge across scale and mediation can be addressed through intermediary organisations also known as “boundary organisations/ bridging organisations” (Folke et al., 2005). Cash and

Moser (2000) propose that governance for linking global and local scales should utilise boundary organisations (e.g., knowledge brokers), utilise scale-dependent comparative advantages, and employ adaptive assessment and management strategies. Under such an institutional arrangement, the role of Governments (or any other facilitating authority, such as a non-governmental organisation (NGO), provincial governments) is to nurture the self-organising ability of actors to voluntarily develop new norms and codes of conduct for sustainability/ safety, by creating space for collaborative experimentation and innovation. A SWOT analysis of coping strategies can inform innovation pathways and reveal the policy, ecological, social, technological, legal, and political changes as well as innovations that are required to transform water systems, in adaptation planning. The literature findings show that there are opportunities for innovation and collaborative learning in developing climate-resilient systems that consider context issues, such as poverty and reversing development planning legacies, that inadvertently embed inequities.

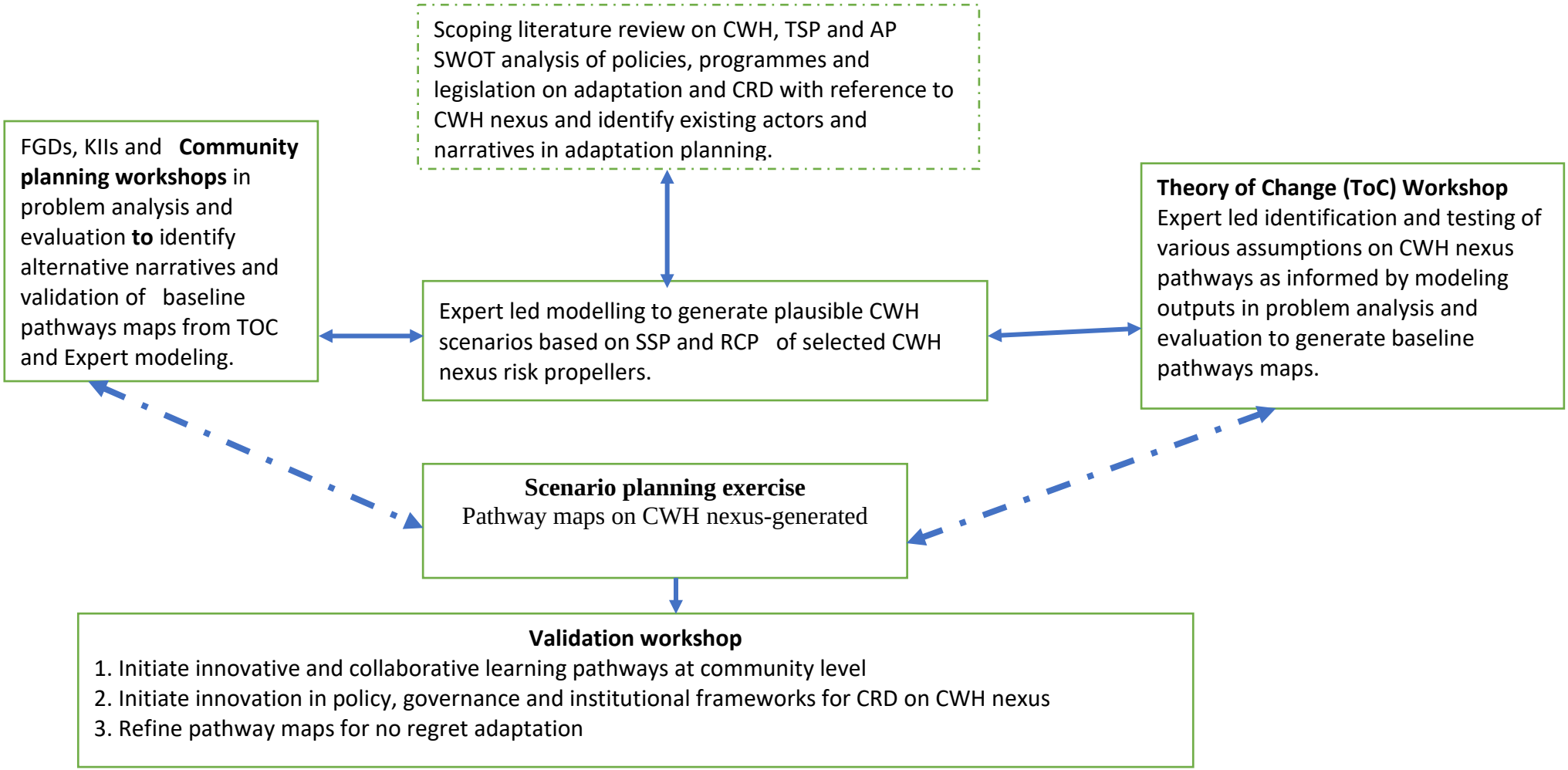
CHAPTER 3: METHODOLOGY

3.1 Introduction

The methodology provides details on the processes used to collect and analyse data to achieve the objectives of the study. It also covers ethical principles and protocols, including transparency, informed consent, and the voluntary participation of stakeholders in the study.

3.2 Research methods

An analysis of sustainability challenges in complex social–ecological systems calls for the integration of multiple analytical methods, frames, and perspectives (Di Felice et al., 2021). This study adopted a mixed methods approach. The objective of the mixed methods approach is to enhance the credibility, legitimacy, and salience of the modelling research process for stakeholders (following Cash et al., 2003) through a co-production approach, whilst increasing our understanding of the decision-making context. Hence, an iterative approach that integrates stakeholder views and model-based analysis was adopted (Figure 3.1). First, the decision context was investigated, and stakeholder viewpoints were gauged, followed by the development and validation of a CWH nexus model.



The broken line indicates that scenario planning is not a stand-alone phase but rather integral in the iterative processes during modelling, ToC, and community planning workshops

Figure 3.1: Methodological approach for the study

The methodological approach (Figure 3.1) involves the following methodological innovations:

- Translation of qualitative climate and socioeconomic narratives into plausible quantitative scenarios of future precipitation and water demand on health outcomes;
- The use of stakeholders' and expert judgment to identify adaptation options and construct APs; and
- Exploration of the robustness of the adaptation options and pathways, against different performance metrics.

3.2.1 Study area

The study area covers selected areas of the VDM one of the five districts of the Limpopo Province of South Africa (Figure 3.2). It is the northernmost district of the country and shares its northern border with Beitbridge District in Matabeleland South, Zimbabwe, and on the east with Gaza Province in Mozambique. The VDM is a Category C Municipality, established in the year 2000 in terms of Local Government Municipal Structures. Limpopo Province, although it is the food basket of South Africa, is characterised by high poverty levels, water stress, and proportionately higher burden of climate-related diseases, such as malaria.

According to the Community Survey 2016, VDM has 382,358 households, in which Thulamela, Makhado, Musina, and Collins Chabane have 130321, 116371, 43730, and 91936 households, respectively. Therefore, Thulamela Municipality has the highest number of households, followed by Makhado, Musina, and Collins Chabane municipalities.

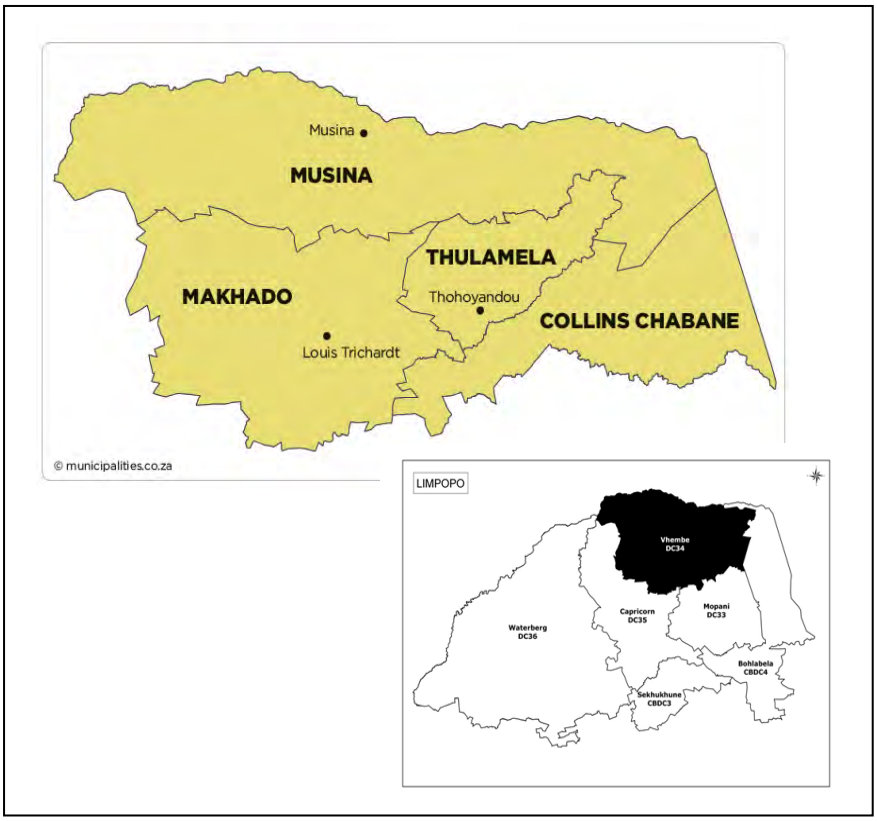


Figure 3.2: Map of the study area

3.2.2 Sampling and data collection approaches

The research design was guided by Policy Coherence for Sustainable Development (PCSD). The PCSD has emerged as a prominent concept in the debates surrounding development and aid effectiveness and, more recently, sustainable development and the policy diffusion perspective. Lacking an agreed definition, policy coherence for (sustainable) development can, however, be understood as "the systematic promotion of mutually reinforcing policy actions across government departments and agencies creating synergies towards achieving the defined objective" (OECD, 2024). Policy network theory, in particular, underscores that coordination is an essential part of PCSD and a central component of governance in efforts to achieve a common goal (Bilodeau and Potvin, 2018).

The primary and secondary data collected through a participatory planning process were triangulated to address the assessment questions. Key data sources included rural communities, government institutions supporting policy implementation on the CWH nexus,

the private sector, NGOs, and policymakers in the CWH nexus. Several instruments, including questionnaires and interview schedules, were administered to collect information from the community and key stakeholders in the CWH nexus. Primary data was collected through KII and FGDs, while secondary data was collected from existing scholarly and grey literature, such as books and policy documents.

The research team adopted a two-stage qualitative sampling strategy that included stakeholders at the local government and community levels. The key criterion for selecting a project site was purposeful for all the local municipalities in VDM. Stakeholders were identified following Appendix 1 and prioritised based on the Mitchell et al. (1997) score on a scale of 1–5 against three salience criteria (power of the stakeholder, the stakeholder's legitimacy as viewed by others, and the urgency of the stakeholder's claims). An interview guide on ToC and pathway thinking (Appendices 2-6) provides a framework for discussions with key informants and FGD groups in the sampled project sites. The interview guide was aligned to the reconstructed ToC and adopted policy assessments. The interview guide explored a range of issues related to adaptive planning, participation, delivery of partners and stakeholders, efficiency, effectiveness, and problems being encountered. A particular focus was on the on-the-ground impacts of policies, whether they were realising the intended objectives, and adaptation scenario planning. In summary, the key data collection methods used included narrative and desktop reviews, scenario planning workshops, focus-group discussion (FGD), key informant interviews (KII) and direct observation.

3.2.3 Desktop and narrative reviews

National and local government level policy documents were considered critical input material. These included the National Climate Change Response Strategy, the Nationally Determined Contribution (2015), the National Adaptation Plan (NAP, 2015-2030), the Climate Change Act, the National Climate Change Action Plan (NCCAP), and the National Climate Change Framework Policy and Act. The review and analysis of the secondary data aimed at identifying CWH nexus issues.

3.2.4 Policy assessment framework/criteria

The review adopted a theory-based assessment approach to examine how the policy is intended to work and the institutions involved. The ToC was reconstructed to provide a framework for linking the assumptions between interventions and the desired outcomes and to guide planning and participation. The policy assessment criteria of CRD, climate change mitigation, and sustainable natural resource management were adopted. The criteria included the assessment of relevance, effectiveness, efficiency, and the coherence of various policy narratives/ imaginaries. The relevance criterion focused on assessing the evolution and the extent to which policy objectives correspond to adaptation needs and issues in the CWH nexus. This informed a participatory assessment on the effectiveness of policy intervention and adaptive planning. This is in addition to the efficiency criterion to assess whether the costs involved are justified, given the changes and effects being realized, the extent to which a public policy intervention is coherent with other interventions, and internal coherence of the public intervention. An additional criterion on the value added of policy interventions at the county level of governance was added to the four assessment criteria.

Special attention was focused on planning across policy sectors, political commitment, and leadership of adaptation and mitigation interventions in the water sector, with a bearing on health vulnerabilities and risk propellers. A judicious combination of quantitative and qualitative research tools was used to gain a sound understanding of the problems and opportunities faced by different stakeholders and communities, as well as their respective local municipalities. The collected data was analysed to explore how the different policy aspects produce a synthesis outlining the different local and national level policy and legal experiences and outline strategic actions (policy recommendations). A Multi-Criteria Analysis (MCA) method was used to identify and compare different policy options.

3.2.5 The climate change institutional assessment (CCIA) framework

The CCIA was used to identify the strengths and weaknesses of the institutional framework in addressing the identified climate change governance challenges. The assessment adopted the elements and key issues addressed in the five pillars of CCIA (organization, planning, public

finance, provincial governments, and accountability). The narrative assessment guide in Table 3.1 was used. Table 3.2 lists the elements and issues considered in the desktop review.

Table 3.1: Dominant and alternative narrative assessment guide on CWH nexus

Actor name	**Classification of the actor in the nexus policy**	**Envisaged scenario**	**Multi-objective projection criteria against year**	**What is the narrative being advanced in CWH**	**Remarks**
	The actor from the dominant (D) policy narrative, e.g., academia, or from alternative (A) policy narrative, e.g., community	Decreasing and increasing moisture/ water flows	2030 2050 2100	1. Justification narratives 2. Normative narratives 3. Explanation narratives	Analysis on whether the narratives are coherent across the environment and socio-technical dimensions and fit for the problem they are supposed to address

1. Justification narrative explains why a process should be done; 2. Normative narrative states what should be done and 3. Explanation narrative explains how it is to be done.

Table 3.2: Desktop review of data and secondary literature

Element	Issues
Access to Climate Information	Availability and effective communication of key information: physical and transition risks; climate targets, plans, and strategies; climate finance; water and health impacts and progress in adaptation.
Stakeholder Engagement	Requirements for: engagement with the private sector, civil society, media, the scientific community, and the public in planning, policy, and evaluations; breadth of representation, satisfaction of participants, and impact on policy.
Independent Expert Advice	Mandate and authority of independent expert advisory body; reporting arrangements; public access to advice; requirement for government response.
Legislative Body	Scope of legislative review and approval of key climate planning and policy instruments (physical and transition risk assessments; climate targets, strategies, and plans; public resource allocations and climate finance; reports on emissions and progress in emission reductions); capacity of legislature for scrutiny of climate policy; access to independent advice.

3.3 Climate change-water–health nexus modelling

The study modelled the link between climate change and climate-sensitive diseases and projected the number of future cases of these diseases. Historical and future climate data used in the study included rainfall, relative humidity, and maximum temperature. Stakeholders, including health experts, relevant government departments, and community leaders, were engaged to identify key climate-sensitive diseases (focal health parameters)

and to investigate their understanding of the link between climate change and health, following Kaddu et al. (2020). Focal health parameters data comprises the number of recorded cases of malaria, bilharzia, and diarrhoea.

3.4 Approach to AP process

Deep uncertainty describes dynamic conditions where there is limited knowledge and agreement on the use of models, description of parameters in those models and what impacts are considered (Kwakkel et al., 2016; Lempert et al., 2003). A better understanding of tele-coupled drivers and outcomes that shape pathways is critical to planning, amidst uncertainty (Leal Filho et al., 2021). To a large extent, vulnerability of a community is a value judgement on future harm or worsening of the state, such as the impacts of flooding on mortality (Hinkel, 2011). In essence, local adaptation planning interventions need to consider systemwide dynamics that impinge on vulnerability across political governance, institutional, economic, and social contexts (O'Brien et al., 2007). In this study, vulnerability of communities to the health risks-climate change nexus is defined through water quality, sanitation and hygiene pathways. Since the outcomes of adaptation policy can, in most cases, only be observed in the far future, it has been suggested that process indicators are appropriate, as metrics monitor the process of adaptation itself, hence whether a heatwave emergency management plan has been put in place or not (Hinkel, 2011). In the current study, it is posited that decision-makers are likely to encounter deep uncertainty when assessing the vulnerability of a community to changing climate patterns, which may be experienced decades from now, through water development and land use planning, as well as urbanisation patterns over the coming decades.

The AP methodology involved imagery of plausible long-term changes of a community, while accounting for climate risks, assessing conflicts in each pattern and possibly avoiding lock-ins (Sparkes et al., 2023). This was operationalised by adopting the definition of "vulnerability" as a value judgement concerning anticipated future harm or undesirable state that undermines lives and livelihoods, such as climate-related flooding and droughts, and their impact on livelihoods and mortality. Figure 3.3 provides the AP process adopted by the study team.

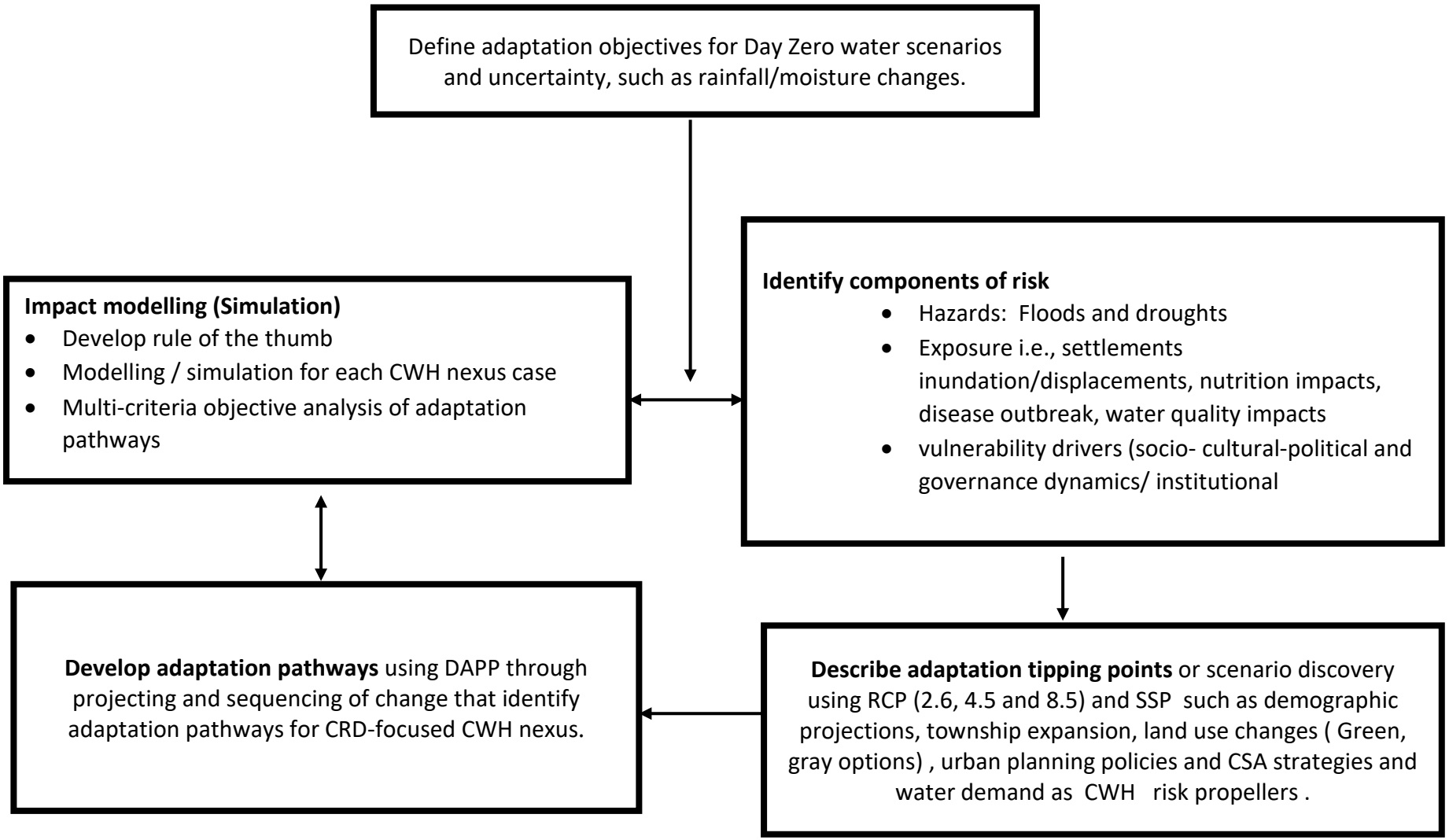


Figure 3.3: The adaptation thinking process adopted for the study

3.5 Participatory planning workshops

Achieving sustainability and resilience transformations under climate change requires transformative and multi-scale visions to stimulate coherent thinking and action towards radically alternative futures (Hölscher et al., 2022). Kowarsch et al. (2017) provided strategic approaches for responding to divergent viewpoints and systematic reflections on designing inclusive processes that foster more rational, open public discussions about them. Detailed procedures in scenario planning and analysis are given by Hölscher et al. (2022). This study combined scenario planning and adaptation pathways' principles to mainstream future uncertainty, with decision-making for community development (Butler et al., 2016). The team adapted this framework, informed by the realities and practicalities of the project team and field stakeholders. This ensured activities were adapted to the time frame and capacity, with attention given to the client's interests and expectations. Reflective interventionist multi-actors' approach (Wilkinson and Eidinow, 2008) was adapted to encourage integration of community perceptions and assumptions, as well as develop explorative scenarios on CWH nexus challenges and to design appropriate no-regret adaptation strategies.

In practice, communities are not homogeneous blocks with the same priorities; therefore, more attention is needed towards methodologies that identify and address each social group's needs, urgencies, history, and social relations, thereby meeting local credibility, legitimacy, and relevance and engaging with trade-offs from different actions (Cradock et al., 2021). Knowledge cultures (strategic, local, and holistic clusters) were used to segregate and categorise actors, hence serving as a tool for ensuring representativeness and community inclusion. Analysis of outputs from the process was used to understand different stakeholders' perspectives on the CWH nexus, including priority on no-regret adaptation strategies at the community level. Collation of available climate change projections, mapping of CWH risks, demographic data and projections, and economic trends formed the baseline data for the workshop deliberations. The workshops adapted Brown's (2008) decision-to-practice learning steps to iteratively integrate knowledge cultures in answering research questions. The FGDs and KIIs followed adaptation pathways (Wise et al., 2014; Werners et al., 2021a) were the primary data collection tools.

The identified no-regret strategies were listed and ranked through multi-objective criteria analysis. Experts identified systemic and long-term issues and related transformative strategies by subjecting them to a multi-criteria objective validation exercise. In pursuit of the study objectives, narrative reviews of existing planning documents and multi-stakeholder planning processes were undertaken to elicit priority transformative adaptation options that address climate- change risks on health and their impact chain. A triple learning loop (short-term, alternative long-term, and development trajectories; thus, BAU, pessimistic, and optimistic scenarios for 2030, 2050, and 2090 on climate-water-food-health impacts) was explored through expert and community perceptions (brainstorming sessions and the Delphi method). A multi-criteria, objective-reflective approach was applied to assess and critique the strategies. The guiding questions were:

1. What are the drivers of vulnerabilities, based on identified focal health concerns?
2. What is the desired socio-cultural, climatic, governance/ institutional, economic (production systems) for addressing CWH challenges?
3. What could be potential future changes in water (moisture) availability and its effect on health under BAU, pessimistic, and optimistic scenarios?
4. Can the current CWH nexus practices be improved?
5. What are the priority no-regret adaptation strategies and actions on CWH?
6. Do current and planned development programs meet community expectations on CWH nexus challenges?
7. Is there a potential for improvement of the current and planned CWH development programs?

3.5.1 Framing the problem

Questions on who is involved and how were crucial to framing the adaptation problem, so that the consequent goals and means could be identified. The sequence of framing the problem was flexible; this was achieved through involving participants in framing the adaptation problem before seeking out relevant data and literature, scientific reports, academic literature, and grey literature to capture their understanding of the problem, before 'testing' this with participants. This was validated with stakeholders. Bosomworth et al. (2018) suggested a shared framing of the problem among participants through several participatory

activities, including a collective hand-drawing of a historical timeline for the area, presentations by traditional owners and scientists, and group work examining reports, plans, and stories of the landscape, to identify key attributes and drivers of the system. Maru et al. (2014) worked with participants to frame the adaptation problem, suggesting that workshop discussions can, almost immediately, identify climate-related, event-based risks (fire and flood), which each illustrate contrasting implications of climate change, for the participants and the communities they sought to represent. Butler et al. (2014) used institutional drivers of problem framing to unpack embedded positions within the system as well as overcome the fatalistic and passive worldview of the poor. Lack of consideration within the other cases of the institutional (normative and cultural-cognitive) contexts with which adaptation planning must engage suggests that much more work is needed on this issue, in participatory approaches to AP planning. Generally, the AP process involves the following:

i. Defining no-regret zero-day adaptation goals and objectives in the CWH nexus;
ii. Understanding the current situation;
iii. Analysis of possible CWH nexus futures, including analyses of vulnerabilities, opportunities, and assessing the efficacy of actions under different futures;
iv. Identifying system and action thresholds or tipping points (points at which an action no longer performs satisfactorily in relation to objectives);
v. Developing adaptation pathways that consist of 'a constellation of actions, where a new action is activated once its predecessor is no longer able to meet the definition of "success" (Haasnoot et al., 2013); and
vi. Draft implementation, monitoring, and evaluation plan for Day Zero no regret adaptation for the CWH nexus.

3.5.2 Defining adaptation objectives

In this study, adaptation objectives describe what water decision-makers and planners are trying to achieve by managing climatic change impacts on health (cost, access and availability); these objectives were guided by organisational requirements and through stakeholder engagement. An example of an adaptation objective that accounts for physical impacts might be (minimising the length of critical cutoff and access during severe droughts), whilst an environmental adaptation objective might be (maximising nature, based on

landscape management). Both of these objectives could also relate to intangible social values held by local residents, such as ensuring recreational opportunities, aesthetic value, and an ongoing feeling of dignity. The required steps are as follows:

- Describe the case study and outline the current situation to better understand the objectives;
- Identify and develop a portfolio of adaptive actions that can be implemented to ensure no-zero day over the planning horizon;
- Develop scenarios over which the adaptive actions were assessed. The scenarios encompass a large range of parameters guided by SSPs and RCPs.
- Set up an assessment model; thereafter, the tipping points of the adaptation actions, in isolation and combination, are calculated.
- The adaptation measures are then assembled in sequences to form maps of adaptation pathways.
- In the final step, a multi-objective criterion – economic assessment identified through stakeholder assessment – is carried out to sub-select the preferred set of pathways.

3.5.3 Defining uncertain factors

Deep uncertainty describes dynamic conditions in which there is limited knowledge and agreement on the use of models, the description of parameters in those models, and the impacts considered (Kwakkel et al., 2016; Lempert et al., 2003). Uncertain factors are those that cannot be influenced by decision-makers, are relevant to the adaptation objectives, but whose future state is unknown. They can be exogenous (*e*) to the system and outside the decision-makers' control, or influence relationships inside the system (*x*) itself; an example of uncertainty in the context of dryland adaptation is relative change in moisture (rainfall) levels in either direction. The range of values that uncertain factors might take in the future is specified *a priori* and based upon stakeholders' participation or guided by scientific evidence, including modelling outputs.

3.5.4 Describing conditions that lead to adaptation tipping points

A tipping point is a threshold where a particular course of action is no longer adequate for meeting the plan's objectives, and a new measure is therefore required, thereby requiring

the creation of alternative, sometimes connected, adaptation pathways, with different combinations of measures. Adaptation tipping points provide a practical way to communicate risks associated with a changing climate and its dynamics (Werners et al., 2013). Robust decision-making (RDM) and the Dynamic Adaptive Policy Pathway (DAPP) aim to design robust policies, and they achieve this in different ways. The RDM and DAPP approaches provide complementary information to decision-makers under conditions of deep uncertainty, thus increasing insights into contextual climate risks and impacts, sequencing and prioritisation of adaptation interventions (Kwakkel et al., 2016). The RDM identifies adaptation policies that perform satisfactorily under many different future scenarios, whilst DAPP provides an adaptive management framework within which flexibility is created, allowing progressive review and update of policy options, as more information becomes available. More comprehensive understanding of an area's sensitivity to climatic risk and impact allows questions such as '*What change is important?*' and '*When might such change occur?*' to be explored. Tipping points in terms of other indicators (cost, associated damage, public preferences, national objectives, amongst others) are among the bases for decision-making and the selection of no-regret nexus pathways. The pathways of interest in the CWH nexus, in this study, were guided by the main health impact pathways of climate change on public health (Haines et al., 2006) as outlined:

- Drainage – flooding, drought episodes and cycles;
- Food security and nutrition – climate-smart agriculture practices, urban agriculture and vertical gardens;
- Sanitation – infrastructure, technology and recycling;
- Urban planning and settlement – smart buildings, green roofs (smart and grey) and off-grid energy systems;
- Communication – information/ behavioural/ risk communication; and
- Policy and innovation – coherence, integration, research and development, as well as microfinancing.

3.5.5. Developing adaptation pathway maps

The concept of pathways is used to describe actions (Wise et al., 2014) as well as scenario trends, such as the Shared Socioeconomic Pathways (SSPs) and the Representative

Concentration Pathways (RCPs) (IPCC, 2019). Visions are an ideal reference point in the future, and could be exploratory in nature; they can be built on SSP and RCP combinations that provide the future socio-economic and climate contexts for achieving the visions, and transition pathways as progressive courses of action to respond to the scenarios and achieve the visions. Once conditions under which adaptation objectives can no longer be achieved have been identified through scenario discovery, scientific trends and projections can be considered to understand - 1) the potential for such conditions to occur in the future based upon available evidence, and 2) an evaluation of what timeframe such changes are projected to occur. The information that was used to develop the adaptation pathways was based on the DAPP framework (Haasnoot et al., 2013), in which the key question is *"Given that we cannot accurately predict the climate, what actions can we take today to best prepare for the future?"* The steps in developing adaptation are:

i. Description of the case study and its objectives – CWH nexus in drylands of South Africa, focusing on rainfall and temperature to assess flood risks and water/food security, over the past 35 years.
ii. Identification of Representative Concentration Pathways (2.6, 4.5 and 8.5 scenarios; wet and dry compared to baseline (10 and 25% wetter compared to baseline drier scenario, 10%).
iii. Considerations due to anthropogenic influences (SSPs) and approaches - Current, green/ smart, and sustainable grey technologies on runoff and water/ food security and settlements/ climate-related diseases, such as malaria, diarrhoea, and cholera.
iv. Definitions of adaptation actions - development of scenarios over which adaptation actions can be assessed. For this study, CWH was developed based on perceived benefits, urgency, and severity of impacts criteria.
v. Development of climate and health/land use/food and nutrition security scenarios. Fundamental criteria, such as the urgency of actions, the severity of the impacts, the uncertainty involved, and the desire to keep options open, could be used to develop a set of promising pathways (Haasnoot et al., 2013).
vi. Setting up of assessment model. Assessment of adaptation tipping points on the basis of socio-economic and demographic dynamics.
vii. Development of adaptation pathway through multi-objective criteria and assessment of the adaptation pathways, including use of TOC and DAPP.

3.6 Scenario planning

Problem framing and policy formulation in an environment of disputed policy narratives and social value beliefs is one of the challenges in conventional planning processes. This study adopted the pragmatic enlightened model (PEM), an inclusive participatory and engagement multi-criteria objective process (Edenhofer & Kowarsch,2015) that presupposes exploration of alternative pathways, in search of robust and contextually-relevant solutions. Basically, scenario planning explores the implications of alternative policies, timings, delays, and metrics, as well as technological and other assumptions for climate policy in general and specific sectors in particular. Presenting alternatives and their uncertainties can at least allow for a constructive public discourse, although, for pragmatism, insights can even be useful and valuable if they are mere estimates or opinions, instead of fully objective and certain knowledge. Serious engagement of researchers with stakeholders and the public could significantly improve the quality of assessment outreach and public discourses on selected pathways, their assessment and experimentation through specific project-tailored interventions. This can inform implementation and ex-post inquiry of actual end consequences as a guide to selection of competing policy narratives, to be explored in-depth, in an environment of disputed policy narratives and social value beliefs.

Increasing water (increased flows) and decreasing water (decreased flows) and their effect on water quality, sanitation and hygiene outcomes are the basis for scenario planning and answering the question *"What should be (vision) and what is it now (present)?"* The scenario planning exercise adapted a multi-stakeholder scenario planning approach (Butler et al., 2016). The approach applied the principles of Participatory Systemic Inquiry (PSI), defined as "learning and deliberation which involves multiple stakeholders in generating deep insights into the dynamics of the systems interventions they are trying to change" (Butler et al., 2016). In this study, the CWH nexus and health risk propellers were explored. The PSI output was "no regrets" adaptation strategies for communities; these are defined as strategies that are flexible enough to yield benefits under any future conditions of change (Hallegatte, 2009). As a structured learning process, PSI enables multi-level stakeholders to see the system from perspectives other than their own (Butler et al., 2015). The PSI has proven to be effective in development contexts because it examines a system as a web of relations between issues

stakeholders are concerned about and those embedded within it; consequently, stakeholders can understand the system in their own terms and take ownership of problems and solutions (Burns, 2012).

A comparison between prioritised, current BAU gaps, and barriers to the implementation of planned adaptation development programs served as the basis for deliberation, with moisture (water flow) changes as the focal reference point for inferring health scenarios. In turn, this informed the design of no-regret adaptation action plans. Sessions applied standard participatory learning methods and used various tools, such as problem and objective trees, FGDs with mixed stakeholder representation, ranking, scenario drawing, and matrix gap analysis (Chambers, 2012). Workshop deliberations focused on community vulnerability, livelihoods, and adaptation in the CWH nexus. These varying pathways of future development are distinguished by socioeconomic features (for example, population and economic development), natural resource developments (for example, fossil fuel availability) and challenges to mitigation and adaptation (O'Neill et al., 2014). The SSPs can be effectively combined with different Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) using a scenario matrix (van Vuuren et al., 2014). In this study, we focused on the three SSPs,

i. SSP1: Sustainability – Taking the green road (low challenges to mitigation);
ii. SSP2: Middle of the Road (moderate challenges to mitigation); and
iii. SSP5: Fossil-fuel development – Taking the highway (high challenges to mitigation).

A brief characterization of these three SSPs is extensively described by O'Neill et al. (2015). Four main questions, as outlined below, were used to elicit responses from the community, followed by ranking and prioritisation so as to generate no-regret adaptation strategies, based on multi-objective criteria analysis.

- "What is the current situation (vulnerabilities, capacities, planning cultures, governance arrangements, stakeholder preferences, assumptions, and values as well as expectations)?
- "What should be" or community vision for no-regret adaptation of CWH?
- "What could be" or the possible scenarios on moisture (water flow) changes and health risk propellers?

- "What can be" or better ways to address gaps (potential) for improvement of existing and planned CWH adaptation plans?

The above questions were evaluated against the following criteria:

- key policy instruments, institutions, and technologies;
- costs and risks;
- impacts and vulnerability;
- effects on additional policy objectives, for example, ecosystem services, health, equity, food security, poverty reduction;
- ante and ex-post analysis of each suggested adaptation goal/policies from a technical, scientific and political angle at scale; and
- political economy on winners and losers.

3.6 Ethical considerations

Ethical issues emerge from value conflicts and conduct during the research process; thus, researchers must try to minimize risks to participants, colleagues, and society while maximising the quality of information collected (Iphofen, 2020). Ethics guide researchers in developing accurate and verifiable knowledge without violating the rights and well-being of those who participate in research (Gillespie, 1995). The current study involved voluntary disclosure of personal and confidential information; hence, the major ethical concerns that were addressed by researchers included informed consent, privacy and confidentiality, anonymity, and responsible conduct (Novak, 2014). The community requested anonymity when providing information on governance issues. The project was granted ethical approval by the University of Venda Research Ethics Committee in July 2024 with certificate number FSEA/23/ES/13/2307. Informed consent was explained to the participants as follows:

- Participation as a multi-stakeholder is voluntary.
- The participants may withdraw from the study voluntarily, with no consequences.
- Participants will disclose their names in the consent forms and sign them.
- The consent forms will be stored safely, and personal details will never be disclosed.

CHAPTER 4: ASSESSMENT OF CURRENT POLICY, GOVERNANCE, AND INSTITUTIONAL SYSTEMS IN THE TRANSFORMATION FOR CRD IN THE WATER SECTOR

4.1 Introduction

This chapter reports on the intersecting social, institutional, policy, and governance dimensions of the CWH nexus and their interactions, which must be considered simultaneously in the transition to future Day Zero for communities in South Africa's drylands, through envisioning scenarios across the studied community and climate change adaptation planning initiatives. Further, the discussions will highlight the multiple dimensions of water system governance for comprehensive risk management (CRM) that not only reduce risk but also address deep-seated vulnerability to future climate change risks. In doing so, the state of knowledge on policy, governance, and the institutional framework, as well as challenges and opportunities, was synthesized. This is key in exploring short-, medium, and long-term decisions under the CWH nexus, as part of innovative multi-sectoral collaborative learning and planning, rather than as an end product in a later phase of the research.

The chapter covered the building blocks of policy, governance, and institutions in the CWH nexus, specifically, reporting on existing policies, institutions, and governance frameworks on adaptation planning around CWH. It also presents an assessment of gaps and opportunities for transformation and resilience building towards anticipated Day-Zero planning and uncertainty in the VDM, Limpopo Province.

4.2 Concepts and tools for exploring institutional governance and policy systems in transformative adaptation planning

For several decades, most water-related crises have been attributed primarily to a mismatch between demand and supply. However, emerging evidence tends to attribute water scarcity in the world's water-scarce countries to poor water governance. Such governance challenges are both sector-specific and the result of the complex interactions among natural, social, and political variables. Management of water resources based entirely on techno-centric assessments, especially under deep uncertainty and the climate crisis, could thus be untenable. As one of the most water-stressed countries, South Africa is under immense

pressure to implement no-regret adaptation measures in most of the areas affected by climate change impacts, thereby addressing drought and flood-related health risks. Day Zero clarion call to reduce water demand and expand new water sources, as a pillar to system-level water resilience in the long term globally, is extremely relevant (Rodina et al., 2024); however, failure to address underlying social dimensions, such as existing injustices, poverty and marginalization, could significantly undermine the envisioned noble resilience objectives. This challenge is not only a multi-scalar governance issue but also introduces complexity in the face of climate change risks and uncertainties.

In practical terms, policy, governance systems and institutional (administrative) arrangements have the potential to either constrain or enable adaptation fundamentally, although actor cognitive dissonances have been a very critical determinant of adaptation discourses and outcomes (Volenzo and Odiyo, 2019; Abel et al., 2016). Here, the term governance refers to diverse institutional and actor relationships in service delivery at scale (Huitema et al., 2009). In essence, the multiple possible modes of policy and decision-making structures, such as networks and stakeholders' fora across government bureaucracy, policy, and community of practice, as well as self-organisation, are included in the concept of governance, as used in this study (Folke et al., 2005). In line with the preceding definition by Folke et al. (2005), both formal institutions, such as laws, official policies, and organizational structures, and informal institutions, such as power relations, practices, operational rules and a whole range of structures, discourses, rules, and norms that bear on project planning cycle, as well as embedded transparency and accountability mechanisms, are all considered.

Since systemic risks impact societies, individually and collectively, in terms of incurred losses, experienced disruptions, collapse, damage to a system or its subsystems (Hochrainer-Stigler, 2020; Renn, 2016), nexus lenses on climate change, water, and health, as well as governance, policy and institutional frameworks, are critical in the design of no-regret adaptation measures. In particular, health, as a crucial facet of this nexus, is intricately linked to the availability and quality of water, the energy required for sustenance, and the nutritional aspects of food production, hence the need for a holistic understanding of these interdependencies is critical as well as integral to strategic planning, in the pursuit of sustainability and no regret adaptation planning (Mutanga et al., 2024).

Based on Munaretto et al. (2018), the scope of governance and analytical lenses implicit in the CWH nexus in this report are defined, conceptualised and contextualised as hereunder.

- **Planning:** It is considered an organised intelligent attempt to select the best available alternative for achieving a specific objective. Planning is critical in successful adjustment, herein referred to as "effective adaptation" to the ever-increasing climate crisis and specifically water resource governance under uncertain conditions. Given that a myriad of physical, ecological, social, economic, financial, educational, technological, and governance factors tend to undermine adaptation objectives, herein referred to as "adaptation deficit", these factors are examined through transformation lenses. Addressing deep-rooted constraints should not only enhance capacity to sustain livelihoods but trigger innovation, herein referred to as "transformation". This is largely dependent on appropriate governance, institutional and policy frameworks, as well as knowledge systems that challenge existing power relations for disaster-risk reduction and resilience building; hence our focus on co-production as a governance issue in anticipatory planning for Day Zero risks.
- **Governance concept and scope of assessment:** CWH nexus approach provides guidance for policy decisions through an explicit focus on interactions between water, health and climate policy goals, as well as instruments that implicitly enhance cross-sectoral collaboration and policy coherence for CRD. Comprehensive governance (Bennett and Satterfield, 2018) is adapted, and the focus is placed on structural, institutional, and process factors, as well as communication and conflict-resolution mechanisms for steering actor relationships in assessing the capability, functioning, and performance of systems. These processes are for delivering services/solving societal problems, such as climate change crises and their impact on the CWH nexus. In this report, the intersecting social, institutional, policy, and governance dimensions of the CWH nexus and their interactions are presented, which must be considered simultaneously in the transition to addressing future drought risks associated with Day Zero, and for envisioning scenarios across the studied community and climate change adaptation planning initiatives. Further, multiple dimensions of the water system governance for CRM that not only reduce risk but also address deep-seated vulnerability to future climate change are examined. In doing so, the study synthesized the state of knowledge on policy, governance and institutional framework, challenges

and opportunities. It also explored how institutions, policy and governance frameworks are likely to impact short-, medium- and longer-term decisions on CWH nexus outcomes, with a view to informing innovative multi-sectoral collaborative learning and planning, rather than as an end product.

- **Analytical approach:** Guided by the concept of comprehensive governance, the study explored what actually "happens", ''how" and ''why'' by focusing on existing capabilities, functioning of policies and strategies, as well as the ensuing performance measures (outcomes) as operationalised in Table 4.1. The CWH nexus and systematic accounting for water, health, and climate sectoral-domain interactions have been conceptualised in both quantitative and qualitative terms, with the aim of better understanding their relationships and providing a more integrated knowledge baseline for planning and decision-making, as well as innovation for desired outcomes; ideally under Integrated community-based disaster risk reduction (CBDRR), in essence self-organisation at local-level implementation scenario. The analytical approach largely borrows from existing analytical frameworks on governance, such as institutional analysis and development (IAD) framework (Ostrom, 2010); value chain analysis (Villamayor-Tomas et al., 2015); actor network theory/network of adjacent action situations (Bilodeau and Potvin, 2018; Kimmich, 2013; Srigiri and Dombrowsky, 2022); integrative model (Nhamo et al., 2020), among other system models.

Table 4.1: Governance system analysis matrix guide

	Structures (jurisdictional and administrative)	**Institutions (formal and informal, operating rules, laws, regulations, constitutional provisions**	**Processes (communication, conflict resolution, coordination, monitoring and learning mechanisms**
Capability (level of financial, infrastructural resources, skills levels etc.)	Are the structures capacitated to undertake their functions	Do the existing institutions facilitate or constrain CWH nexus governance	Are the monitoring, evaluation and Reporting Mechanisms/systems recognised and activated?
Functioning outputs including policies, plans, strategies and projects	What are the programmes, policies/plans, strategies on CWH nexus?	Is there coherence of policies, plans and strategies around CWH nexus?	Are there coordination and communication mechanisms on CWH nexus policies/ plans/ strategies?
Performance (outcomes)	Do the intergovernmental/ multilevel (scale) coordination	Do the existing institutions attempts to operationally,	How well do the coordination and communication structures address CWH integration

	Structures (jurisdictional and administrative)	Institutions (formal and informal, operating rules, laws, regulations, constitutional provisions	Processes (communication, conflict resolution, coordination, monitoring and learning mechanisms
	structures exist and address CWH nexus integration?	financially, institutionally, and strategically integrate CWH nexus in programming interventions at implementation scale	and provide conflict resolution mechanisms?

4.3. Structures, institutions, and processes in CWH Nexus governance and adaptation planning

4.3.1. Governance in adaptation planning

In practical terms, governance systems and arrangements have the potential to either constrain or enable adaptation fundamentally, with actor cognitive dissonances being a very critical determinant of adaptation discourses and outcomes (Abel et al., 2016; Volenzo and Odiyo, 2019). Governance of water is centred around mechanisms that involve the acquisition and exercise of influence over policy and decision-making processes (herein referred to as politics) in society. Accordingly, divergence on values, as well as conflict on the legitimacy of scientific evidence adopted in structuring policy problems and decision-making, inadvertently impact socio-ecological outcomes of various policy actors (Roth, 2017; Robina et al., 2018). This warrants nuanced attention on methodologies that account for potential conflicts, diverse socio-cultural contexts, agencies, and historical trends to ensure representativeness, acceptability, as well as enhance relevance to context (Cradock-Henry and Frame, 2021).

Implicitly, governance of water resources is predicated on tensions and water policies that safeguard individual and collective interests, as well as respect for international obligations. This is essentially a rights-based approach for minimising conflicts and optimising synergies in a contested influence-driven decision space for assessing alternative strategies for accessing drinking, sanitation, and hygiene needs at scale (Hurlbert and Gupta, 2024; Mirumachi and Hurlbert, 2022). This necessitates the use of anticipatory adaptation planning frameworks to

ensure wider actor engagement (Behnassi et al., 2019; Bosch et al., 2019). The ensuing complexity and uncertain nature of the emerging social-ecological challenges, under such governance, necessitate the use of adequately flexible planning tools (Munene et al., 2018; Roy et al., 2021).

Governance lenses enhance the identification of the underlying causes of policy problems, facilitate effective decision-making, and support policy coordination and integration, thereby enhancing coherence across tele-coupled systems and sectors (Weitz et al., 2017). In particular, governance of knowledge has emerged as one of the most critical societal transition metrics in decision-making and assessments of adaptation governance (Butler et al., 2022). This is in addition to the inclusion of highly exposed social segments that tend to be disproportionately impacted by extreme climate changes (Eriksen et al., 2021; Eastin, 2018). Co-produced visions, goals, and strategies can involve perspectives across multiple sectors, scales, and communities to gather the full range of ideas, innovations, and possible actions to address trade-offs and inform transitions toward CRD. A better understanding of the nexus pressures that underpin pathways is key to planning, amidst knowledge gaps on the future climate dynamics and their impacts, herein referred to as “deep uncertainty” (Filho et al., 2021).

Trust, ownership, and learning are integral cognitive lenses in governance for transformation, specifically in the linkage of technical dimensions to actual decision-making and policy processes (Nilsson and Eckerberg, 2009; Mathetsa et al., 2024). This mainly arises from the observation that prioritising options, and the resulting policies, are derived from value systems embedded in institutions, the policy frames held by stakeholders, and the ways stakeholders are informed (Nilsson, 2005). Implicitly, changes in decision-makers’ perceptions shape changes in policy (Lenschow and Zito, 1998). Such changes in perceptions and, by extension, policy, can be achieved through reframing strategies on how stakeholders define problems and assess causal narratives. This is the focus of the overall research objective for the project's subsequent phases.

4.3.2 Adaptation deficit

The world is increasingly interconnected through climate change spillovers, natural hazards and systemic risks that cut across socio-economic scales (Lawrence et al., 2020; Gaupp et al., 2020). The Intergovernmental Panel on Climate Change report (IPCC, 2022), for example, provides a snapshot of evidence on the large-scale damage and increasingly adverse environmental footprints in terrestrial, freshwater, coastal, and open ocean marine ecosystems, caused by climate change. The domino effects of climate-related impacts, such as floods, droughts, and cascading chain impacts, such as waterborne diseases, food insecurity, and conflicts, undermine sustainability objectives across scale (Reichstein et al, 2021). In particular, the growing occurrence of complex hydrometeorological risks, such as droughts and floods, calls for adjustment and exploring opportunities, commonly referred to as adaptation in a sustainable manner. Maladaptation is one of the key concerns (Aggarwal et al., 2018) as well as understanding dynamics that influence the nexus beyond cross-sector interactions (Weitz et al., 2017). Shifting vulnerabilities impair the ability to successfully adjust, take advantage of rising opportunities as well as long-term prospects for reducing the risks (Lo et al., 2020).

Adaptation may not be sufficient if only effective outcomes and impacts are considered. In particular, poorly designed actions on climate change may undermine intra- and intergenerational equity and sustainability efforts (Eriksen et al., 2021). This is captured in the IPCC Fifth Assessment Report (AR5) and the Special Report on 1.5°C (IPCC, 2018). Adaptation may result in suboptimal outcomes, which are adverse social-environmental externalities or costs, generally referred to as shifting vulnerabilities or maladaptation.

Eriksen et al. (2021) argued that adaptation interventions can create, reinforce, redistribute, or create new vulnerabilities rather than effectively responding to climate change-related risks. Suboptimal outcomes in the implementation of adaptation actions and policies are generally considered a proxy for ineffectiveness, herein referred to as “adaptation deficits” (gaps). Adaptation deficit may arise from a myriad of physical, ecological, social, economic, financial, educational, technological, and governance factors (Dupuis and Knoepfel, 2013), and embedded externalities, as well as risk information deficits (Volenzo and Odiyo, 2019). Adaptation deficits exist due to suboptimal climate-related disaster risk reduction efforts,

which are partly due to fragmentation in policy, advocacy, and programming spaces, incremental silo approaches, as well as scale deficits (IPCC, 2022).

Bridging the adaptation deficit has emerged as a critical discourse in adaptation planning and governance (Wise et al., 2014). The use of no-regret policies has the potential to enhance effectiveness, thereby curing such deficits. No-regret adaptation and mitigation measures that are in line with CRD principles and Transformative Scenario Planning (TSP) tools support the implementation and realisation of sustainable development objectives (IPCC, 2022; Stringer et al., 2022). Development strategies are considered to be 'no regret' if they do not entail the risk of adverse third-party costs to society, under all plausible scenarios (Butler et al., 2016). Implicitly, no regret adaptation planning incorporates proximate and underlying factors to ensure climate adaptation policy objectives are delivered, the realisation of the risk notwithstanding (Hallegatte, 2009; Omore et al., 2019).

No regret adaptation fundamentally consists of imagining a policy output over a series of decision points distributed across the planning cycle and beyond so as to ensure flexibility, rather than restricting the evaluation metrics and criteria to the present alone (Hallegatte, 2009). Given the complexity and uncertain nature of social-ecological challenges, such interventions should also be flexible enough (Munene et al., 2018; Roy et al., 2021), hence the need for pathway thinking. Co-produced visions, goals, and strategies that integrate perspectives across multiple sectors, scales, and communities to gather the full range of ideas, innovations, and possible actions in addressing trade-offs and informing transitions toward CRD are integral to no-regret adaptation.

4.3.3. Role of Disaster Risk Reduction (DRR) approaches in addressing adaptation deficit

Over the years, it has been observed that climate change adaptation stems from the global policy agenda rather than practical implementation-level needs or problems (Thomalla et al., 2006)**.** On a global scale, a risk-informed and integrated approach to sustainable development Strategic Framework 2022-2025 (UNDRR, 2021) identifies climate emergency as a high priority, embedded in the 'accelerator' on the climate agenda and climate risk reduction. Result 1.2 of the Strategic Framework stipulates that "Governments and other stakeholders are supported to integrate climate change and disaster risk reduction into relevant strategies

and policies across and within sectors". There is, therefore, a need for practical policy action at the community level, where the effects of climate change are felt.

The DRR refers to the systematic development and application of policies and strategies to minimise vulnerabilities and impacts of disasters, through a combination of technical measures to reduce physical hazards and enhance social and economic capacity to adapt (UNSDR, 2015); hence, there is a need to embed CCA within the DRR lens. DRR includes policies and interventions that aim to reduce existing risk, manage residual risk, and prevent the creation of new risk (UNDRR, 2021). This also informs integrated community disaster planning. Approaches to DRR policies include technocratic risk management, poverty vulnerability reduction, and the addressing of failures in current development (Sherman et al., 2016). It thus focuses on:

- reducing socio-economic vulnerability and building capacity to address any adaptation deficit/ challenges/ constraints;
- addressing present and future disaster risks; and
- building long-term social-ecological resilience.

Integration improves coherence between different goals and actors. Enhanced coherence can help ensure that development does not create or exacerbate existing or future levels of risk, and that development gains are protected from the impacts of disasters and climate change. At a global level, integrating National Adaptation Plans (NAPs) and climate/forecast information into national and subnational DRR strategies is one example that aims to better align DRR objectives with national adaptation goals. In this regard, DRR is viewed as a cost-effective investment in preventing future losses and can be addressed within the context of sustainable development and poverty reduction by integrating risk considerations into policies, plans, and programs (UNSDR, 2015).

The centrality of systems and the complexity of socio-ecological systems (SES) in nexus framing is exemplified through several analytical approaches, such as climate-resilient health, climate-resilient livelihood systems, climate-resilient food systems, and climate-resilient water systems, suggesting the cruciality and emergence of a multilevel, integrative research and policy agenda. The utility of nexus models and planned transformation for effective

adaptation (Feola, 2015) is widely acknowledged, although low uptake in decision-making and programming remains evident. This is largely attributed to a poor understanding of the complex SES dynamics and linkages among policy and decision makers (Hochrainer-Stigler et al., 2024). The net effect has been increasing maladaptation, poor buy-ins and/or low scaling of promising nexus practices and innovations, as well as deepening of shifting vulnerabilities worldwide.

4.3.3. Resilience thinking in addressing adaptation deficit

Climate Change Adaptation (CCA) refers to adjustments to actual or expected climate change to moderate negative impacts and exploit beneficial opportunities (IPCC, 2014). DRR and CCA are interlinked as they both focus on risk and seek to reduce vulnerabilities and build resilience of people, systems, and societies, in order to achieve and sustain development. According to the IPCC's Sixth Assessment Report (AR6) (IPCC, 2022), risk provides a framework for understanding the increasingly severe, interconnected, and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems. Globally, policy responses to the climate change crisis have mainly been through adaptation and mitigation strategies (Di Gregorio et al., 2017). Accordingly, effectiveness has emerged as critical to adaptation and mitigation planning (Folke et al., 2005).

The extent to which any given policy instrument and available resources contribute to the attainment of a specific policy goal (Mees et al., 2014), including unintended outcomes (Dupuis and Knoepfel, 2013), is a proxy for effectiveness in policy analysis. Effectiveness also connotes policy coherence and the extent of vertical and horizontal integration (Dupuis and Knoepfel, 2013). Intuitively, effectiveness reflects the extent to which institutions interact to address the fundamental drivers of the problem, such as the climate crisis (Burch et al., 2019; Barreteau et al., 2020). Resilience is a ubiquitous metric for assessing effectiveness.

Resilience describes the long-term capacity of a socio-ecological system to respond to change and to continue developing towards socially desired aspirations and shared values (Folke, 2005). Resilience building is, thus, the shared foundation of the Paris Agreement (PA) on Climate Change, the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015-2030, and the 2030 Agenda for Sustainable Development. In this study, resilience is defined as the capacity to sustain livelihoods, develop, innovate, and transform in the face of crises, such as

climate change (Rockström et al., 2023). The shared goal is ever more important as the IPCC's latest report on the Physical Science Basis confirms that human-induced climate change, including frequent and intense extreme events, has caused widespread adverse impacts, related losses and damages to nature and people, beyond natural climate variability (IPCC, 2022), increasing disaster risk, pushing impacts beyond nations' capacity to adapt, thereby threatening development.

The definition of a community as a system underscores the need for integrated planning approaches and the centrality of policy, governance, and institutions in adaptation planning and resilience building. This basically involves the use of organisational and procedural instruments in planning. The cognition dimension in governance is particularly critical, as it bears on the conceptualisation, framing, and, ultimately, the effectiveness of adaptation responses and sustainability outcomes (Fraschini and Pregnolato, 2023), as well as the coherence of adaptation plans, programs, and policies. From the aforesaid, community resilience can be inferred as the existence, development, and engagement of community resources by community members to enable them to thrive in an environment characterised by change, uncertainty, unpredictability, and social sustainability. In essence, the resilience of a community/region is a combination of the resilience of its subsystems, including its critical infrastructures, economy, civil society, governance (including emergency services), and supply chains/dependencies. Implicitly, a silo planning approach in adaptation can result in maladaptive outcomes, hence the need for a systematic approach (Maru et al., 2014).

The Day Zero clarion call to reduce water demand and expand new water sources, can be seen as a pillar to system-level water resilience, and in the long term, globally, it is extremely relevant (Rodina et al., 2024), however, failure to address underlying social dimensions, such as existing injustices, poverty, and marginalisation, could significantly undermine the envisioned noble resilience transition objectives. Accordingly, it is very urgent to find an optimal solution for the largely governance-related problems in water resources, particularly the climate change-exacerbated water crisis and deep uncertainties captured in the 2022 IPCC report (IPCC, 2022*)* and social injustice (Rodina et al., 2024).

4.3.4 Governance, policy, and institutions in addressing adaptation deficit

Governance involves a plurality of public and private stakeholders, hybrid practices (administrative systems and quasi-market strategies), and a multi-jurisdictional phenomenon that spans different institutions, sectors, and levels of actors (Bennett and Satterfield, 2018). Governance is thus a multi-dimensional concept encompassing the actors, processes, structures, and institutions involved in decision-making and implementation. These include corporate, customary, governmental, and judicial systems at different scales, from the local to the global. On the other hand, institutions are generally understood as "rules of the game," characterised by formal or informal interactions among stakeholders and social structures (North, 1991). Ostrom (2005) defines institutions as ''the prescriptions that humans use to organise all forms of repetitive and structured interactions."

Various institutions come together to form governance systems – actors, their interactions, and the accounting and transparency mechanisms. Institutions and governance systems define how people and societies organize themselves and their interactions at different scales; they are the underlying causes of global change (positive or negative, for example, disasters or sustainability). Institutions and governance systems determine, to varying degrees, access to, control over, allocation of, and distribution of goods and services in society; and consequently, coping mechanisms, communities' capacities to disasters, resilience, vulnerability to disasters, among others.

- **Agency**

Agency, in terms of the individual and the system, is critical to transformative adaptation (Pelling et al., 2011) and to the deliberate exercise of individual or collective will (Bandura, 2006). Broadly, agency refers to processes that enable people to influence decisions, co-construct alternatives based on their framings and make a reasoned choice within a particular decision-making process. It is basically the ability to make and act upon a reasoned choice. Agency is, thus, influenced by:

- **values system** in which the purpose of the decision-making process can be articulated;
- **a knowledge system** that can be used to describe how different options will affect systems and people; and
- **a rules system** that empowers actors to implement decisions.

Capability and willingness to act urgently are necessary conditions, although not sufficient, for collective action as well as for the effectiveness of social capital. Fostering agency, values, as well as capacities and empowerment require the integration of diverse knowledge, plural pathways and associated contestations, at individual and collective levels (Scoones et al., 2020). Among the multiple social learning concepts presented in literature, this study employs and further extends the cognitive lenses to sustainability transformation, under deep uncertainty in the subsequent phase of the research.

At the practical level, agency connotes the empowerment of individuals and communities to act on their own, serving as a critical lens in governance and transformation, as well as in CBDRR (Scoones et al., 2020). Within the decision process, values and knowledge tend to be treated as sets of independently defined variables, implying that a decision-maker can incorporate any relevant knowledge and values to reach a decision within the bounds of the societal rules that govern the process. Fostering agency, values, capacities, and empowerment requires the integration of diverse knowledge, plural pathways, and associated contestations at individual and collective levels (Scoones et al., 2020). Among the multiple social learning concepts presented in the literature, this study employs and extends cognitive lenses to sustainability transformation under deep uncertainty. The decision-making, agency-focused perspective represents the outlook of actors engaged in a particular decision-making process, with its various constraints of time, resources, and institutional arrangements.

- **Self-organisation and co-management**

Social network analysis is an analytical tool in self-organisation that traces interactions between people or organisations, such as CBDRR, with the aim of examining how the structure of social relationships affects actors through **constraining some actions** and **providing opportunities for other actions**. The social network analysis construct is used to investigate how the structure of social relationships affects **policy formation and the likelihood of success**. Local-landscape interaction, process and institutional linkages are critical, as local innovations, for essentially multi-level governance (MLG), have the potential to trigger systemwide transformation (Geels, 2005). Accordingly, a shift from hierarchical top-down to horizontal and nested models constituted by transnational and private actors, as well

as self-organisation, is likely to catalyse agency and locally-driven innovation (Neidig et al., 2024).

Self-organisation refers to the ability of actors, such as communities, catchments, watersheds, regions, ecosystems, and landscapes, to voluntarily develop new norms and codes of conduct for sustainability and disaster-risk reduction through flexible and innovative collaboration. This is implicit in Water Management under the Water Act in South Africa. Self-organisation creates new institutional platforms for adaptive management, for tackling emerging issues, such as climate change, as well as DRR for watershed/ecosystem/forest, livelihood challenges. Self-organised actors, structures and processes further enhance the challenge of dominant policy framings on long-term development options, through scenario planning (Drimie et al., 2018; Marshall et al., 2018). In so doing, the process tackles biased problem framing, creates shared understanding, as well as nurtures commitment towards addressing deep-rooted drivers of vulnerability in the community (Pereira et al., 2018).

Self-organisation is informed by the principle of subsidiarity and guides the assignment and assessment of governance responsibilities associated with any resource management in general and, specifically, responsibility and ability of the actors, especially at the local level (Marshall, 2008). Cash and Moser (2000) proposed that governance for linking global and local scales should utilise boundary organisations, leverage scale-dependent comparative advantages, and employ adaptive assessment and management strategies. Governments, or any other facilitating authority, such as NGO and provincial governments, should thus nurture the self-organising ability of actors to voluntarily develop new norms and codes of conduct for sustainability/ safety and to create space for flexible and innovative collaboration towards sustainability and DRR.

As part of social change, self-organisation involves devolution of management rights, which provides an arena/ platform for local users to self-organise and develop, refine, and implement rules for ecosystem management and disaster management/ Disaster Risk Reduction. Under self-organisation, people respond to change by doing, learning, developing a social memory and building adaptive capacity, to deal with future changes in the multi-level governance system and multi-disaster risk environment (Reed et al., 2009). Such open institutions and emergent governance are appropriate for addressing ambiguity in the needs of the diverse actors, information constraints and uncertainty.

- **Social networks for governance: Institutions as networks for co-management and adaptation planning**

Social network analysis traces interactions between people or organisations to examine how the structure of social relationships affects actors, either by constraining some actions or providing opportunities for others (Reed et al., 2009). The ‘‘hollowed out’’, decentralised style of governing has occurred across bureaus, including those agencies responsible for resource management; For example, wildlife management regimes emerge from a range of authorities, contexts and partnerships. The regimes, comprising all of the rules relating to human interaction with a particular species, are made up of institutions at many different levels, such as international treaties, national statutes, regional policies and operational rules. In this analysis, institutions are defined as rules of the game (North, 1991) or ‘‘the prescriptions that humans use to organize all forms of repetitive and structured interactions’ (Ostrom, 2005).

Institutions, like other patterns of interactions, can be analysed as networks. Formal institutions describe routine transactions among policy actors, whereas informal institutions reflect emergent behaviours and norms, as well as power differentials within a group (Mees et al., 2014). Carlsson (2000) noted that policy networks can be considered organized entities that reflect specific institutional arrangements. Many studies of policy networks focus on emergent networks of policy actors who act collectively to influence or respond to formal institutions in decision-making, information exchange, advisory services, and the diffusion of policy innovation (Lubell and Fulton, 2008). Institutions are rarely designed as rational assignments of responsibilities and authority, although there is a risk that they reflect past asymmetries in influence over policy and decision-making processes, and they may deepen contestations over policy framing (Marsh and Smith, 2000).

Co-management is a governance strategy, especially between indigenous actors and governmental actors or other post-colonial situations, that aims to bridge differences amongst parties that may have a long history of conflict. Carlsson and Sandstrom (2008) and Berkes et al. (1991) hypothesised that well-performing co-management systems are composed of networks that are centrally and densely organised; networks with high closure rates can improve internal decision-making processes by reducing transaction costs between actors and facilitating conflict resolution. In terms of outcomes relevant to co-management

processes, highly connected networks have been associated with greater efficiency and effectiveness in prioritising tasks (Reed et al., 2013) and meeting goals (Provan and Milward, 1995).

A recent body of literature has emerged, investigating the linkages between natural resource networks, the ways resources are governed, and the outcomes of governance. The concept of network-closure captures a group of actors who are well connected, either because many connections exist between network members or because they are connected through a few common members. Such connectivity is necessary, although not sufficient, for collective action towards common goals (Coleman, 1990). A recent body of literature has emerged investigating the linkages between natural resource networks, the ways resources are governed, and the outcomes of governance. Highly-connected networks, in natural resource governance, have also been found to increase confidence in policymaking (Schneider et al., 2003). Bodin and Crona (2009) identify four network measures of closure that are important in shaping actors' ability to manage relationships and promote environmental management/sustainability/DRR.

- **Network density** describes the extent to which actors are connected to each other and indicates potential pathways towards collective action.
- **Cohesiveness** describes the extent to which a network is fragmented into subgroups and can make coordinating the whole network more complex (Bodin and Crona, 2009).
- **Network centrality** describes the power and control structure of the network, or who has the most influence within the group. It has been hypothesised that well-performing co-management systems comprise networks that are centrally and densely organised. Networks with high rates of closure can improve internal decision-making by reducing transaction costs among actors and facilitating conflict resolution. Subgroup interconnectivity reflects linkages among subgroups and can affect subgroups' ability to work productively together (Borgatti and Foster, 2003). In terms of outcomes relevant for co-management processes, highly connected networks have been correlated with efficiency and effectiveness in prioritising tasks, such as contingency planning,

preparedness, mitigation and the pursuit of goals, such as livelihood sustainability and safety.

4.3.5 Policy field and policy coherence in adaptation planning

Policy is defined as a deliberate effort to influence the behaviour and decision-making of various agents via various means, inter alia, regulatory, communicative, informational, and economic instruments (Mees et al., 2014; Massey and Huitema, 2013). It implies a statement of intent backed by governance mechanisms, such as regulatory tools, as well as the requisite financial and human resources to address a given issue, such as climate change risks (Massey & Huitema, 2013). The policy envisions a synergistic approach to tackling an economic or social issue. Theoretically, policy encompasses fundamental changes in approaches and steering mechanisms that address a policy problem through holistic framing and innovative instruments (Hall, 1993). In relation to climate change adaptation, policy can be defined as decisions and actions that mediate adjustment to and minimise adverse impacts, while taking advantage of opportunities presented (Dupuis and Knoepfel, 2013). The choice and implementation of policy instruments influence future climate risks and sustainability outcomes (IPCC, 2019).

Policy field refers to the highest unit of governing in terms of institutions, policy products/inputs, shown through policy, programs, legislation and rules and expertise from knowledgeable persons, coalitions and think tanks (Massey and Huitema, 2013). Working in a policy field is absolutely necessary in the management of a public issue or set of issues across steering mechanisms, such as the state, non-state actors and the primary agents or citizens, with the potential to deal with problems or issues in a particular field, in a systematic rather than in an ad hoc manner (Massey et al., 2014). The minimum requisites for a policy field are institution order (IO), substantive expertise (SE) and substantive authority (SA). Table 4.2 summarises an ideal description of a policy field.

Table 4.2: Summary metrics of policy field assessment in adaptation planning

Policy component	Description and operationalisation	Evidence for assessing the policy component
Institutional Order (IO)	Refer to authorised legitimate government institutions with power and/ or expertise to steer or oversee an issue, that is, the institutions that order and structure policy responses (Massey et al., 2014).	Types and number of government institutions that produce policy products/outputs and are devoted to adaptation (Massey et al., 2014). This includes the presence of a lead agency that coordinates and oversees the whole adaptation process and acts as secretariat for disaster risk assessment, evidenced through: • Multi-stakeholder coordinating body; • Technical committees; and • Legal framework.
Substantive Authority (SA)	What gives meaning and legitimacy to the policy actors, particularly the coordinating agency.	It is reflected in policy products and outputs, including programs, legislation and rules (Massey et al., 2014).
Substantive Expertise (SE)	Evidence of expert knowledge among state and non-state actors in adaptation planning (Massey & Huitema, 2013).	Presence and/or absence of working/steering groups, task forces, policy networks, citizen interest groups, policy papers and proposals, studies, reports, as well as issue papers.

4.4. Methodology

This section provides details on the existing policy, governance, and institutional framework for no regret adaptation planning, based on the CWH nexus. This is a buildup to the sustainable transformation planning (STP) tools (Butler et al., 2016). The research design was guided by Policy Coherence for Sustainable Development (PCSD). The PCSD has emerged as a prominent concept in debates surrounding development and aid effectiveness and, more recently, also in the sustainable development and policy diffusion perspectives. PCSD, although lacking an agreed definition, can be understood as involving "the systematic promotion of mutually reinforcing policy actions across government departments and agencies, creating synergies towards achieving the defined objective" (OECD, 2001). Policy network theory, in particular, underlines that coordination is an essential part of PCSD and is a central component of governance to achieve a common goal (Bilodeau and Potvin, 2018). The elements considered in the desktop review are shown in Table 3.1.

4.4.1 Policy field assessment

Policy field assessment for adaptation planning was conducted using the metrics in Table 3.2 adapted from Massey et al. (2014). This assisted in determining the institutions, policies and expertise that exist and their capacities to address climate change impacts.

4.4.2 Policy, governance and institutional assessment criteria

The review adopted a theory-based approach to assess how the policy is intended to work and the institutions involved. The criteria in Table 4.2 (summarised in Figure 4.1) included coherence, effectiveness, efficiency, impact and sustainability. These criteria are also included in the evaluation guideline for climate, ecosystem and health by the Department of Planning, Monitoring and Evaluation (2022). The criteria, as used in this study, assessed the evolution and extent to which policy objectives correspond to adaptation needs and issues in the CWH nexus. This informed a participatory assessment on the effectiveness of policy intervention and adaptive planning.

Table 4.3: Criteria and guiding questions used in the assessment (adapted from OECD, 2021)

Criteria	Guiding question	Explanation
Coherence	How well does the intervention fit?	The compatibility of the policy/strategy with other interventions in a country, sector or institution.
Effectiveness	Is the intervention achieving its objectives?	The extent to which the policy/strategy is achieved, or is expected to achieve its objectives and its results, including any differential results across groups.
Efficiency	How well are resources being used?	The extent to which the policy/strategy delivers, or is likely to deliver, results in an economic and timely way.
Impact	What difference does the intervention make?	The extent to which the policy/strategy has generated or is expected to generate significant positive or negative, intended or unintended, higher-level effects.
Sustainability	Will the benefits last?	The extent to which the net benefits of the policy/strategy continue or are likely to continue.



Figure 4.1: Summary of evaluation criteria (OECD, 2021)

4.5. Results and discussion

4.5.1 The decision context: governance, policy, and institutional arrangements on CWH in South Africa and the study area

The post-apartheid Constitution of South Africa (Act No. 108 of 1996) provides for a three-tier hierarchical governance system (national, provincial and local) that fits within the transformative multi-level governance's analytical framework. It also specifies the mandate of these three spheres of government. There is a relatively well established network of institutional and legal frameworks, such as the Intergovernmental Relations Framework (IGR) Act 13 of 2005, introduced to facilitate coordination among the three spheres of government and support collaboration.

South Africa follows a multi-governance approach to respond to climate change impacts. Multi-level governance, as shown in Figure 4.2, involves working together vertically and horizontally across different levels of government to deliver policies more effectively and build climate resilience (ICLEI Africa, 2021). Petrie et al. (2019) summarised the progress made by South Africa in developing the policy and institutional architecture in response to climate change through the lens of multi-level governance and multi-stakeholder climate action. The

study indicated that multi-level climate governance has yet to be formally and effectively institutionalised. Climate change affects many local government mandates, but clear roles and responsibilities for responding to these changes at the sub-national level are lacking. The notion of multi-level governance implies that tackling climate change requires collaborative processes and actors operating at multiple interlinked scales. It also brings into focus both vertical and horizontal forms (Figure 4.3) of coordination (Petrie et al., 2019).

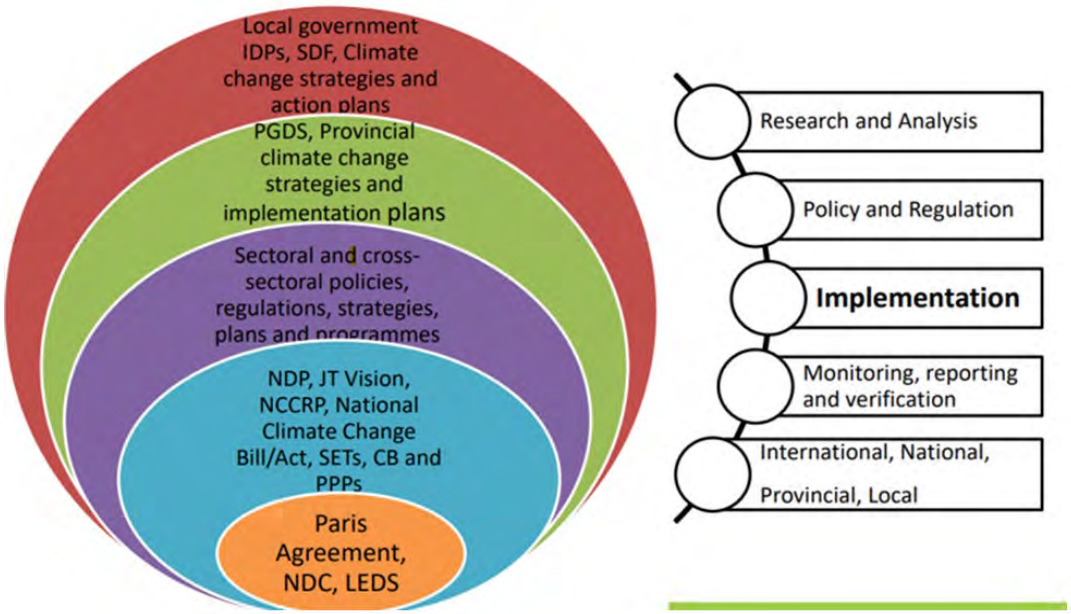


Figure 4.2: Multi-governance response to climate change impacts (Petrie et al., 2019)

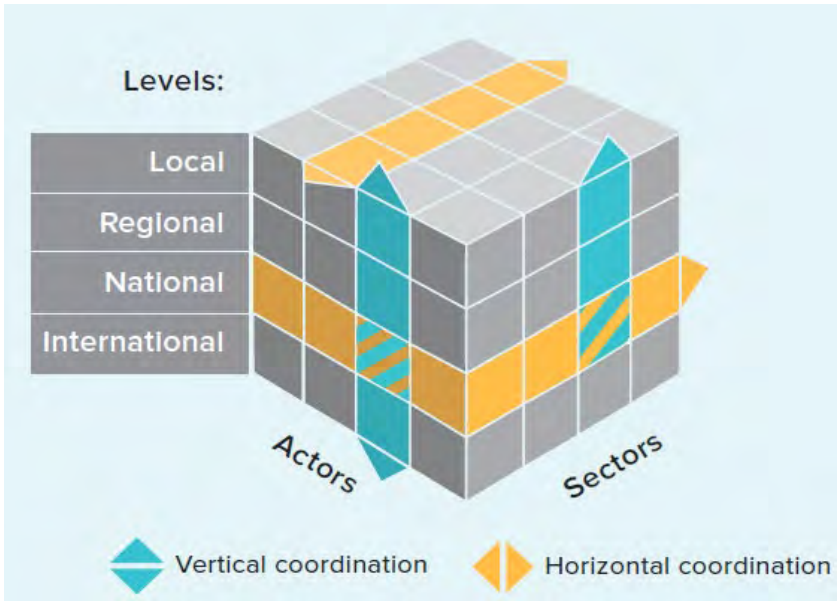


Figure 4.3: Vertical and horizontal coordination of the multi-government approach (Petrie et al., 2019)

Within the CWH context, government departments and institutions that play a role in climate change response in South Africa at national, provincial, and local levels, including their roles and the policies they have developed, are presented in Table 4.4.

Table 4.4: Government departments and institutions playing a role in climate change response in South Africa

Department	**Role**	**Policies and climate change adaptation strategies**
DEFF	Coordinates the country's climate change response.	National Environmental Management Act, Climate Change Response strategy, National Climate Change Response White Paper, Climate Change Act of 2024
DWS	Ensures that the country's water resources are protected, managed, used, developed, conserved and controlled, by regulating and supporting the delivery of effective water supply and sanitation.	National Water Act, 36 of 1998 National Water Resource Strategy of 2004, 2013 and 2020, White Paper on a National Water Policy for South Africa
DoH	Improves health status through the prevention of illnesses, diseases and the promotion of healthy lifestyles, and consistently improves the health-care delivery system, by focusing on access, equity, efficiency, quality and sustainability.	National Climate Change and Health Adaptation Plan, National Heat Health Action Guidelines
CoGTA	Institutionalises multi-level governance among local, regional and national levels	Disaster Management Act 57 of 2002 Leadership and Governance Framework Act, 2003 Traditional Leadership and Governance Framework Act (2003
Office of the Presidency	Presidential Climate Change Commission: Oversees and facilitates a just and equitable transition towards a low-emission and climate-resilient economy	Just Transition Framework
	National Planning Commission: Advises the government, and indeed all of society, on the implementation of the NDP: Vision 2030	National Development Plan

The Bill of Rights under the Constitution guarantees fundamental human rights to all people. This includes the right to a safe and healthy environment for well-being and to equitable inter- and intra-generational access to sufficient water. Under the Constitution, the national government is mandated to promulgate and legislate progressive policies, water sector-specific laws, and strategies that are appropriately aligned with the country's Constitution (Adom and Simatele, 2021). This is set out in its key national policy documents, for example, the National Development Plan 2030 (NPC, 2011) and the National Climate Change Response

Policy (NCCRP), as well as through ratification of global documents, such as the Sustainable Development Goals (SDGs).

South Africa is very committed to principles of intra- and intergenerational equity and sustainable development that do not compromise ecological integrity (Simpson and Jewitt, 2019); however, many South Africans continue to face socio-economic challenges and the ramifications of climate change (Naidoo, 2005; Sibanda and Batisai, 2021). By acknowledging that historically rooted institutional biases are key elements of community health outcomes and the associated shifting vulnerabilities (Davis and Cook, 2005), the 1994 transition to majority rule in South Africa aimed to reduce socio-economic inequality, expand basic services, and embrace human rights principles as the foundation of constitutional solutions (Klug, 2021). Inequality across racial and regional lines (Klug, 2021), as well as widening gaps between the rich and poor (Naidoo, 2005; Sibanda and Batisai, 2021), have been exacerbated by climate change-related disaster risks.

The National Water Act aims at ensuring that the nation's water resources are protected, used, developed, conserved, managed, and controlled in ways that take into consideration such factors as, *inter alia,* meeting the basic human needs of present and future generations, promoting equitable access to water, redressing past discrimination, facilitating social and economic development, and protecting aquatic and associated ecosystems. The need for equity and fair procedures is found throughout principles 12–25 of the water policy (DWAF, 1996). The National Water Act, 36 of 1998, attempts to transform water governance through the lens of land tenure and rights systems. This streamlines how water is controlled and managed from a system of rights, based on land ownership, access, and livelihoods. Under the National Water Act, several strategies and plans are envisaged to actualise constitutional provisions as well as to achieve regulatory visions on water.

As a sequel to the National Water Act, the National Water Resource Strategy of 2004, 2013, and 2020 provides for the protection, use, development, conservation, management, and control of water resources. The water policy in South Africa mirrors the policy sectors under the IWRM paradigm (Volenzo and Odiyo, 2019). The White Paper on the National Water Policy for South Africa (DWAF, 1996) reflects the aspirations of the post-apartheid constitutional

order, international customs and practice and landmark international instruments, such as the Dublin world conference on Water and Environment, Agenda 21, the 1996 Stockholm Global Water Partnership (GWP), ratification and domestication of international treaties and protocols, such as the Ramsar on wetlands and shared water systems, under SADC protocols (DWAF, 1996).

The National Water Act of 1998 divides South Africa into Water Management Areas and prescribes processes for the evolution of strategies and management institutions within them. The Act advocates for the use of stakeholder participation principles in the development of institutional and management systems, Catchment Management Agencies, Catchment Management Strategies, and Water Users' Associations. Chapter 9 of the National Water Strategy Revitalisation Strategy 2 (DWA, 2013) recognises that water management operates within a social, economic, and ecological environment, for effective and integrated management of water resources. In essence, top-down consultation should be replaced by citizens' participation (DWAF, 2001); this is especially critical, given the increasing need to address historical injustices in which access to water, as well as the need for transformative approaches for no-regret adaptation planning outcomes, have emerged as some of the urgent priorities. The multi-governance aspect of existing CWH nexus challenges and the need for effective and sustainable adaptation through nexus lenses are apparent, yet poorly concretised into coherent policy and practice.

The pursuit of water security-policy objectives in South Africa is domiciled within various state departments (Mabhaudhi et al., 2018). The 1997 White Paper identifies Irrigation Boards and Water Users Associations (WUAs) as critical institutions for the development and implementation of water-demand management programs and initiatives at the local level, especially within the agriculture sector (DWA, 2013). The Water Services Act 108 of 1997 is the fundamental framework for water service institutions. The Act stresses the right of access to basic water provision and sanitation, safeguards water resources, and promotes development for individual welfare. The Water Services Act delegates water quality monitoring and management to Water Services Authorities (WSAs), the Department of Water Affairs (DWA), the Department of Health (DoH), and Local Government and Civil Society (Hodgson and Manus, 2006). The primary responsibility for ensuring the provision of safe

drinking water and monitoring quality rests with WSAs. The local municipal governments are delegated the responsibility to ensure a bulk supply of water for drinking, sanitation, and hygiene.

The water policy, although it safeguards free water for the most vulnerable people and the ecosystem (including protecting ecological flows), in practice, water governance is dominated by free-market tendencies. South Africa's political economy tends to prioritise market economy philosophies, with negative externalities in the provision of environmental goods and services, adversely impacting access to clean water, as well as negatively impacting human health; such challenges are exacerbated by climate change (Nhamo et al., 2020). Efficiency may be achieved through user-pay principles, although advancing the narrative of user pay and full water cost recovery tends to compromise human rights to water (Larrain, 2014).

The South African Presidential Climate Commission (PCC) was formed to coordinate planning and actions for transitioning to net zero and CRD by 2050 (Taylor et al., 2023). This, however, is not downscaled to local implementation levels, due to sectoralised operational rules, budgetary allocations, and financing for nexus projects. Unlike other acts on CWH, the Health Act is silent on participatory planning at the community and national levels. This can undermine concerted efforts to transformative adaptation planning, given that climate change is a risk driver of most health risks, such as waterborne diseases.

Table 4.4 indicates the policies and strategies within the CWH nexus in South Africa. At the provincial and local levels, the focus was on those within the Limpopo Province and VDM. The development of a climate change strategy for South Africa is done at the national level. The national authorities delegate to the provincial departments the authority to adapt their provincial policies and/or strategies from the national ones. At the local level, the districts and municipalities develop their strategies in line with the provincial strategies; similarly, the implementation of these policies is at the provincial and local levels.

Table 4.5: National, provincial and local policies/strategies within the CWH nexus

Policy/strategy	CWH aspects	Remarks
Climate Change Act No. 22 of 2024	Recognizes effects of extreme weather on human health; mandates the health sector to develop Sector Adaptation Strategy and Plan	It aims to enable the development of an effective climate change response and a long-term, transition to a low-carbon and climate-resilient economy and society for South Africa, in the context of sustainable development
National Climate Change Response White Paper	Advocates for the reduction of incidences of respiratory diseases and to improve air quality, develop and strengthen existing public awareness campaigns, develop heat-health action plans, improve biosafety, develop a spatial and temporal health data capture system and integrate food security and sound nutritional policies into all adaptation strategies.	It was mentioned that implementation of adaptation strategies will be integrated in the DoH strategic plan, however, the DoH strategic plan 2020/21-2024/25 does not include climate change adaptation issues.
National Climate Change Adaptation Strategy (NCCAS) (DFFE, 2020)	Each province and municipality should draft and update climate change strategies that include adaptation responses and associated implementation plans to guide climate response in their province. These strategies and associated implementation plans should be reviewed and updated every five years.	As the NCCAS is, however, a national strategy, it does not detail how adaptation will take place in the sectors impacted by climate change.
Just Transition Framework (IPCC, 2022)	The framework focuses on managing the social and economic consequences of climate mitigation and adaptation policies, while putting human development concerns at the centre of decision-making	The just-transition framework is not exhaustive, nor a detailed implementation plan, but rather a first organising frame to give effect to a just transition in South Africa.
National Climate Change and Health Adaptation Plan (2014-2019) (DoH, 2014)	A 5-year strategy that provides a broad framework for health sector action towards climate change adaptation, with objectives focused on describing the economic, environmental and health context for the proposals contained in the White Paper, outlining a broad programme of activities to be undertaken by the South African health sector, timeframes and financial implications.	The DoH will establish, in high-risk areas, a series of model projects for implementation of adaptation actions with a focus on prevention and intersectoral action. Lessons learned in the model projects may be considered for scaled up implementation in other relevant parts of the country.

Policy/strategy	CWH aspects	Remarks
National Heat Health Action Guidelines (DoH, 2020)	Guidelines to ensure that the health sector is prepared to effectively respond to rising temperatures across South Africa.	The guidelines are aimed at supporting Provincial DoH, District Health Services and municipalities to design, implement and improve Heat Health Action Plans to prevent the negative effects caused by increasing temperatures and heatwaves. The implementation of the plan will take place at the provincial and local level, with oversight from national level.
National Environmental Management Act 107 of 1998	Advocates for the right to an environment that is not harmful to communities' health or well-being.	The Act establishes principles for decision-making on matters affecting the environment
National Water Policy White Paper of 1997	Advocates for public safety and disaster prevention including those related to climate change.	Its purpose is to set out new integrated policy positions for protection, use, development, conservation, management and control of South Africa's water resources (Karodia and Weston, 2001).
National Development Plan	Responding effectively to climate change through adaptation to promote transition to an environmentally sustainable, climate-change resilient, low-carbon economy and just society.	It states that the best form of adaptation to climate change will come from strong policies, backed by sound technical understanding and operational capacity. Local, provincial and national governments will need to embrace climate adaptation by identifying and putting into effect appropriate policies and measures.
Disaster Management Act of 2002 Disaster Management Amendment Act 16 of 2015	The 2015 amendment indicates that each organ of state should provide measures and indicate how it will invest in disaster risk reduction and climate change adaptation	Provides an integrated and coordinated disaster management policy that focuses on preventing or reducing the risk of disasters, mitigating the severity of disasters, initiating emergency preparedness, as well as rapid and effective response to disasters.
National Water Resource Strategy of 2021	Develop water resources, feasibility, reconciliation, balance and climate change adaptation studies and plans.	The strategy details an approach to be taken to ensure climate change adaptation in the water sector.
Limpopo Provincial Climate Change Response Strategy	Adaptation measures for the health sector indicate that these should formally join, participate in, and leverage capacity and information from global climate change health networks and knowledge-sharing platforms. In addition,	Responsibility for implementation would rest the DoH, but in coordination with LEDET, DWS, DEA, and the Department of Education (DoE)

Policy/strategy	CWH aspects	Remarks
	they should secure, dedicate, and allocate substantial funding for better climate-related health surveillance and monitoring in the Province and to carry out studies within Limpopo on health impacts of climate change; fund and implement a comprehensive public health and climate change awareness and adaptive capacity building programme as well as redouble efforts to improve overall socio-economic status and health indices.	
Climate change vulnerability assessment and response plan (VDM, 2016)	Identified adaptation actions include managing health impacts from increased storm events, heat stress, waterborne and communicable diseases (typhoid fever, cholera & hepatitis) and occupational health problems.	The actions should be included in the Service Delivery and Budget Implementation Plan (SDBIP); however, both SDBIP for 2022/2023 (VDM, 2023a) and 2023-2024 (VDM, 2023b) have no aspects of climate change adaptation.

These policies are relevant, coherent, and effective in responding to climate change impacts. Table 4.5 shows the assessment of the policies and strategies, in Table 4.2. All the policies and response strategies are compatible with each other and are expected to deliver their objectives and generate significant positive impacts if implemented. From the policies/strategies' perspective, they are also likely deliver results in an economic and timely way, However, in a practical sense, it is difficult to establish this, and this would require further analysis with respect to funds that are available for implementation of such policies, as well as the benefits that will be derived from that.

Table 4.6: Assessment of the policies and strategies

Policy/strategy	Relevance	Coherence	Effectiveness	Efficiency	Impact
Climate Change Act of 2024	✓	✓	✓	✓	✓
National Climate Change Response White Paper	✓	✓	✓	✓	✓
National Climate Change Adaptation Strategy (NCCAS)	✓	✓	✓	✓	✓
Just Transition Framework	✓	✓	✓	✓	✓
National Climate Change and Health Adaptation Plan (2014-2019)	✓	✓	✓	✓	✓
National Heat Health Action Guidelines)	✓	✓	✓	✓	✓
National Environmental Management Act	✓	✓	✓	✓	✓
National Water Policy White Paper of 1997	✓	✓	✓	✓	✓
National Water Act, 36 of 1998	✓	✓	✓	✓	✓
National Water Resource Strategy of 2021	✓	✓	✓	✓	✓
Limpopo Provincial Climate Change Response Strategy (LEDET, 2016)	✓	✓	✓	✓	✓
Climate change vulnerability assessment and response plan (VDM, 2016)	✓	✓	✓	✓	✓

The sustainability criterion considered funding, institutionalisation and expertise, following the Department of Planning, Monitoring and Evaluation (2022) guidelines. Table 4.6 indicates that the Minister of Finance, Ministers in the Environment, Water and Health sectors, private and public banks, National Treasury, IDC, as well as other national, provincial, and municipal, financial institutions and small business, have to fund the implementation of the policies/strategies. Similar to the economic aspect of the efficiency criterion, the funding aspect of the sustainability criterion will also require further analysis. This is also because details on this are not provided in policies/strategies documents, except for the NCCAS, which

has an intervention strategy to enable substantial flows of climate change adaptation finance from various sources (Table 4.7). It was not, however, possible to assess expertise capacity, as this requires a detailed analysis of experts at the local, provincial, and national levels within the CWH nexus.

Table 4.7: Assessment of policies/strategies on the sustainability criterion

Policy/strategy	Financial	Institutions	Expertise
Climate Change Act of 2024	The Minister responsible for environmental affairs must prescribe a mechanism to support and finance climate change response, planning and implementation by national, provincial and local government in consultation with the Minister of Finance.	✓	✓
National Climate Change Response White Paper	Government, public and private banks, Ministers of Finance, Economic Development, and Water and Environmental Affairs will appoint a multi-stakeholder working group to oversee the realisation of these actions within three years of the publication of this policy.	✓	✓
National Climate Change Adaptation Strategy (NCCAS)	The NCCAS has an intervention strategy to enable substantial flows of climate change adaptation finance from various sources.	✓	✓
Just Transition Framework	National Treasury, Reserve Bank, IDC, DBSA and Land Bank as well as other national, provincial, and municipal, financial institutions, small-business financing agencies and stakeholders, should identify financing needs and ways to meet them.	✓	✓
National Climate Change and Health Adaptation Plan (2014-2019)	Guidance on how to access funds for health adaptation to climate change, was developed.	✓	✓
National Heat Health Action Guidelines	No information provided on funding.	✓	✓
National Environmental Management Act	Minister of Finance makes available, funds for the functioning of the Forum on environmental management and governance.	✓	✓
National Water Policy White Paper of 1997	Mix of finance from commercial and concessional source.	✓	✓
National Water Act, 36 of 1998	To be financed by the Minister of Finance.	✓	✓
National Water Resource Strategy of 2021	Realignment must enable institutions to leverage finance for water infrastructure and sustainable management.	✓	✓
Limpopo Provincial Climate Change Response Strategy	Funding could be secured from development partners and international institutions.	✓	✓
Climate change vulnerability assessment and response plan	Funding to be considered within the SDBIP.	✓	✓

4.5.2 Results on policy field assessment and level of integration within CWH in South Africa and VDM

The results of the policy field assessment, along with established remarks, are presented in Table 4.7. The existence of institutions and cross-sectoral structures in response to climate change impacts is displayed in Table 4.8. However, lack of awareness, low institutional capacity, knowledge gaps, siloed research approaches, inadequate human skills and fragmented research are some of the factors that affect institutional and expertise capacity in South Africa.

The Minister of Water and Sanitation is responsible for overall effective water resources management. This responsibility is discharged by DWS, which also oversees the overall implementation of the Act (DWA, 2013). The Act also allows for the Catchment Management Agencies (CMAs), whose role is water management at the catchment level and is responsible for the progressive development of catchment management strategies. The Act also states that the CMAs will use the catchment management strategy consistently with the National Water Resource Strategy (NWRS), within their water management area. It is important to note that most of this responsibility is delegated by the Minister. The third tier in this framework operates at a local level, below the water management area (WMA). The Municipal Systems Act of 2000 provides for the mainstreaming of environmental concerns into planning, community participation, and the empowerment of collaborative governance in development planning and community empowerment, in pursuit of universal access to water and service delivery goals. The National Health Act of 2003 acknowledges decentralisation, cooperative governance and participation, but is silent on community participation.

The matching or confluence of key SES interaction attributes and the institutions is designed to steer them to fit (Young, 2006; Ostrom, 1990). Fit is reflected in the extent to which policy captures and addresses scope issues, such as externalities, temporal dimensions, and the preferences and motivations of agents (Young, 2006; Rijke et al., 2012). Given that policy design coherence and integration minimise trade-offs and exploit synergies, effective policy integration is judged on the extent to which mitigation and adaptation objectives are

mainstreamed into sectoral policies (Di Gregorio et al., 2017), as well as the extent to which climate change and overall development goals are integrated. We argue that CRD underscores policy integration. The level of policy integration on CWH in VDM is given in Table 4.8**.**

Adaptation planning often shows a lack of understanding by planners of the fundamental drivers of behaviour and patterns that are essential for planning and designing more resilient, equitable, and appropriate strategies. Inherent in these inter-dependencies are trade-offs between temporal and spatial scales in planning activities, as well as between sectors; identifying these trade-offs is integral to transparency in planning and adaptation. Incorporating approaches that acknowledge inter-dependencies in future planning, which is part of the subsequent community planning research activities, is aimed at preventing a siloed understanding of trade-offs and uncertainties for Day Zero transformative planning.

Table 4.8: Summary policy field on CWH adaptation planning in South Africa

Policy component	Description and operationalising	South African context	Remarks
Institutional Order (IO)	Types and number of government institutions that produce policy products/outputs and devoted to adaptation	• National, provincial and local government and their departments Institutional order is the government institutions that produce substantive authority, such as ministries, ministerial offices and parliament.	The following cross-sectoral structures are present: • Parliament • Inter-ministerial Committee on Climate Change • Presidential Commission on Climate Change • Provincial Forums on Climate Change • Municipal Forums on Climate Change Horizontal integration is evidenced through comprehensive cross-sectoral strategy, overarching goals and a central authority while vertical integration is evidenced by procedures that facilitate the adoption and implementation of climate change objectives, such as formation of sectoral climate change units and climate change plans. Vertical integration also includes the devolution of climate policy to sectoral ministries and the presence of a high-ranking institutional mandate and corresponding enforcement mechanisms; however, cross-level coordination for nexus issues is largely lacking, thereby decreasing effectiveness of policy intent
Substantive Authority (SA)	Policy products and outputs including programs, legislation and rules (Massey et al., 2014)	Examples of the policies/strategies: • National Climate Change Response strategy • Climate Change Act • National Climate Response White Paper 2011 • National climate change Adaptation strategy 2017 • Disaster Management Act • The Municipal Systems Act (2000) Strategic Plan 2020-2025 of the Department of Mineral Resources and Energy (DMRE) integrated resource plan that advocates for co-operation between the DMRE, Department of Water and Sanitation (DWS) and Department of Forestry, Fisheries and the Environment (DFFE), towards implementing one environmental system will be encouraged (Department of Mineral Resources and Energy, 2020).	• Lack of awareness, low institutional capacity, knowledge gaps, inadequate financial resources, and a lack of political will to carry out nexus programmes fragmentation and sectoralisation, weakens horizontal integration. This is reflected in strong vertical governance structures, such as those that mainstream climate change into sectoral policies where there are weak overarching governance structure for cross sectoral coordination. This results in sectoral control or sectoralised climate agenda, fragmented responsibilities and embedded conflicts.

Policy component	Description and operationalising	South African context	Remarks
Substantive Expertise (SE)	Evidence of expert knowledge among state and non-state actors in adaptation planning framing, as well as the interplay of adaptation (Massey & Huitema, 2013)	Universities, Research organisations (e.g WRC), Government agencies, Climate Change Units (CCU) in land use sectors such as Ministry of Agriculture, Forestry and Various NGOs / CBOs	Integrative approaches are highly acknowledged at the higher policy level but poorly internalised and implemented at the local level, however**,** the silo approach is still evident despite efforts to increase integration through various discourses, such as the nexus approach. Inadequate human skills and fragmented research with agenda for low public expenditure on research and limited participation by the private sector, coupled with poor succession planning affects effectiveness. Fragmentation and sectoralisation, thus weakens horizontal strategies. This is reflected in strong vertical governance structures such as those that mainstream climate change into sectoral policies overarching governance structure for cross sectoral coordination; sectoral control as well as sectoralised climate agenda, fragmented responsibilities and embedded conflicts. This weakens policy integration inertia and powerplay, hierarchy of rules or operating rules conflicts Southern Africa has witnessed a surge in research projects and publications on nexus since 2013 (Naidoo et al., 2021). This includes publications by think tanks on nexus projects funded under Development Community- European Union (SADC-EU) nexus, Food , Agriculture and Policy Analysis Network (FANFRAN); Africa Climate , Land, Agriculture and Biodiversity (CLAB); African Research Universities Alliance centre of Excellence in Sustainable Food Systems (ARUA-SFS) and Water-Net among others. WRC is in the forefront of nexus research Project funding on CWH nexus enhances the likelihood of increased science policy practice integration Several uncoordinated projects towards green economy under climate finance mechanisms are still evident, despite efforts to increase integration through various discourses such as WEFN. WRC research policy agenda in the last decade, however captures this need and could inform Science- Policy- Practice on nexus approaches, in the future

Table 4.9: Level of policy integration on CWH nexus in South Africa and VDM

Type of coherence/ integration	Definition (operationalisation)	Degree of coherence/ integration				
		Strong /Substantial	Intermediate/ Partial	Weak	No	Remarks
Strategic	The extent to which multi-hazard analysis planning approaches are recognised in policies, programmes and plans, essentially a system approach on CCA/DRR and SDGs.		xxx			Attempts at the Integration of the SDGs agenda, the Sendai Framework for Disaster Risk Reduction, and the Paris Agreement through multi-hazard approaches have been recognised in policies, including citizen science and co-production at higher political levels, but are yet to be operationalised at the implementation level due to silo approaches in planning and/ or misalignment of mandates. Consequently, path dependency is still evident, notably in fragmentation in policy, advocacy, and programming spaces, incremental silo approaches, as well as scale deficits that dominate planning spaces in adaptation. The need for all government spheres to collaborate and co-operate is a priority emphasized in both the Constitution and National Environmental Management Act (NEMA, 107 of 1998).This co-ordination bodies such as the South African Local Government Association (SALGA) and the Department of Co-operative Governance and Traditional Affairs COGTA include the use of Integrated development plans (IDPs) as comprehensive planning tool that facilitate developmental local government; these have been used as vehicles for integrating brown (developmental) and green (environmental) agenda issues that have conventionally been addressed separately and embedding sustainable development discourse into strategic planning.
Conceptual Integration of risk and resilience lenses in policy design	Risk and resilience lenses linkages		xxx			Yet to fully use nexuses approach although extensive political will could eventually guide this. In particular, this is not envisioned through Comprehensive Risk Management Framework where integrated community-based risk reduction mechanisms is lacking
Institutional integration	The extent to which risk-centered approaches are envisioned and integrated into policies, plans and programmes	xxx				Existence of high political will in terms of PCC which was formed to coordinate planning and actions for transitioning to net zero and CRD by 2050. However, this only exists at national level and is poorly envisioned at implementation level (provincial, municipality and community). while vertical integration is evidenced by procedures that facilitate the adoption and implementation of climate change objectives, such as formation of sectoral climate change units and climate change plans devolution of climate policy to sectoral ministries as well as the presence of a high-ranking institutional mandate and corresponding enforcement mechanisms. Less of this is reflected at implementation (provincial, municipal and community) levels where fragmented policy responses with limited understanding of the complex linkages between resource systems and sectors prevail. In particular poor horizontal integration is evidenced through lack of comprehensive cross-sectoral strategy, overarching goals and a central authority on nexus issues such as CWH nexus, and WEF. Implementation support (capacity development for institutions supporting community development) for projects concerned with

						people, so that they are in a processes of learning, enabling, and empowering with open-ended time frames allowing for participation and change (social transformation) are evidently missing or poorly conceptualised
Operational integration in (co) funding, joint planning of project appraisal and implementation	The extent planning (activities/ plans are cross-sectoral (jointly implemented		xxx			Although high political will exist, multisectoral integration, governance and programming, hence nexus framing at the core of sustainability debates, is lacking. Policy coherence is particularly undermined by the sectors' different institutional frameworks, divergent targets on adaptation and mitigation, lack of communication, and lack of clarity on rights and responsibilities across sectors
Financial	Whether and how funding strategies, financing and investments' frameworks bring together DRR and CCA and address underlying issues			xxx		Many laws exist, although their implementations are either misaligned or sectoral-biased especially in terms of silo budgeting and financing that adopt implementation with no synergies being captured at the local scale
Monitoring, Evaluation and Reporting (Learning)	Multi-hazard analysis coordination mechanisms that bring together coordination (reduce potential conflicts) and synergies between the SDGs, DRR, and CCA.		xxx			• Stakeholder forum for joint planning, monitoring and evaluation and implementation support is envisioned at high level but lacking at implementation level. In particular horizontal and vertical integration framework and governance are poorly pursued in risk- resilience nexus goals. • The legal and policy framework seem to be supportive of community participation, but the integration of attitudes, indigenous knowledge, practices and leadership structures in the sustainable management of water resources though critical, remains low to non-existent (Nare et al., 2011). Overcoming the low policy-practice interface could be resolved through a community-based approach anchored on technological, empowerment and communication, is likely to resolve the constraint. • Lack of elaborate system on the design, appraisal, implementation, financing, monitoring and evaluation mechanisms for assessing effectiveness. • Power struggles amongst key policy actors; overlapping ministerial mandates that are thinly spread across different departments; poor involvement of communities, hence lack of ownership over implementation agendas, as well inadequate conflict resolution and communication mechanisms, all of which undermine the well-intended policy objectives

4.6. Main findings of this chapter

The main findings are:

- Multilevel governance system on CWH characterised by legal and institutional pluralism, which in turn introduces additional complexity, breeds constitutionally anchored mandate conflicts, organisational and investment fragmentation that undermine effectiveness in the medium and long term. This, in turn, contributes to implementation inertia and paralysis.
- Multifaceted interdependence and complex relationships of CWH, concurrently intersect directly, as well as indirectly, with rural and urban planning, land use, food security, and behavioural dynamics. Health, a crucial facet of this nexus, is intricately linked to the availability and quality of water, food security, nutrition, and, ultimately, climate dynamics. Accordingly, there is a need for a holistic understanding of these interdependencies. This is a characteristic of complex adaptive systems, which is why a system approach is needed to identify policy problems for no-regret adaptation planning. Nexus recognition at the strategic level, despite various policy actors at the implementation level, continues to act in silos. Such silo approaches in policy and decision-making processes are underpinned by sectoral approaches that fail to account for complex linkages between resource systems and sectors (Adom et al., 2022; Mabhaudhi et al., 2018; Nhamo et al., 2020; Seeliger et al., 2018; Mutanga et al., 2024). In such scenarios, the ensuing pursuit of narrowly sectoral-specific goals within a tele-coupled system undermines synergies (Liu et al., 2017). Fragmented programming of nexus issues could also be associated with past legacies in planning (Pahl-Wostl et al., 2020).
- Lack of meaningful participation by relevant policy actors could be one of the major reasons for poor performance of nexus policy implementation (Lech and Simon, 2018). The country, although it has one of the most elaborate and consultative climate governance systems in the world, this is not effectively cascaded to local implementation scales. Limited human and technical capacity, as well as structural issues challenge effective participation and collaboration This is attributed to many sources, such as power struggles amongst key policy actors, overlapping of ministerial mandates that are thinly spread across different departments, poor involvement, hence lack of ownership over implementation agendas, as well inadequate conflict resolution and communication

mechanisms, all of which undermine the well-intended policy objectives (Lech and Simon, 2018).

- Inclusive collaboration, integrated stakeholder fora, and decentralisation are critical to effective nexus implementation (Rasul and Sharma, 2016). Normative and justification narratives, although they are evident in most nexus policies in South Africa, they are short on explanation (the how) narratives on implementation, enforcement, monitoring and evaluation (Lech and Simon, 2018). In part, this can be attributed to the tendency for silo planning among nexus related agencies, also their over-reliance on consultants, politicians and administrators and passive participation of communities in policy problem assessment and implementation of nexus programmes. Such behaviour is in conflict with the findings of Seeliger et al. (2018) on the need for integration of nexus stakeholders at operational level.
- Governance of CWH, as in other nexus approaches, is characterised by legal pluralism. Legal pluralism often triggers struggles over policy problem definition, budgetary, implementation and fragmentation at local level. The ensuing fragmentation leads to loss of synergies at local and ultimately national scale. The existing Integrated Development Plans (IDPs) framework has the potential to inform integrated planning and specifically the integration of climate policy goals into SDGs (Leck and Simon, 2013).
- Participatory planning is well recognised in legal and institutional frameworks, such as the National Water Act of 1998, Municipal Systems Act No. 32 of 2000, the Constitution and Disaster Management Act; however, it does not expand on the explanatory (the how) narrative of participation. Consequently, silo approaches are still widespread in nexus programming. In view of climate change-related public health risks, the effectiveness of community participation strategies envisaged under South Africa's National Water Act of 1998 and IWRM needs to be reviewed through risk- resilience strategies for DRR in water-related public health risks (Volenzo and Odiyo, 2019). Integrated approaches, environment livelihood security, nexus, ecological public health and communication for development perspectives need to be in place to increase effectiveness of participatory processes (Volenzo and Odiyo, 2019). The existing ward committees provide a critical social structure for community entry and enhancing policy integration on the CWH nexus.

- Financing, technologies and innovations, as well as behavioural dimensions, are integral to effective adaptation planning, especially the adoption of nexus innovations and practices that could enhance sustainability at household level (Musetsho et al., 2024).
- The institutional, policy and governance systems give insight into social practices, biophysical and social drivers of vulnerability and root causes of risks, past path dependencies and historical triggers of adaptation and/or transformation needs. Back-casting approaches, which connect past decisions and actions with present and future aspirations, are a promising methodology for understanding the nexus between past policy, governance and institutional systems and planning, to ensure flexible, inclusive and equitable action that advances sustainability (Werners et al., 2018).
- There is a need for increased policy coherence, effective operationalisation and implementation of nexus policies through appropriate governance instruments and institutions. The institutionalisation of SDG targets can be a tool in this direction. A landscape approach could link CWH sectoral targets with SDG goals; for instance, ensuring sustainable food production systems (Target 2.4) and sustainable management of all forests (Target 15.2), and integrating climate change measures into national policies, strategies and planning (Target 13.2); all offer the potential for synergies with the target of Goal 6 - access to clean water. All of these interlinked examples could influence the ability to achieve some of the broader and less well-bounded targets, such as 1.5 (build the resilience of the poor to climate, economic, social, and environmental shocks) in CWH adaptation planning. Theoretically, the appropriate application of the landscape approach can contribute to the development of long-term self-regulating transparent institutions, for ensuring not only the achievement of SDG targets, but also coherence in the pursuit of long-term sustainability.

4.7. Summary

Policy integration is necessary, although it may be inadequate and insufficient, particularly when it fails to elaborate the design, appraisal, implementation, financing, monitoring and evaluation mechanisms for assessing effectiveness. This could be the case even when integration increases the visibility of climate change challenges in national policy discourses (Biesbroek et al., 2010). According to Nhamo et al. (2018), most policy fields tend to overlook

cross-sectoral linkages during policy problem framing and implementation, with a resulting sector that is focused on policies undermining collaboration, hence causing ineffectiveness of responses to nexus policy problems. Inadequate awareness, a lack of multi-stakeholder and multi-sectoral coordination platforms to promote dialogue among institutions, low institutional capacity, knowledge gaps, inadequate financial resources, as well as lack of political will to pursue integrated programming of nexus strategies and plans, are fundamental constraints to implementing the nexus program in South Africa (Mathetsa et al., 2019; Naidoo et al., 2021).

Stakeholder involvement, increased awareness, and capacity building are the foundation for sustainability governance (Schmidt et al., 2020). One of the significant institutions in the grassroots participation matrix in South Africa is the ward committee. Ward committees are composed of elected representatives and are chaired by a councillor. Through the councillor, the ward committees have the power to make recommendations on any development matter to the metropolitan or local council. The structure is desirable because it aligns with bottom-up approaches that can give the community a voice in matters that affect them.

Participatory intent may fail to achieve its objectives. In view of public health risks, the effectiveness of community participation strategies envisaged under South Africa's National Water Act of 1998 as well as the IWRM paradigm needs to be reviewed through participatory frameworks for resilience building and disaster risk reduction, with respect to water-related public health risks (Volenzo and Odiyo, 2019). There needs to be integrated approaches, ELS, nexus, ecological public health and communication for development perspectives to increase effectiveness of participatory processes. Innovative integrated Community Disaster Risk Reduction approaches and models in co-production of knowledge, CWH needs-assessment (policy problem definition), project appraisal and design, as well as effective collaboration of policy actors, could thus lead to policy, institutional, and governance innovation on addressing nexus planning. The use of communication to achieve development and behaviour change (Srampickal, 2006) is integral to the proposed innovation. This also suggests the essential nature of social learning or mutual gaining of knowledge by actors, through sharing values, developing strategies, implementing actions, and reflecting upon feedback in nexus planning, for future drought risks.

The use of anticipatory adaptation planning frameworks to ensure broader actor engagement in exploring innovative CRD pathways is highly recommended, as co-produced actions by multiple actors are likely to capture divergent worldviews, knowledge, and values regarding CWH and the construction of context-specific, no-regret adaptation pathways. Adopting the principle of indivisibility, such as the landscape approach in nexus planning and implementation, requires integrated approaches, rather than a focus on siloed knowledge and policymaking. This is especially true for climate action and development decision processes towards sustainability, more so at the local scale. In so doing, a focus will be placed on how governance decisions have shaped development pathways and how power dynamics have led to inequitable and maladaptive outcomes, which should serve as the basis for anticipatory Day Zero no-regret planning on the CWH nexus.

CHAPTER 5: MULTI-STAKEHOLDER PLANNING PROCESSES TO ADDRESS ANTICIPATORY FUTURE PLANNING ON CWH NEXUS

5.1 Introduction

This chapter is focused on multi-stakeholder planning processes for transformative adaptation and resilient CWH outcomes, under climate risk and deep uncertainty. It unpacks the convergences and dissonances in the framing of CWH risks and uncertainties by identifying the underlying drivers of vulnerability to climate-related uncertainties, as well as the experiences of diverse households and vulnerable communities. These discussions enabled the exploration of climate change adaptation interventions that align with the realities and lived experiences of households in South Africa's drylands. The chapter thus presents results from the assessment of gaps and opportunities for transformation and resilience-building, in line with anticipated Day Zero planning risks, under uncertainty in VDM, Limpopo Province.

5.2 Definition of concepts used in participatory planning processes

Technological considerations are necessary in a transformative agenda; however, effective science-policy-societal interfaces require keen attention to alternative narratives in framing the problem and identifying potential solutions to complex societal challenges, such as climate-change-related challenges (Allouche, 2024; Béné, 2022). The 2023 UN Water Conference on accelerating change to solve the water crisis identified the need for governance reforms as necessary conditions for sustainability in water-resource planning. The nexus frameworks, which are essentially a polycentric governance approach, are recommended as appropriate analytical lenses for overcoming silo-planning drawbacks. Effective participation is inherently integral to governance and transformative imperatives. The observation is largely informed by a justice lens, which includes the voices, knowledge, and experiences of marginalised communities as necessary for enhancing the relevance of development and adaptation initiatives, as well as for operationalising the resilience concept (Rodina et al., 2024**;** Cutter, 2016; Harris et al., 2017).

Effective participation is particularly critical in the transformative planning agenda. The underlying objective in participation is to influence or transform power relationships and to make the target institutions responsive to community/people's views, aspirations, and needs. Participatory approaches improve the quality of the decision-making process by integrating available information and creativity (innovation) to resolve societal challenges (Chambers, 1994; Scoones, 1998). Stakeholders' participation thus enables better understanding and dialogue, fosters hybridisation of solution frames, facilitates nuanced focus on relevant problems and ultimately confronts the underlying drivers of change by informing strategy and policy formulation (Mostert et al., 2007).

This chapter presents the findings from participatory planning processes conducted in 3 communities within the Collins Chabane and Thulamela local municipalities in VDM. This section thus elaborates on and operationalises the various aspects of participation and envisaged outcomes used in the report. Essential definitions utilised during the process are as follows:

- **Agency**: a process that enables people to influence decisions, co-construct alternatives based on their framings, and make a reasoned choice, within a particular decision-making process; in other words, one's ability to pursue goals that one values. The decision-making, agency-focused perspective represents the outlook of actors when engaged in a particular decision-making process, factoring in various constraints of time, resources, and institutional arrangements.
- **Assumptions: n**ecessary factors or resources needed for the success of an intervention/project/plan/ policy.
- **Capacity development**: the process by which organisations and society systematically stimulate and develop their capacities over time to achieve social and economic goals, through, for instance, knowledge, skills, attitudes (education, training, awareness as well as information/risk communication campaigns), systems, as well as institutions' development.
- **Community**: a social system that encompasses enough distinct institutionalised social structures or individuals, groups and organisations. It is the smallest unit of a social structure within a society. In this report, a community is defined as a geographical entity (such as a cluster of households or a small village, or a

neighborhood in a town). Essentially, community members share the same living environment and similar exposure and vulnerability to a hazard.

- **Context:** the social and political, as well as the current state of a problem, in this instance, CWH nexus challenges.
- **Coping mechanisms**: short-term strategies in response to a disruptive event, with shocks and within a range of responses that will not jeopardize survival or lifetime aspirations. Some strategies may increase vulnerability; for example, in response to high fuel prices, some households or individuals may resort to charcoal, which in turn increases the rate of deforestation and/or household level pollution.
- **Culture**: learned and expected way of life shared by members of a society, for example settlement structures (heritage), technology, tools, attitudes, beliefs, social institutions, motivations, systems of value known by the group, food, dressing, and language. It is the preferred way of thinking, feeling, and doing what a population has developed and made part of its physical environment and biological nature.
- **Disaster-risk reduction:** the development and application of policies, strategies and practices designed to minimise vulnerabilities and impacts of disasters through a combination of technical measures to reduce physical hazards and enhance social and economic capacity to adapt (UNISDR, 2015).
- **Empowerment:** the capacity of people to make effective choices, envision alternatives, participate in decision-making, negotiate with influence, control and hold accountable institutions that affect their lives and livelihoods (World Bank, 2007). Basically, being empowered allows people to participate in all the phases of the planning cycle.
- **Participation**: a process whereby individuals, groups, and/or organisations choose to take an active role in decision-making processes that affect them.
- **Pathogen pollution:** the introduction of a pathogen to a new host species or population, usually anthropogenically driven, and includes zoonotic spillovers. Principally, it applies to organisms found in water and terrestrial ecosystems because of the presence of faecal material or improper disposal of sewage in the environment.

- **Planning**: an organised, intelligent attempt to select the best available alternative for achieving a specific objective. Gans (1968) defines planning as a method of decision-making which emphasises choice of problem/ goals and means for their achievement, that is, rational goal-means determination. This suggests that decisions are based on the goals people are seeking and the most effective program/ project for achieving them. Planning involves selecting missions and objectives and deciding on the actions to achieve them; it requires decision-making - choosing a course of action from among alternatives. Plans thus provide a rational approach to achieving preselected objectives; examples include using various land-use plans to achieve sustainability, disaster risk reduction, and wildfire prevention.
- **Resilience**: ability to anticipate, cope, respond, and recover from setbacks, and adapt well to change, in the face of adversity. The resilience of a community/region is a function of its subsystems, including its critical infrastructure, economy, civil society, governance, emergency services, and supply chains/dependencies (the importance of a system's approach to planning**).** Resilience can also be defined as "the ability of an entity, for example, an asset, organisation, community, region, to anticipate, resist, absorb, respond to, adapt to, and recover from a disruptive event". In this report, resilience is defined as the capacity to sustain livelihoods, develop, innovate, and transform in the face of crises, such as climate change, as stated in Rockström et al. (2023).
- **Social capital/assets:** the relationships and networks among people within a community and actors with the potential to influence such relationships.
- **Social learning:** achieving concerted action in complex and uncertain situations; individual learning that takes place in a social context, hence is influenced by social norms, for example, by imitating role models (Bandura, 1977). It is also a process of social change in which people learn from each other in ways that can benefit wider social-ecological systems, "an intentional process of collective self-reflection through interaction and dialogue among diverse participants (stakeholders) learning how to collaborate (developing new relational capacities between social agents and understanding others' roles and capacities differently)".

- **Transformation**: fundamental changes in the structural, functional, relational, and cognitive aspects of socio-ecological and technological systems that lead to emergent patterns of interactions, self-organization and associated outcomes (Patterson et al., 2017). Transformation of any given community is seen as a lasting solution to socio-economic challenges. Transforming communities from passive observers to primary and active agents in change management has been shown to positively impact community resilience. This is especially relevant where change or adversity creates vulnerability and increases disaster risks.
- **Vulnerability**: the potential/susceptibility/predisposition to suffer harm or loss. It refers to "the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard". **Vulnerability** of communities to health risks associated with climate-change impacts on water quality, sanitation, and hygiene is considered in this study. The definition of vulnerability as future harm/deterioration of water security, as a result of flooding impacts and health outcomes (for example, diarrhoeal diseases) has been adopted (Hinkel, 2011).
- **Water tenure arrangements**: these are the rights and rules (both formal and informal) determining how individuals and groups can use water resources and the way users relate to one another (FAO, 2020). Such rights and rules can be established by formal law (for example, legislation or judicial decisions), customary arrangements, or other instruments. It includes how water is appropriated through (a) land acquisitions and (b) infrastructural development, (c) pollution, (d) changes in cultivated crops; (e) afforestation; (f) land–atmosphere interactions (nature based); (g) a switch to more efficient irrigation systems; and h) virtual water trade.

5.3. Transformation planning tools

Scenario building, for anticipated changes in water security dimensions, such as availability, access, and cost, as well as quality dimensions (Stringer et al., 2022), is a critical health risk propeller underlying climate change. These can inform water and health managers, as well as policymakers, about plausible future adaptation needs and strategies. Such innovative

strategies can contribute to transformative adaptation policies for the water sector and feed into present and future water resource management planning in general, and resilient water systems in particular. Under multi-stakeholder approaches, pathways are often framed as the actions needed to manage conflicts and risks for achieving mutually- agreed upon societal goals (Sparkes et al., 2023). In turn, they have the potential to address drawbacks associated with techno-centric top-down approaches in adaptation planning.

Transformation focuses on no-regret policies in planning (adaptation to climate change impacts). Essentially, transformation revolves around the rethinking and reframing of policy and practice, engaging multiple knowledge and questioning the subjectivities inherent in discourses and problem understanding; basically, this is a form of triple-loop learning, hence social learning, which are critical in pursuing such a transformational agenda (Eriksen et al., 2015). Transformative analytical frameworks are thus inclusive of the interests, aspirations, and interactions of individual, community, state, and non-state actors**.**

In sustainability discourses, transformation refers to fundamental changes in the structural, functional, relational, and cognitive aspects of socio-ecological and technological systems that lead to emergent patterns of interactions, including self-organisation and associated outcomes (Patterson et al., 2017). Triggering transformative change focuses on the drivers and outcomes of coupled systems' dynamics that shape pathways, at the institutional and community levels, to achieve positive, long-term effects on the well-being of the poor and vulnerable, amid risk and uncertainty (Rodina et al., 2024; Leal Filho et al., 2021). The study operationalised system dynamics through a nexus lens on CWH and multidisciplinary participatory processes that unpack cognitive dissonances associated with chain impacts of climate change on sanitation and hygiene outcomes, at the community level.

The needed transformations, although urgent, are by default contested and constrained by deep uncertainty, especially for climate-related challenges. Inadvertently transformative changes focus on drivers and outcomes of coupled systems' dynamics that shape pathways at institutional and community levels to achieve positive long-term effects on the well-being of the poor and vulnerable, amidst risk and uncertainty (Rodina et al., 2024; Leal Filho et al., 2021). Following Eames and McDowall (2010), multi-criteria objective and participatory

scenario workshops were used as collaborative tools to navigate contested goals and viewpoints. The multi criteria objective was based on 6 key assumptions developed during the ToC exercise and iteratively used to rank pathways on the CWH nexus and CRD principles.

5.3.1 The role of participatory planning in transformation for Day Zero water scenarios and CRD

The systemic nature of current and predicted future climate-related shocks and impacts, such as waterborne disease outbreaks, facing humanity, specifically underscores the need for transformative interventions that address underlying drivers (Rodina et al., 2024; Barret et al., 2021; Herrero and Thornton, 2020). Transformation is a critical pillar in addressing future disease risks and climate-related shocks (Herrero and Thornton, 2020). Transformative resilience requires multi-scale visions that stimulate coherent thinking and action towards radically alternative futures (Hölscher et al., 2022).

The acknowledgment of system ambiguity and integration of non-expert knowledge promotes co-creation and capacity building. The APs are highly context-specific and grounded in local institutions (Totin et al., 2021). Hence, they mainly focus on historical, socio-economic, cultural, and political contexts (Arkema et al., 2017; Islam et al., 2014). Balancing competing societal objectives implies a focus on justice and equity dimensions, as integral lenses in CRD pathways (Wieners et al., 2021); participation is critical in such endeavours. Transformation is underpinned by the realisation that power structures and diversity of values, cultural changes, as well as generally accepted ways of life and practices, form the basis for risk attitude and response at scale, as well as successful adaptation planning.

For several decades, most water-related crises have been attributed primarily to a mismatch in demand and supply. However, emerging evidence tends to attribute water scarcity in the world's water-scarce countries to poor water governance. Such governance challenges are both sector specific, as well because of the complex interaction of natural, social and political variables. Management of water resources based entirely on techno-centric assessments, especially under deep uncertainty and climate crisis, could be untenable. Accordingly, it is

very urgent to find optimal solutions for the largely governance-related problems in water resources, notably social injustice (Rodina et al., 2024) as well as climate-change exacerbated water crisis and deep uncertainties captured in the 2022 IPCC report.

The CRD attempts to integrate adaptation and mitigation lenses at scale, while paying attention to inter-generational equity outcomes (Leal Filho et al., 2021). Given that equity and sustainability are inextricably interlinked, CRD is significantly biased towards the social pillar in which poverty and vulnerability, and the underlying issues of power, equity, and justice are prioritised. In essence, CRD seeks to dampen the risk of shifting vulnerabilities through a systematic, holistic programming approach (Buurman and Babovic, 2016; Leal Filho et al., 2021). The objective is to inform the appraisal, prioritization, and implementation of responses in adaptation planning (Fazey et al., 2016), as well as to guide the resolution of wicked socio-economic impacts of climate change (Leal Filho et al., 2021). The CRD accounts for diverse options and strategies, coordination, and implementation as strategic foci that overcome sectoral, policy, and disciplinary silo-framing traps (Rasmussen, 2018). By facilitating meaningful participatory opportunities, CRD approaches, such as AP, mediate procedural justice (Wood and Dougill, 2018); address maladaptation risks (Suckall et al., 2014) and facilitate the integration of diverse world views and knowledge cultures, across multiple scales (Ficklin et al., 2018). Operationalising CRD pathways thus demands explicit engagement with aspirations of actors, working with multiple pathways to embed flexibility, anticipation and learning into planning, as well as the prioritisation of justice and equity lenses (Werners et al., 2021a; Butler et al., 2022). Historically, integration has been informed by the realisation that independent projects have made an insignificant contribution to progress in community development. For instance, it is recognised that enhanced coherence between disaster risk reduction (DRR) and climate change adaptation (CCA) policy and action can contribute to ensuring that development does not create new or exacerbate existing and future risks, therefore, development gains are protected from the impact of disasters and climate change.

Participatory assessment and planning processes identify community capacities and needs; hence it is a tool for multi-disciplinary planning and multi-hazard planning assessment. Such transformative people-centred processes are likely to spur learning, enabling, and

empowering social transformation for CRD. Its potential in implementation support and use in innovative platforms for CRD transitions is apparent, although not explored in existing studies.

5.3.2 Adaptation pathways development

No regret policies generate net social and/or economic benefits, as well as guarantee desirable results in every climate scenario, the severity of impacts notwithstanding (IPCC, 2014). No regret adaptation fundamentally consists of imagining a policy output over a series of decision points (scenario planning) distributed across the planning cycle and beyond, in order to ensure flexibility, rather than restricting the evaluation metrics and criteria to the present alone (Hallegatte, 2009). Tipping points or thresholds provide clues that a chosen course of action is no longer adequate for meeting the planned objectives; therefore, a new measure is required, hence motivating the creation of alternative course(s); such standalone and/or combined actions are known as APs.

The AP assessment considers the diverse individual and community-value judgments, hence vulnerability from political, institutional, economic, and social contexts. Such scenario building for anticipated changes in water security dimensions, such as availability, access, and cost, as well as quality dimensions (Stringer et al., 2022) are critical health risk propellers underlying climate change and can inform water and health managers, as well as policy-makers, on plausible future adaptation needs and strategies. Such innovative strategies can contribute towards transformative adaptation policies for the water sector, and feed into present and future water resource management planning in general and just resilient water systems in particular. Under multi-stakeholder approaches, pathways are often framed as the actions needed to manage conflicts and risks for achieving mutually agreed-upon societal goals (Sparkes et al., 2023). In turn, such approaches have the potential to address drawbacks associated with techno-centric top-down approaches in adaptation planning.

5.4 Methodology

The analysis of sustainability challenges in complex social-ecological systems calls for the integration of multiple analytical methods, frames, and perspectives (Di Felice et al., 2021).

This methodology section provides approaches for data collection and analysis, with a focus on the transformative approaches that were utilised in the collection of data. The study used a mixed-methods approach to collect primary and secondary data through a participatory planning process. These were triangulated to address the assessment questions. Key data sources included rural communities, government institutions supporting policy implementation on CWH nexus, private sector, non-governmental organisations (NGOs), policy makers in climate change-water-food-health nexus. Primary data was collected through focus-group discussions (FGDs), selected households and direct observations. Triangulation and validation of the impacts from community perceptions were thus elicited as the basis for participatory deliberation and identification of priority no regret adaptation scenarios (Saltelli and Giampietro, 2017; Di Felice et al., 2021) and pathway thinking (Wise et al., 2014; Butler et al., 2015; Omore et al., 2019; Werners et al., 2021a). The iterative approach adopted integrated experts' views as captured in Figure 5.1. The approach involves the following methodological innovations:

- Translation of qualitative climate and socioeconomic narratives into plausible quantitative scenarios of future precipitation (flood-drought cycles) and water demand on health outcomes.
- The use of stakeholders and expert judgment to identify adaptation options and plausible APs.
- Exploration of the robustness of adaptation options and pathways against different performance metrics (assumption or ranking) criteria that were adopted by the expert team and adapted for all stakeholders and community members.

5.4.1 Stakeholder sampling

An iterative two-stage qualitative sampling strategy of stakeholders, at the local government and community levels, was taken. The key criteria for the selection of the project sites were purposive, based on the prevalence of climate-related diseases and climate extremes. An interview guide on ToC and pathway thinking (Appendices 2-6) provided a framework for discussions with KIIs and FGDs; the interview guide was aligned to the reconstructed ToC. The interview explored a range of issues relevant to CWH nexus adaptation planning. National and local government-level policy documents formed critical input material in the development of the ToC workshop guide material.

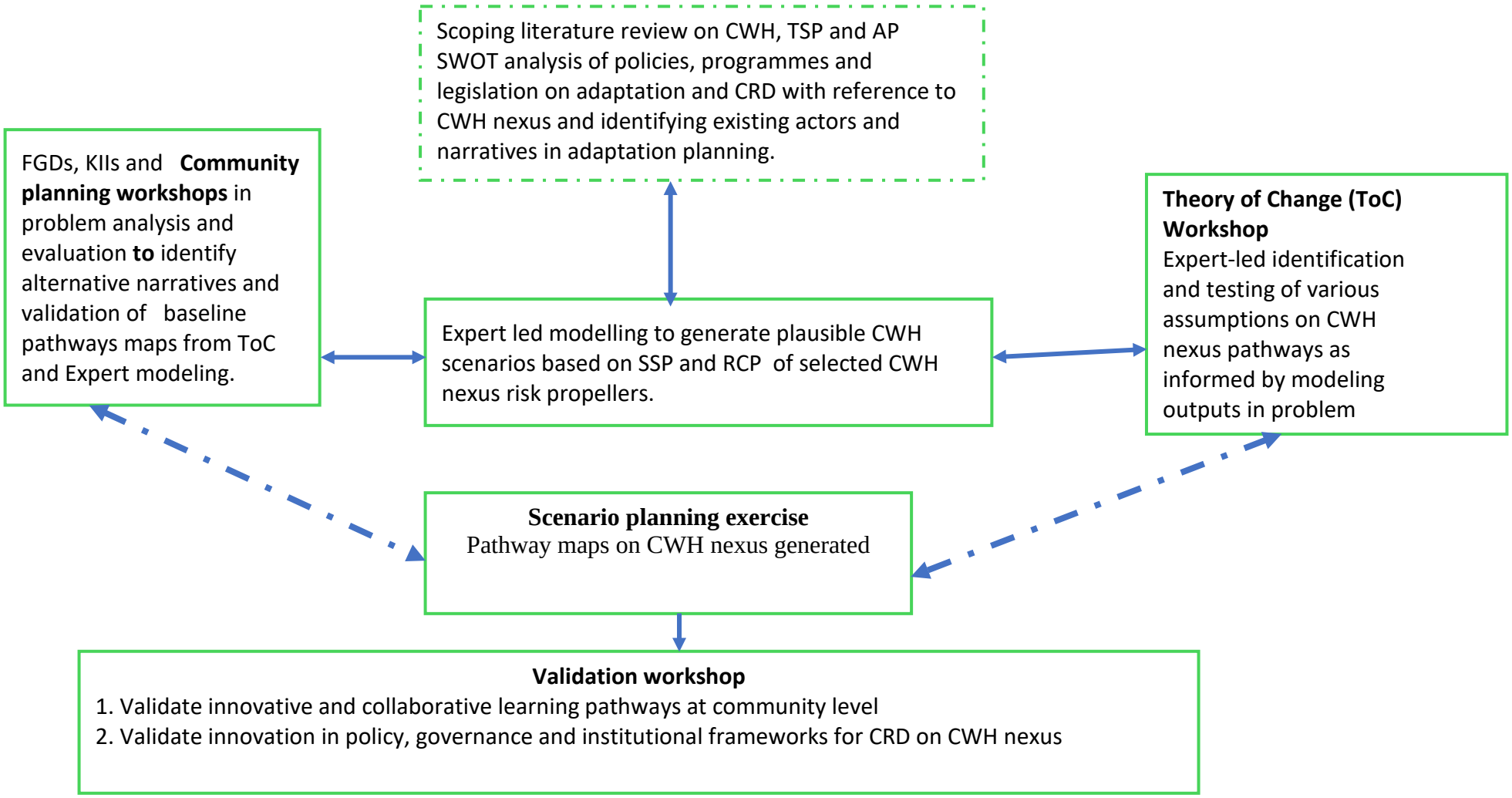


Figure 5.1: Summarised methodological approaches of the study. The broken line indicates that scenario planning is not a stand-alone phase but rather integral in the iterative processes during modelling, ToC, and community planning workshops

5.4.2 Participatory processes and workshops for development of adaptation pathways/maps

Achieving sustainability and resilience transformations under climate change requires transformative and multi-scale visions to stimulate coherent thinking and action towards radically alternative futures (Hölscher et al., 2022). Kowarsch et al. (2017) provided a strategic approach to responding to divergent viewpoints and systematic reflections on designing inclusive processes that foster more rational, open public discussion. Detailed procedures in scenario planning and analysis are given by Hölscher et al. (2022). Propositions regarding the preconditions for sustainable APs are presented by Wieners et al. (2020). This study combined scenario planning and APs principles (Appendices 1-3) to mainstream future uncertainty into decision-making, for community development (Butler et al., 2016). The study adapted this framework, informed by the realities and practicalities of the project team and field stakeholders. Reflective interventionist multi-actor approach (Wilkinson and Eidinow, 2008) was adapted to encourage the integration of community perceptions and assumptions, as well as to develop exploratory scenarios on CWH nexus challenges and the design of appropriate no-regret adaptation strategies. The general questions guiding the participatory planning workshops were:

- What are the drivers of vulnerabilities, based on identified focal health concerns?
- What is the desired socio-cultural, climatic, governance/institutional, economic (production systems) for addressing CWH challenges?
- What could be potential future changes in water (moisture) availability and its effect on health, under business as usual (BAU), pessimistic, and optimistic scenarios?
- Can the current CWH nexus practices be improved?
- What are the priority no-regret adaptation strategies and actions on CWH?
- Do current and planned development programs meet community expectations on CWH nexus challenges?
- Is there potential for improvement of the current and planned CWH development programs?

- **The ToC process and development of adaptation pathways**

The ToC (Figure 5.2) is an evidence- and experience-based process for pursuing a logical set of outcomes (Thornton et al., 2017; Campbell et al., 2018) as well as the development of context-specific approaches for convergence between practitioners, scientists and policy makers, through a coordinated set of efforts that address underlying development change. It describes a sequence of events that are expected to lead to a desired outcome. The ToC supports the development of a logical model (Figure 5.3) for monitoring, evaluating, adapting and communicating. The use of ToC can inform evidence-based policy design (unpack context-specific challenges and identify potential solution space), policy instrumentation, networking between state and non-state actors, and participatory assessment and planning (Reed et al., 2022). In the current study, the ToC process focused on no-regret adaptation considering CWH's flexible and robust pathways in water planning (drinking water, sanitation and hygiene). The logical framework analysis starts out from the idea that the actions of a project will produce changes that can be predicted, observed or measured to a certain extent, however, a development project aims to produce changes in a target situation beyond its direct control. A project cannot achieve all the changes it aims for directly, but must act as a catalyst for change. Such changes will contribute to improved conditions in the project target area (sequence of cause-and-effect relations known as, "project hypothesis"). These are described as 'if' and 'then' scenarios - that is, if the project takes certain actions, then this will set in motion a sequence of changes leading to the achievement of the development goal. In this study, the development objective was to advance CRD for the CWH nexus.

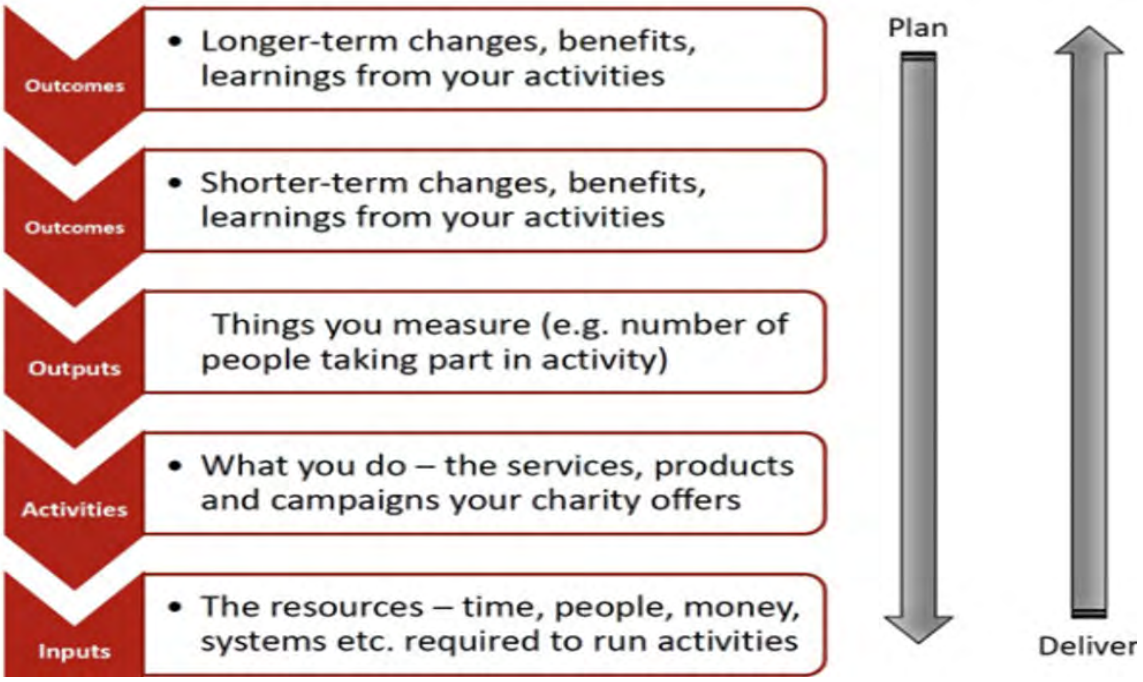


Figure 5.2: Components of the ToC

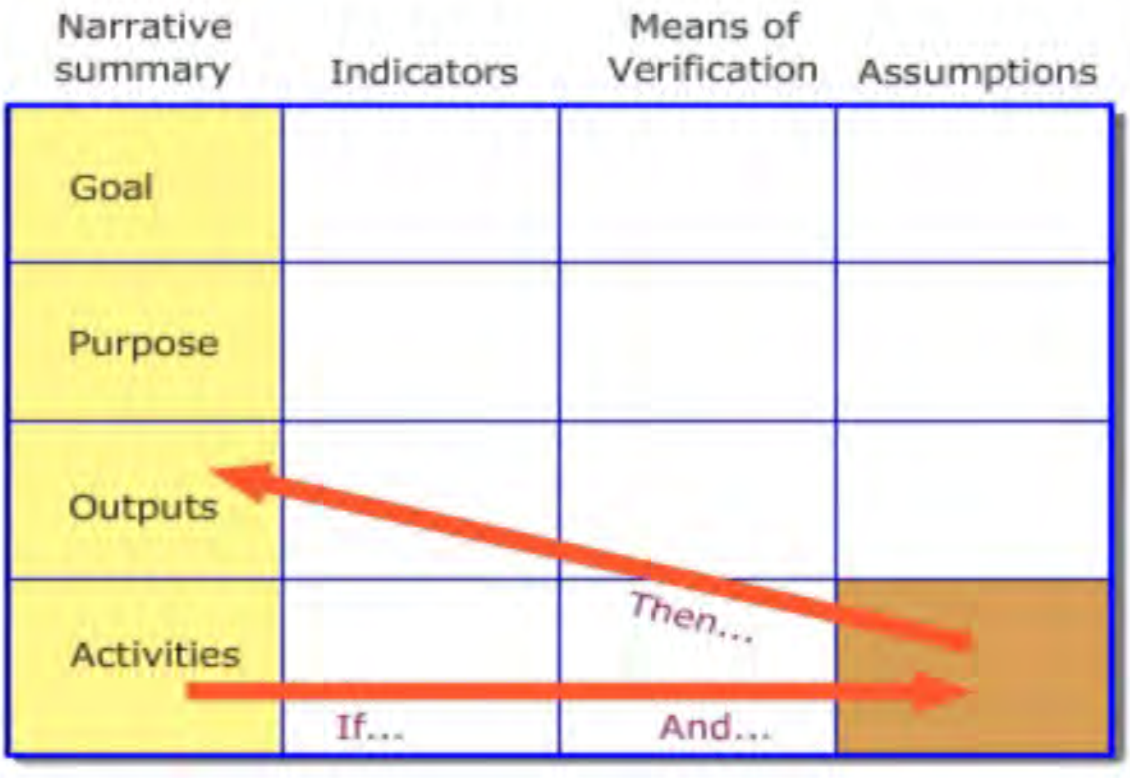


Figure 5.3: Generic logical framework

The ToC was used as a process of reflection to explore change and how it happens and what it means for society, with reference to the CWH nexus; the exercise was underpinned by beliefs, assumptions, and hypotheses about how change happens (social, organisational, political, institutional). Specifically, the ToC guide (Appendix 2), was used to:

- identify the change pathways (APs that are context-specific to selected villages in the VDM; and
- identify assumptions (scenarios informed by science and experience) through stakeholder deliberation and reflective thinking.

Data used in ToC process included climate change and vulnerability context, possible entry points for interventions (APs), main drivers of vulnerability, enabling environment for adaptive capacity and planning, partnerships, existing projects/plans/programmes and focal actors, and specific data related to the selected change areas. The team developed assumptions (what we need to do) to guide the achievement of transformative adaptation (Appendix 7) or more aggressive climate mitigation and adaptation strategies that prevent future Day-Zero droughts in dry areas and water sector planning in general. Such a transformative adaptation needs to:

- reduce socio-economic vulnerability and build capacity to address any adaptation deficit/challenges/constraints;
- address present and future disaster risk; and
- build long-term social ecological resilience.

Accordingly, the development of the pathways, focusing on the following aspects, was considered in formulating the assumptions:

- policy, governance systems and institutional (administrative) arrangements have the potential to enable adaptation in a fundamental way;
- alternative narratives can be used in framing the problem and identifying potential solutions to complex societal challenges, such as climate change;
- effectively addressing systemic risks undermines adaptation actions and policy efforts;

- alternative development priorities, preferences and pathways can address the social drivers' and processes' vulnerability;
- system approach can address the justice angle and address water appropriation, water tenure and power/water grabbing;
- synergy can be achieved between individual and collective action; and
- mitigating shifting vulnerabilities can be used as proxy for effectiveness.

- **Guiding principles for the ToC process**

The deliberations in the groups were based on the following guiding principles:

- Long term change: what the initiative seeks to support and for whose ultimate benefit (climate-resilient CWH). This was answered through the following questions:

  - ✓ What is the current situation (the key drivers of change: economic, cultural, technological, institutional and governance, climate and biophysical) at the community level?
  - ✓ What are the climatic changes in the community – temperature and rainfall?
  - ✓ How are the climatic changes impacting water and health, and associated scenarios - BAU and optimistic?
  - ✓ What have been the responses and challenges, if any?
  - ✓ What is the extent of effectiveness (social-technical and economic) for the existing and proposed adaptive measures? This is basically an adaptation of Strength, Weakness and Threat (SWOT) and Political, Economic, Social, Technological, Legal, and Environmental (PESTEL) models).
  - ✓ Are there better ways to current responses (adaptations) with reference to government, behavioural and informational, governance and institutional frameworks?
  - ✓ What is the desired situation?
  - ✓ How can we get where we aspire to be, in terms of hygiene and sanitation situation under a changing climate?

- ✓ What are the 3-5 development pathways that will enable the envisaged change?
- ✓ What are the 3-5 important relationships (cross-cutting issues) that exist between the identified change?
- ✓ What are the short, medium- and long-term measures for no regret adaptation, suggested by the actors and as informed by chosen assumptions?
- ✓ What are the likely best future practices (visions) and the underlying assumptions - based on good practice criteria such as efficiency, relevance, coherence, and sustainability dimensions?

o What are processes/sequences of change, and how are these anticipated to lead to the desired long-term outcome (CRD) based on the Logical framework?

- **Assumptions of the ToC process**

In this study, the question "*What are the underpinning assumptions on choices made?"* was explored. Specifically, the question explored how the envisaged changes in CRD around the CWH nexus might be realised, that is, which interventions in terms of activities and outputs are appropriate for influencing change in the desired direction. Assumptions (Appendix 7) were operationalised as hypothetical cause-effect links and explanation of world views, beliefs, rationales, analytical perspectives and evidence that inform analyses of the problem and outcomes, about a development issue being pursued (in this case, climate resilient CWH nexus). In effect, assumptions were considered as socio-economic factors that influence choices at personal, organisational, and analytical levels. This formed the basis for debate, enrichment, reflection and strengthening of logic among the 5 professional groups at the workshop. These were presented in the form of animations agreed upon *a priori* in the ToC and community workshops. ToC and community workshops' participants and narratives influenced the summary outcome of the animation (Appendix 8), as well as discussions based on Google Maps/ territory pathways/routes, and iceberg metaphors.

- **Development of adaptation pathways/maps**

Pathway approaches basically answer the questions - *"What could be or is an unfolding scenario in short, medium, and long term?"* and "*What should be?"*- or vision strategies and responses that address the risk propellers. Unlike the ubiquitous logframe tool in conventional project planning, which addresses only cause-and-effect and means-end relationships, pathway thinking tests the assumptions underlying the visions advanced by diverse actors (Omore et al., 2019). Specific analytical tools for data gathering, analysis and synthesis in pathway thinking, although diverse (Haasnoot et al., 2013), this study used theoretical thinking iceberg and Google map metaphor models (Figures 5.4 and 5.5, respectively) to unpack cognitive dissonances and convergencies. The iceberg model is a systems thinking tool that can help in understanding problems at a deeper level (root causes). The metaphor of an iceberg is used to illustrate the idea that there are hidden factors that contribute to an issue, in addition to what is immediately visible. In the context of climate change adaptation, an iceberg can be used to identify the root causes of climate change and its impacts, thereby informing policy decisions. The Google map illustration indicates that different adaptation pathways can be taken to reach the desired short or long term goals with respect to climate change adaptation and/or CRD.



Figure 5.4: Iceberg metaphor illustration



Figure 5.5: Google map metaphor illustration

The pathways concept was used to describe actions (Wise et al., 2014) as well as scenario trends, such as the Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways or RCPs (IPCC, 2019). Visions are ideal reference points in the future, and can be exploratory in nature; they are built on SSPs and RCPs combinations that provide the future socio-economic and climate contexts for achieving visions, and transition pathways are seen as progressive courses of action to respond to the scenarios and achieve the visions. In this study, the notion of vision was implemented by adopting the definition of vulnerability, as value judgement concerning anticipated future harm or undesirable state that undermine lives and livelihoods (that is, climate-related flooding and droughts impacts on livelihoods and mortality. The question here was - *"Given that the climate cannot be accurately predicted, what actions can be taken today to best prepare for the future?"*. This was gauged against assumptions in developing adaptation pathway maps based on RCPs 2.6, 4.5 and 8.5 scenarios multi-objective criteria (Table 5.1). In this study, the definition of vulnerability of communities to health risks-climate change nexus through water quality, sanitation and hygiene pathways, was adopted.

Table 5.1: Matrix for pathway planning and underlying assumptions

Pathway	Assumption
Baseline scenario (RCP 2.6)	Currently manifested in hygiene and sanitation outcomes (operationalised under poor economic growth and poor governance).
BAU at a future date (RCP 4.5)	No or sub-optimal action on baseline situation.
Best Scenario at a future date	Presence of no regret pathways for resilient CWH outcomes was represented as improving economic growth and good governance.
Intermediate scenario (RCP 8.5)	Best scenario under increasing drought or flood scenarios (risks and uncertainty).

- **The ToC workshops at the expert and community levels**

The adaptive thinking approach guided the participatory research processes and scenario planning exercises (Haasnoot et al., 2012; Haasnoot et al., 2013; Vervoort et al., 2014; Colloff et al., 2016; Kwakkel et al., 2016; Brown et al., 2020; Sadr et al., 2020). Backcasting, as one of the scenario planning tools that examined a suite of exploratory decision pathways (Remans et al., 2024), was adapted in this study. The backcasting approach is critical for identifying context-specific collective actions for adaptation and social learning, thereby advancing shared goals through multi-stakeholder discourses and aligning agreed perspectives on adaptation with the desired vision, thereby integrating uncertainty into planning (Rodina et al., 2024). Performance threshold-oriented approaches inform planning by providing alternative sequences of actions in response to projected future scenarios, and they broadly correlate with the outcome of meeting short and long-term adaptation needs (Sparkes et al., 2023); stakeholder approaches were preferred, given the data-scarce context of the study area.

Back-casting in community workshops was used within the impact chains approach, a mixed quantitative-qualitative methodology for assessing climate risks (Arabadzhyan et al., 2021). Impact chain approach strongly counts on the engagement of local stakeholders, communities, private entities, and public departments officials responsible for the policies, to identify the connections between climate drivers, for example, the increase of the average temperature and

related risks, highlighting the context and sector-specific determinants of vulnerability and adaptive capacity. According to Zebisch et al. (2021), the impact chain approach is an acceptable risk assessment when compared to the top-down approach with generic indicator schemes, as it sets the scene for a participatory identification of potential entry points, for the adaptation measures. There are methods and strategies to increase the dialogue between the scientific community and local knowledge and needs identified by communities and governments. The back-casting process was guided by four iterative questions:

1. What is the desirable future (envisioned best scenario) we propose for the community? or What are the critical elements of change to the current Business-as-Usual scenario?
2. What are potential innovations or solutions at individual, household, institutional and governance levels required to address BAU challenges and attain the Best Scenario?
3. What are the key steps (pathways) towards the identified vision, considering effectiveness or the assumptions underlying them?
4. What reflections and mapping of 3-5 pathways can be arrived at, based on the assumptions in 3 above?

One expert and 3 community level face-to-face ToC workshops were used to identify pathways and assumptions underlying them; each of the workshops was carried out as scheduled in Table 5.2. The selected villages were Tiyani and Ha-Ribungwani (located in Collins Chabane local municipality) and Dopeni Village (located in Thulamela local municipality) (Figure 5.6). Based on Kirchherr and Charles (2013), the participants' role and knowledge of CWH issues, lived experiences, and expertise were used in the stratification of participants during the workshops, with gender and age being the factors considered at the community level. In the workshops, the facilitator gave a presentation - introducing the study, climate extremes in South Africa's context on water and climate change, and required responses, introduction concepts, logical framework, ToC, Google map, and iceberg metaphors, and no regret adaptation. Participants in the community workshop also completed a questionnaire (Appendix 5).

Table 5.2: Schedule of participatory workshops and attendance

ToC workshop	Dates	Community	Number of FGDs	Number of participants
Expert level	07/10/2024 and 11/10/2024	Expert led	5	32
Community workshop 1	22/10/2024 and 28/10/2024	Tiyani	3	34
Community Workshop 2	23/10/2024 and 25/10/2024	Dopeni	3	49
Community workshop 3	29/10/2024 and 01/11/2024	Ha-Ribungwani	4	54

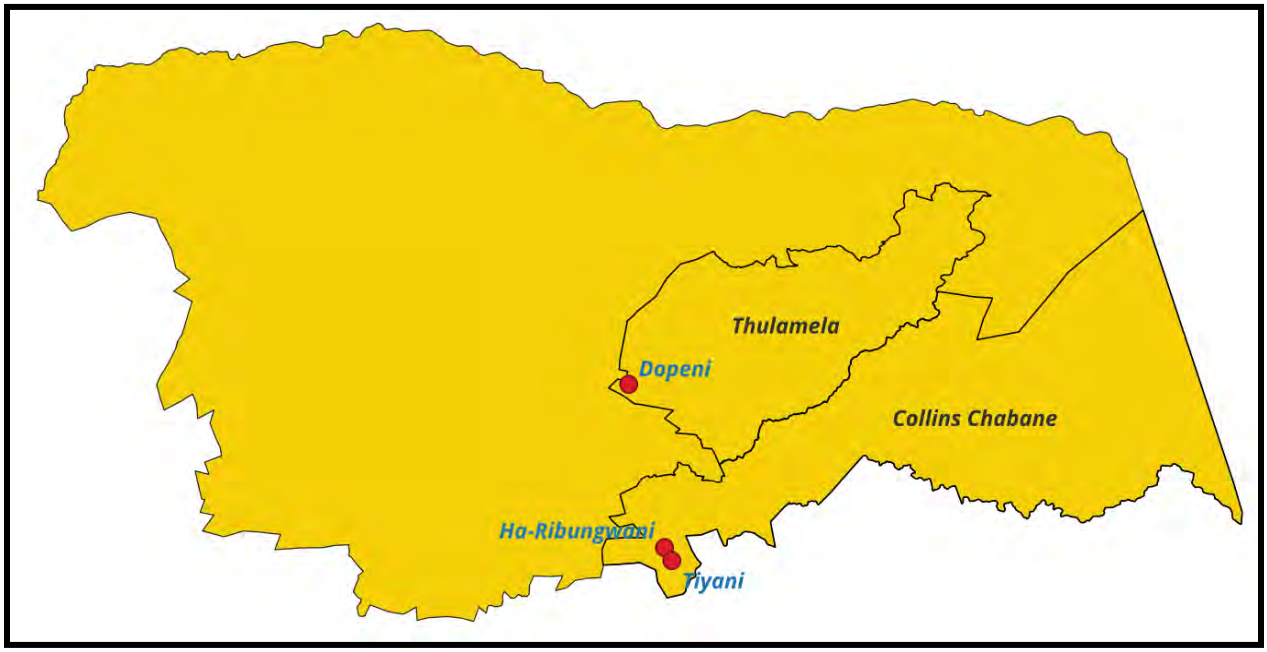


Figure 5.6: Location of the 3 villages where the community workshops were conducted

In pursuit of the study objectives, the expert led workshop was guided by narrative reviews of existing planning documents on climate-change impact (hygiene and sanitation) chain analysis, thus the water and health sector nexus. This elicited problems and solutions framing space, hence priority transformative adaptation options that address climate-change risks on water and its impact chain. The participants of the expert level workshops were divided into 5 sectoral groups based on professional areas of expertise (agriculture, health, water, academia, and policy makers/implementers). Policy makers/implementers constituted participants who are decision-

makers, within their areas of expertise at the local government. Figure 5.7 indicates the activities of the expert level ToC workshops.



Figure 5.7: Expert level ToC workshop

Triple learning loop (short term, alternative long term and development trajectories) and (BAU, pessimist and optimistic scenarios for 2030, 2050 and 2090) on climate-water-food-health impacts through expert and community perceptions) through brainstorming sessions was explored, after an initial context-specific sensitisation on climate impacts on water and health. In this way, communities and grouped-sectoral level experts identified systemic and long-term issues and related transformative strategies by subjecting them to a multi-criteria objective assumption-guided ranking exercise. The reflective approach of the multi-criteria objective analysis assessed and critiqued the pathways based on their assumptions. The identified no

regret strategies were, thus, sub-consciously ranked, thereby avoiding any preconceived bias among the participants. To allow for coherence, animations representing problematic areas on CWH developed during Toc workshops were presented to communities in the workshops on the climate change context and its chain impact on the CWH nexus, to allow for reflection. The communities had to choose context-specific animations through consensus. Appendix 6 indicates the community and ToC workshop evaluation and learning by participants. Figures 5.8 and 5.9 indicate the community level TSP processes.



FGD session Ribungwane community



Sensitization session on ToC findings and CWH at community level



FGD at Dopeni community



FGD at Tiyani Community

Figure 5.8: Community level TSP processes







FGD at Ribungwane on pathways narratives



FGD at Tiyani during brainstorming on APs

Figure 5.9: Community FGDs during TSP processes

- **Validation workshop**

A validation workshop was conducted on 18 September 2025 at the University of Venda to validate the findings of the participatory workshops (1 for the expert level and 3 for the communities of Tiyani, Ribungwane, and Dopeni). The workshop had 22 participants (Figures 5.10 and 5.11) who constituted 13 experts and 9 community representatives. It was aimed at presenting the synthesised findings from the participatory workshops and validating them. The expert participants included representatives of the Limpopo Department of Economic Development, Environment and Tourism (LEDET), VDM, Department of Water and Sanitation (DWS), Department of Health (DOH), academia (University of Venda and Vhembe Technical and

Vocational Education and Training (TVET). The representatives (including leaders from council and ward committees) of Tiyani, Ribungwani, and Dopeni also participated in the workshop. This assisted in achieving the aim of validating the findings of the multi-stakeholder planning process, in addition to providing feedback to representatives of community leaders.



Figure 5.10 : Overview photo of the participants



Figure 5.11: Validation workshop participants

5.5 Results and discussion

5.5.1 Respondents, context specific and intersectionality in adaptation planning for Day Zero scenario

Figures 5.12 (a and b) indicate the number of respondents of the questionnaire survey from each village and the gender of participants in the community workshops, respectively. Most participants were from Ha-Ribungwani Village, with the majority (42) being females. This indicates a good representation of females in the development of no regret adaptation strategies. In most rural areas, women bear the responsibility of securing water, food, and taking care of sick family members, hence are directly impacted by climate change. They, therefore have knowledge which can significantly contributed to the development of implementable strategies.

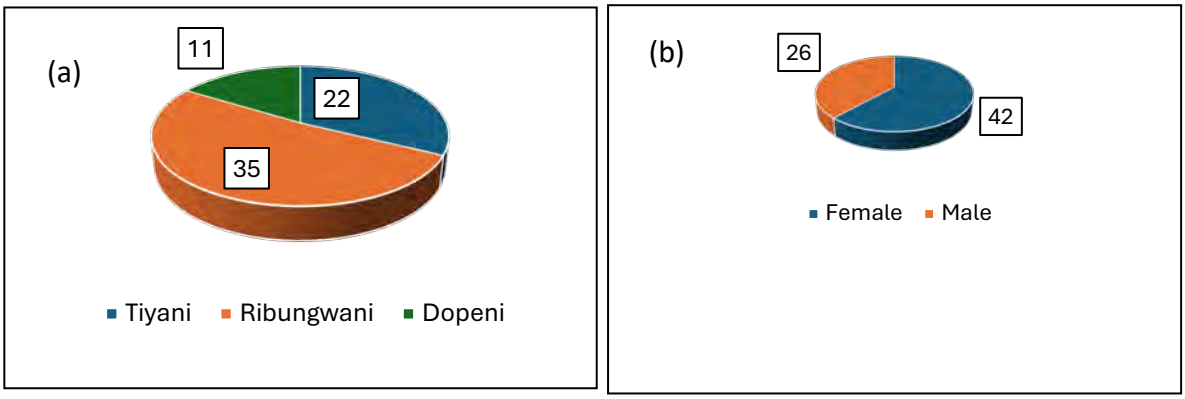


Figure 5.12: (a) Number of respondents from each village and (b) gender of participants

Most of the participants (95.6 to 98.5%) were mostly concerned about water quantity, water quality, health/disease, environment, and food for their children (Figure 5.13). This indicates a high concern for a planning horizon of 30 years. There was equal concern (95.6%) for health, environment, and food for self and grandchildren. The respondents were less concerned for their grandchildren on issues of water quantity, water quality, health/disease, environment and food with percentages of 88.2, 92.6, 94.1, and 95.6, respectively, as compared to the other planning horizons.

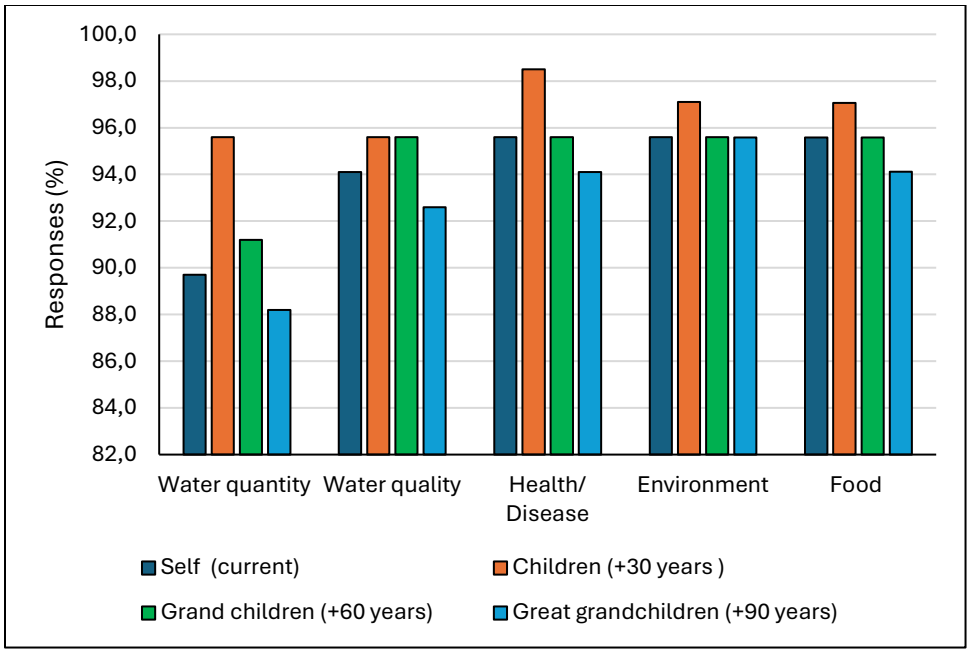


Figure 5.13: Concerns about water quantity, water quality, health/disease, environment and food, at different planning horizons

The majority of the respondents (about 48%) were neutral on the changes, suggesting a lack of knowledge on how to access water security dimensions (Figure 5.14). The respondents were also mostly neutral on changes in water colour, water taste, food borne diseases, skin diseases and dental discoloration. This was followed by very high responses on undesirable state which remained the same for water security, water quantity, water colour, water taste, food-borne diseases, skin diseases and dental discoloration. Appendix 9 indicates the details of the observed changes in components of CWH at household level.

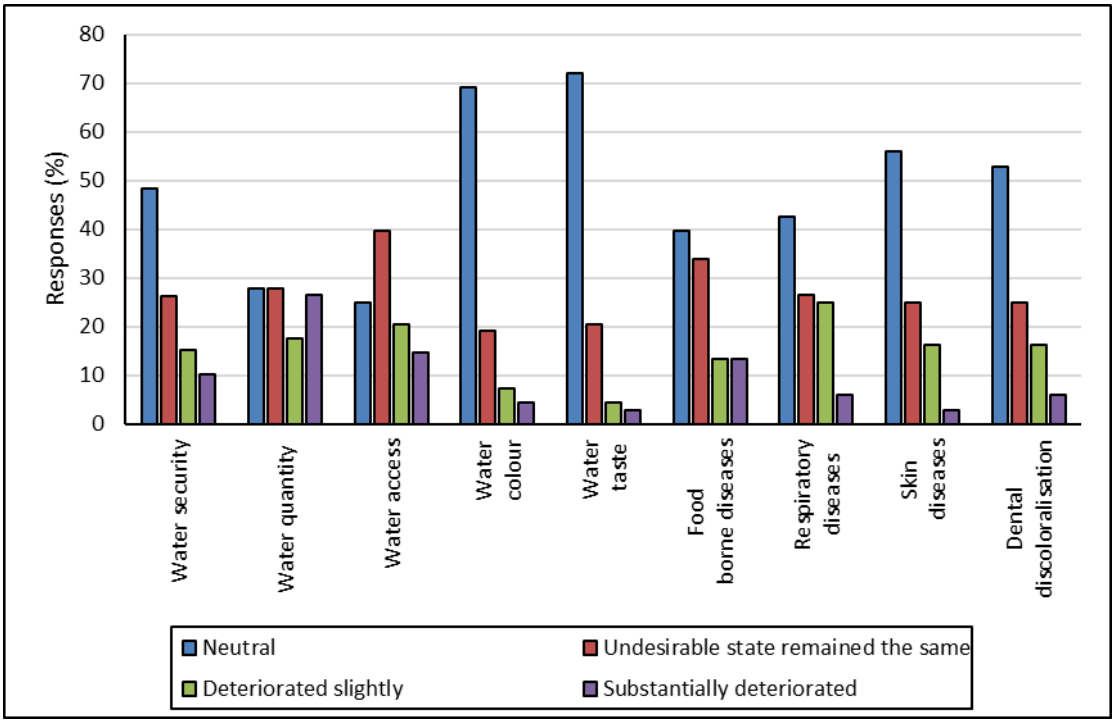
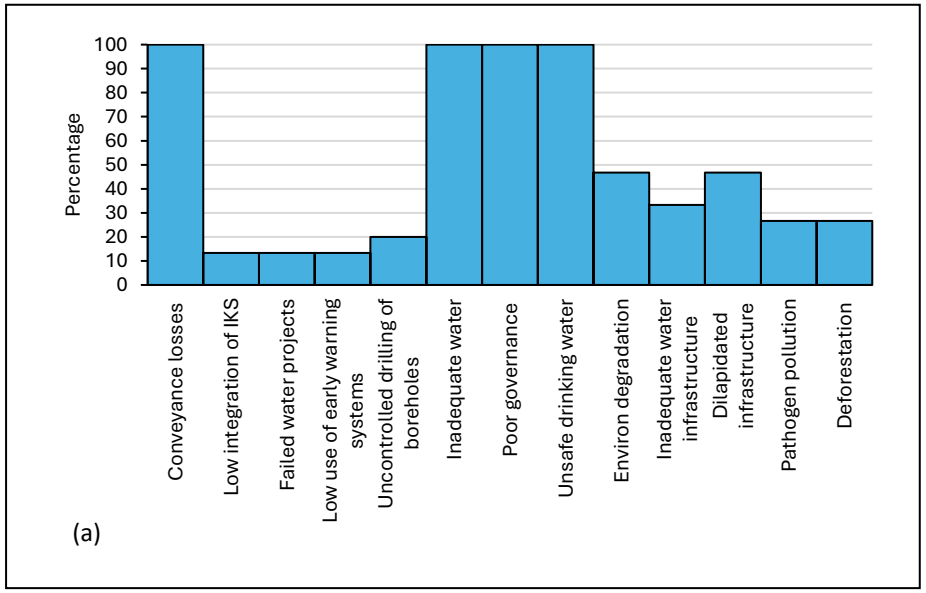
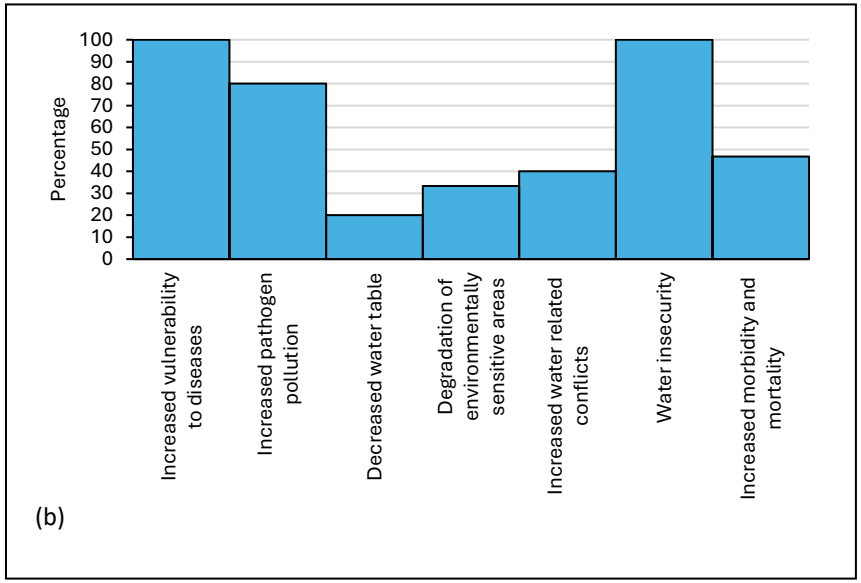


Figure 5. 14: Perceptions on changes in water security, water colour, water taste, food-borne diseases, skin diseases and dental discoloration

5.5.2 Scenario analysis on CWH nexus, existing and suggested adaptation measures

Figure 5.15 (a) to (c) presents the baseline, BAU and suggested pathways to best scenarios' contexts on CWH, at household level, from the questionnaire survey. There was unanimous agreement by the respondents across various communities, that conveyance losses, inadequate water access, poor governance, and unsafe drinking water are issues affecting water situation at household level (Figure 5.15 (a). Dilapidated infrastructure and environmental degradation were also cited by about 46.7 % of the respondents. Other challenges included uncontrolled drilling of boreholes at 20% and low use of IKS and failed projects at 13.3%.





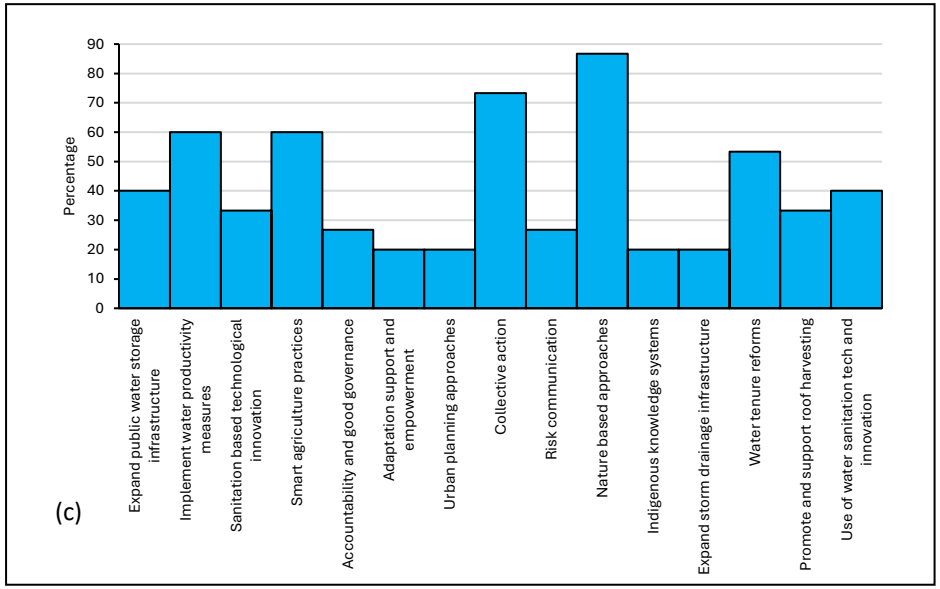


Figure 5.15: (a) Baseline, (b) BAU, and (c) best scenarios contexts on CWH at the household level

All the FGDs unanimously agreed that increased vulnerability to waterborne diseases and water insecurity can be expected if the current water situation is not addressed, under changing climate risks and uncertainty (Figure 5.15 (b)). This is followed by increased pathogen pollution at 80%, increased morbidity and mortality from waterborne diseases at 46.7%, and increased water-related conflicts at the household and community level. A 20% decrease in the water table is the least projected BAU scenario if transformative planning approaches are not adopted.

Flexibility is a critical metric in no regret adaptation and fundamentally involves imagining the policy over a series of decision points distributed throughout the future, rather than constraining the decision-making process and the design of the policy to the present (Hallegatte, 2009). Figure 5.15(c) provides the suggested best scenario, which constitutes flexible pathways under changing climate risks and uncertainties. Nature based approaches and collective action at 86.7 and 73.3%, respectively, emerged as the best scenarios suggested by communities and experts. Smart agriculture and water productivity at 60%, water tenure reforms at about 53.3%, water sanitation technologies at about 40% were the other pathways identified by FGDs. IKS and urban planning were mentioned by 20 %, expanding water infrastructure by 40% and risk communication, accountability and good governance at 26.7%. Most of the suggested pathways point towards the need for deep transformation. The identified pathways provide opportunities to address current infrastructure (technological) focused lock-ins, and their implementation can support a no regret adaptation, for Day-Zero scenarios.

Figures 5.16 to 5.18 indicate visual display/animations of baseline, BAU and best scenarios contexts on CWH, developed by the FGDs. The expert level and community FGDs indicated current bad conditions, BAU and intermediate scenarios, which are expected to become worse. Challenges that will be faced include increased temperature, drought, water conflicts, unsafe drinking water, disease burden, deforestation under BAU and intermediate scenarios. However, improved conditions are envisaged under the best scenario, which will involve implementation of no regret adaptation strategies. These strategies include nature based solutions, social

mobilisation, advocacy and behavioural change, transparency and accountability as well as water conservation.

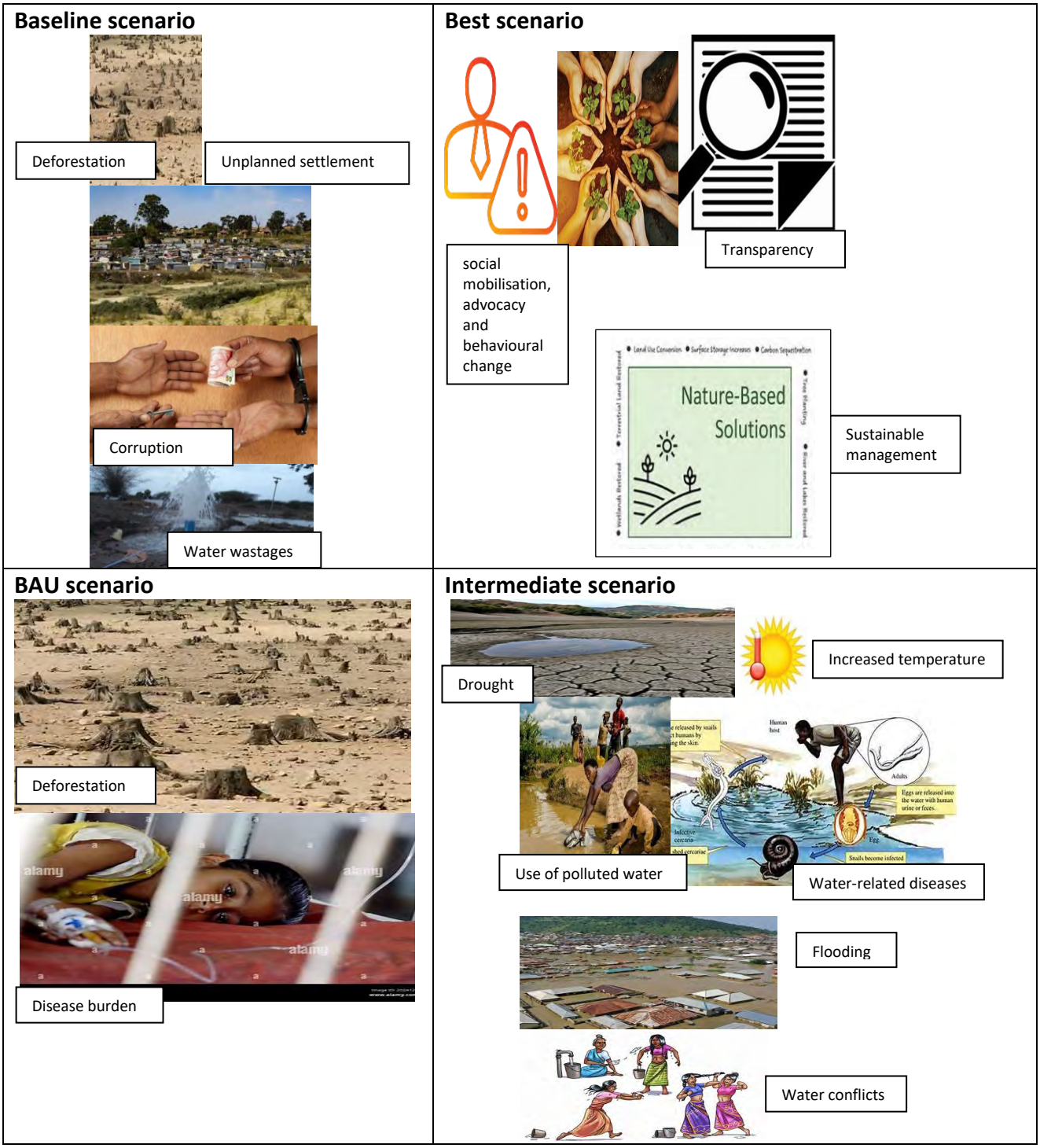


Figure 5.16: Visual display of baseline, BAU and best scenarios by expert level FGDs

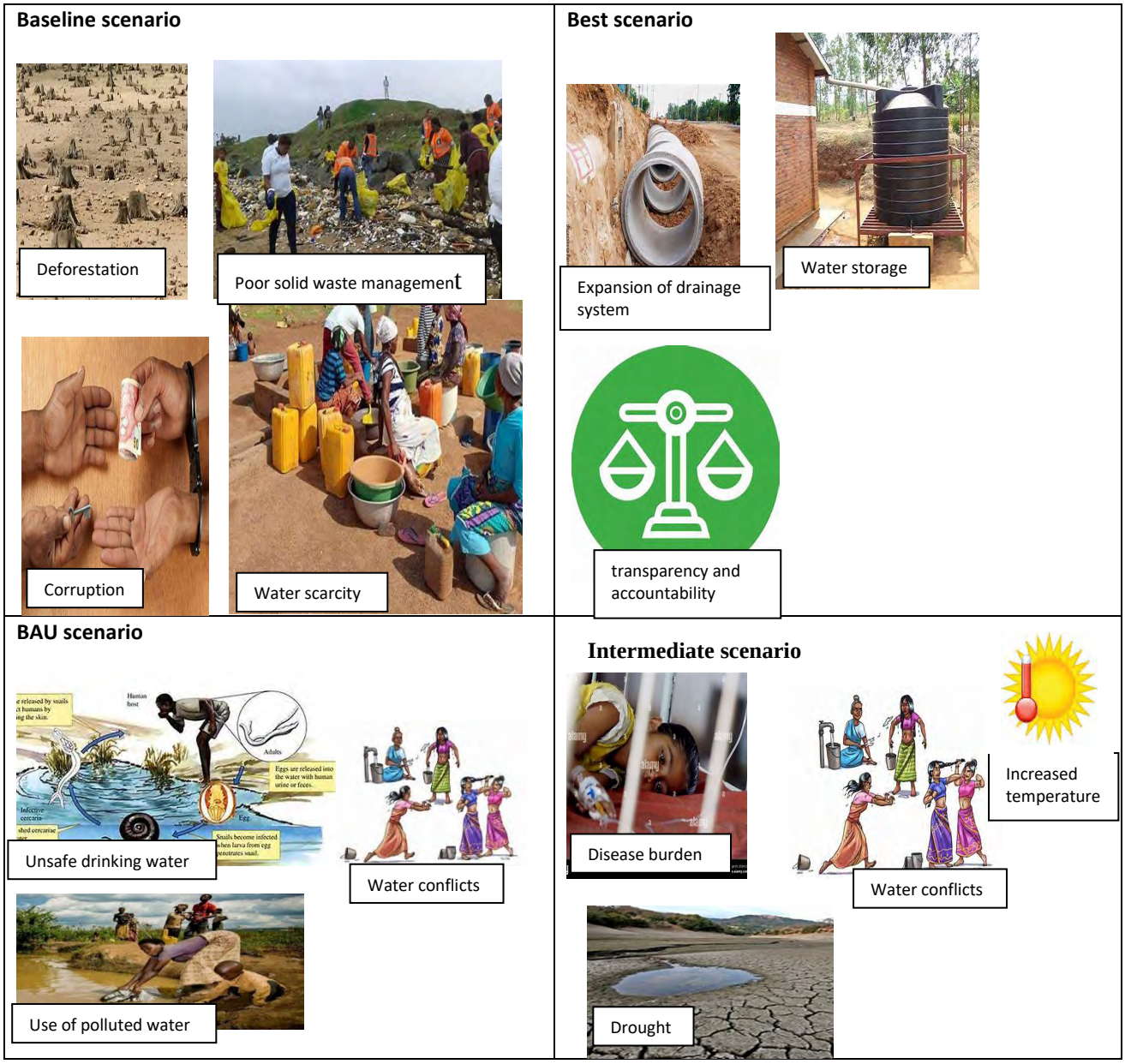


Figure 5. 17: Visual display of baseline, BAU and best scenarios by Tiyani community FGDs

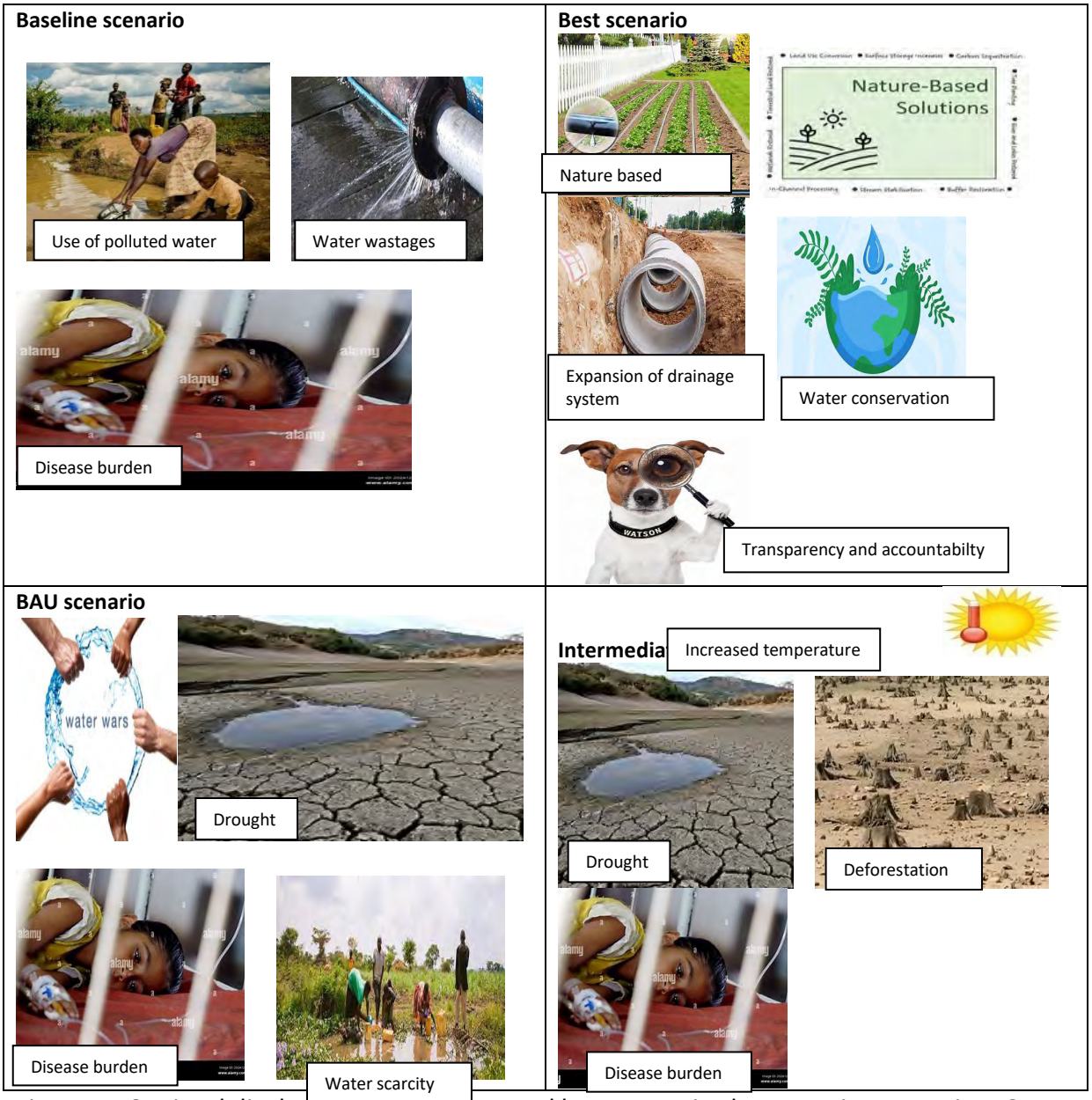


Figure 5.18: Visual display of baseline, BAU and best scenarios by Dopeni community FGDs

Figure 5.19 indicates the currently used pathways at household level. At 14.6 and 15.3%, respectively, smart agriculture and nature based services are the widely used approaches to climate change adaptation. Smart water technologies follow at 13.2% while indigenous knowledge is the least utilised, as indicated by 7.3% of the respondents.

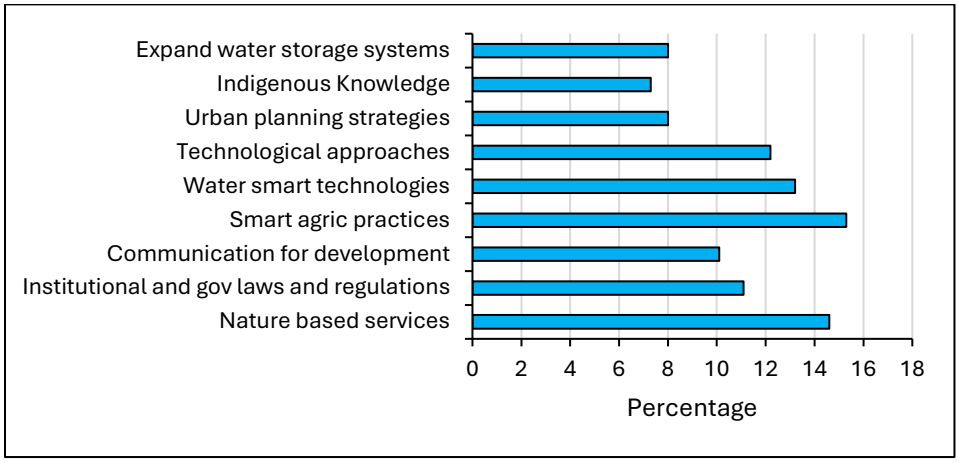


Figure 5.19: Currently used adaptation strategies

Figure 5.20 provides suggested future adaptation pathways from the sampled households. Water and sanitation innovations, as well as smart water technologies at 61.5 and 59.6 %, respectively, were the most preferred adaptation strategies. Climate services and risk messages were preferred by about 53.8%, with urban planning, indigenous knowledge, and institutional and governance reforms preferred by 48.1%. Smart agriculture was preferred by 51.9% of the respondents. The least preferred strategy was communication for development/advocacy as indicated by 30.8%.

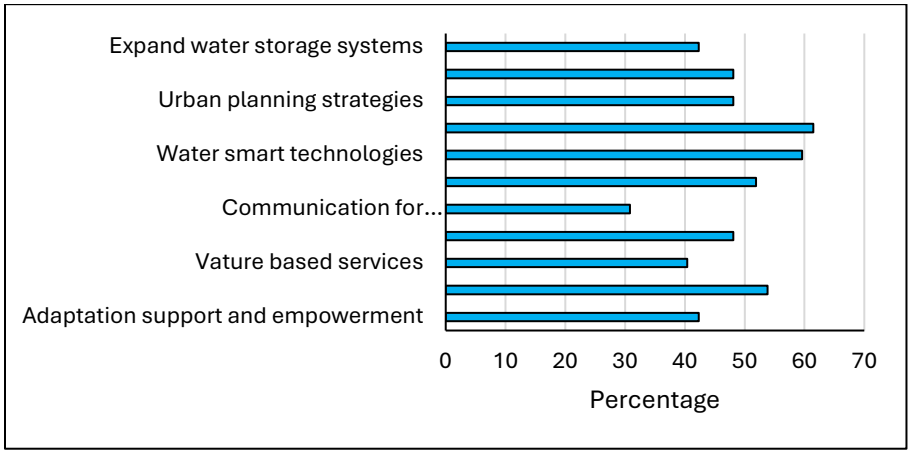


Figure 5.20: Suggested future adaptation strategies

5.5.3 Uncertainty and risks on CWH due to the intermediate (RCP 8.5) scenario

At 64.3%, increased vulnerability to food and nutrition risks emerged as a major uncertainty that needs to be considered while planning for Day Zero water scenarios (Table 5.3). This is closely followed by limited knowledge on impacts of climate change on vulnerability to water-related conflicts, morbidity and mortality from water-borne diseases, hospitalisation as well as pathogen pollution at 57.1%. Urban effect uncertainties at about 29% and displacement of people at 21% were also mentioned by FGDs. Deep uncertainty describes dynamic conditions where there is limited knowledge and agreement on the use of models, description of parameters in those models, and what impacts are to be considered (Kwakkel et al., 2016; Lempert et al., 2003). In the current study, it is posited that decision-makers are likely to encounter deep uncertainty when assessing the vulnerability of a community to changing climate patterns, that may be experienced decades from now, through water development, land use planning, as well as urbanisation patterns.

Table 5.3: Uncertainty and risks to Best Scenarios on CWH

Future uncertainty scenarios	Percentage
Increased water conflicts	57.1
Increased morbidity and mortality from water-borne diseases	57.1
Increased hospital admissions	57.1
Increased pathogen pollution	57.1
Increased displacement of people	21.4
Increased hunger and malnutrition	64.3
Increased urban heat effect	28.6

5.5.4 TSP tool evaluation

Respondents mostly agreed (32.4 to 47.4%) and strongly agreed (33.2 to 50.2%) that TSP positively impacts trust, degree of empowerment, networking, knowledge, policy, and decision-making within the CWH nexus (Figure 5.21). Appendix 10 provides detailed descriptions of the trust, degree of empowerment, networking, knowledge, policy, and decision-making dimensions of the CWH nexus. The knowledge dimensions include taught knowledge of climate impacts on

hygiene, sanitation, water quantity, the hygiene-sanitation nexus, water quality, diseases, agriculture, food, and better health. The empowerment dimensions are individuals' influence on adaptation planning, due to - actors shared interests, TSP transparency, belief that their voice can be heard in the future, actors complementing each other, influence planning to meet needs, empowered to understand individual and communal responsibilities, empowerment for collective action, and to perceive current and future conditions. The level of trust for actors in adaptation planning, the degree to which they feel that free expression of opinions prevailed, the degree to which they feel the interaction is mutual, and the degree to which they feel the research team respected their opinions, are trust dimensions. The network dimensions include the likelihood of seeking collaboration on CWH, the extent to which new contacts have been made and the likelihood of better collaboration. Appreciating the TSP tool as a better tool in adaptation planning in the community, the degree to which exchanged information will positively influence CWH adaptation, hygiene, sanitation, and water use practices is a policy and decision-making dimension.

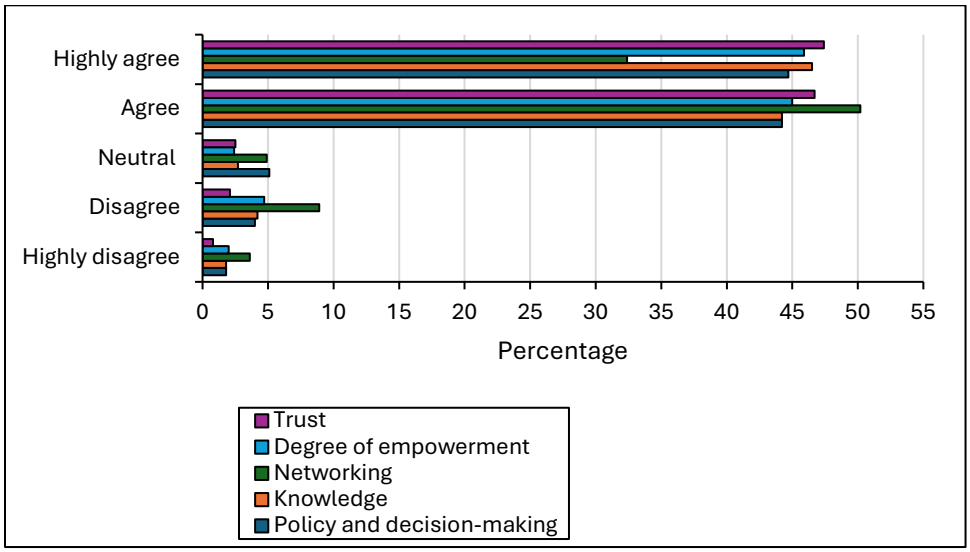


Figure 5.21: Impact of TSP on trust, degree of empowerment, networking, knowledge, policy and decision-making, within the CWH nexus

Table 5.4 provides a test of the hypothesis (independent-samples according to the Kruskal-Wallis test) on effect of context-specific perception of TSP on various aspects of decision-making and transformation. The results indicate that the distribution of empowerment and decision-making

varies across communities, whereas the distribution of knowledge, network, and trust is the same. From the analysis, it is apparent that decision-making and empowerment are context-specific, hence, they should inform transformative planning, while the distribution of knowledge, networks and trust is not context-specific and can therefore be adapted to context. The findings agree with Totin et al. (2021), who indicated that adaptation pathways are context-specific and grounded in local institutions as well as historical, socio-economic, cultural, institutional and political contexts (Arkema et al., 2017; Islam et al., 2014).

Table 5.4: Influence of context on TSP outcomes

Null hypothesis	Significance	Decision
The distribution of decision-making is the same across communities	<0.001	Reject the null hypothesis
The distribution of empowerment is the same across communities	0.028	Reject the null hypothesis
The distribution of knowledge is the same across communities	0.673	Retain the null hypothesis
The distribution of network is the same across communities	0.177	Retain the null hypothesis
The distribution of trust is the same across communities	0.654	Retain the null hypothesis

5.5.5 Results from the validation workshop

The workshop started with a presentation that focused on CWH priority concerns identified by participants across different planning horizons, scenarios (baseline, business as usual (BAU), and best), and contexts at the household level, as well as the currently used and suggested future adaptation strategies. Figures 4.10 and 4.11 show participants of the validation workshop. Participants validated and endorsed the key findings from the participatory workshops, confirming their accuracy and relevance. It was further established that water quantity, water quality, health and diseases, the environment, and food security remain priority concerns for communities in VDM. There was also a strong agreement that adaptation strategies should be tailored to specific planning horizons (short, medium, and long-term) to ensure their effectiveness and sustainability.

Table 4.10: Remarks from the validation process and discussions

Institution	Remarks
LEDET	• The findings reflect on the realities of climate change impacts on water security, water quality, rainfall, and increased temperatures, which affect health and livelihoods. Poor waste management is also a big concern. Illegal dumping in many areas is polluting rivers, and some community members highlighted how sand mining is becoming a major threat to local water sources. These activities are not only damaging the environment but also making clean, safe water harder to access. The scenarios and adaptation strategies discussed in the presentation capture these issues well and offer a helpful direction for future planning. • There are growing concerns about water security, health, and nutrition under baseline and business-as-usual conditions. With sustainable practices, improved infrastructure, and stronger accountability, communities can move toward healthier and more resilient futures. This emphasises the need for urgent and coordinated action to bridge the gap between current risks and the best-case outcomes desired. Adaptation strategies provide an opportunity to integrate community engagement to strengthen collaboration to reduce the impacts of climate change and build a healthier, more sustainable future for all. It might be valuable to set short-term milestones to track progress more effectively.
VDM	• There is a need to implement interventions to minimise the expected detrimental effects on human beings; enforcement of regulations at the local level is also required. • The current generation has abandoned indigenous knowledge systems; for example, the protection of water sources (springs) by traditional leaders. Leadership needs to work together with communities to assist in implementing strategies, thereby minimising climate change impacts • Climate risk messages are also crucial to alert communities. • Increased trading in firewood and clearing of land for orchards in Thohoyandou and the surrounding area, which are signs of deforestation; there is a need to look at the benefits of such activities, as many may lead to detrimental impacts in the near future.
Academia	• The group support the findings. There is a need to manage the environment to avoid further impacts on humans. There is also a need to act immediately and work with communities, as they are the beneficiaries. The study is interesting because it involves community members who have also contributed to developing the solutions. • Community leadership should facilitate the implementation of indigenous knowledge systems. • Vhembe TVET has already adopted some of the mentioned strategies, for example, water smart technologies, smart technology in agriculture, and the use of greenhouses. The college offers training programs for farmers on implementing smart water technologies. • Identified pollution will further cause diseases, such as malaria and food-borne diseases. • Communities should avoid water wastage and conserve natural resources. • There was emphasis on nature-based services and indigenous knowledge systems. It was noted that indigenous plants require less water and are adaptable to the harsh (semi-arid) environment. Indigenous livestock are also adaptable to the environment and may thrive during dry periods; thus, adopting indigenous agricultural practices may lessen the impacts of climate change in communities. • Indigenous knowledge can be implemented in line with the “ubuntu” principles. Considering that resources are for all and should be utilised sustainably for wetland restoration and conservation. • The University of Venda and the government need to liaise with Thohoyandou SAWS on how to disseminate climate risk messages to communities. • Youth may also be encouraged to explore technologies (drones) for monitoring crops and livestock. • Another way of using technology is using social media to create awareness and messages on water restrictions and water conservation.
DWS	• If communities do not protect the environment, climate change impacts will be exacerbated, with dire consequences on water resources and human health. • Since communities have noted water wastage and shortages, smart water technologies may assist in reducing water shortages. • Communities need to explore the use of alternative water sources, such as rainwater harvesting.
DOH	• Communities are already experiencing climate change impacts. DOH has developed initiatives to combat food security and improve livelihoods, human health, and fight diseases. They had farm resilience and greenery projects for rural communities, promoting household gardens. There was low uptake due to following a top-down approach; therefore there is a need to bring such projects down to the community level. • Re-establishment of school gardens to encourage school children to get involved in agriculture at an early age, is also essential.

Institution	Remarks
Dopeni	• The community appreciates that the research has generated findings that can be beneficial to them. They are motivated and emphasized the need to go back to indigenous knowledge systems as well as passing down the knowledge to younger generations. • They are expecting assistance with the implementation of intervention strategies. For example, they have several boreholes for which they need support in implementing self-supply schemes to combat water shortages. • Some wetlands need to be protected to avoid further impacts on livelihoods.
Tiyani	• Climate change is a primary concern in Tiyani. Leadership is facing challenges in managing water resources for the 6 communities under Tiyani. • They appreciated being involved in a project of this nature, wherein their contributions were considered. They noted the importance of planting trees to protect the environment. • They have had to implement a self-supply borehole scheme to minimize water supply challenges, since the municipality was unable to provide water. They require assistance for continuous maintenance of the system. • They also identified sand mining as one of the challenges affecting water resources, hence, there is a need to enforce bylaws to combat this.
Ribungwane	• They view the study as a good strategy for solving societal problems at Ribungwane. Water availability is one of their big challenges, so, the study may assist in solving their water challenges. The community is already experiencing the impacts of climate change. The study has derived strategies that may drive community change and minimize the impacts. • Illegal dumping requires restrictions, issuing of fines, and the identification of areas dedicated to dumping.

5.6 Summarised main findings from TSP tool in participatory planning

- Cognitive dissonance by profession (within and between) and within and between planning and implementation contexts
- Assumptions/scoring unpacks deep-seated professional and community biases that are context specific that enable planners to unpack robust adaptation pathways
- TSP tools have potential to support cross-sectoral collaboration and social-technical innovation. It is thus an empowerment tool that builds capacity, assists in making effective choices, envisions alternatives and participates in decision making, negotiate with influence, control and hold accountable institutions that affect lives and livelihoods
- ToC and TSP are complementary
- Water-related issues and adaptation go beyond water sector-specific lenses on demand and supply.
- Co-developing socially robust solutions for sustainable futures on CWH, is a necessity for future learning, co-creation of knowledge and collaborative action. Such multidisciplinary processes could be critical in exploring synergies, developing compromises for difficult conflicts of interest and facilitating good dialogue within the nexus adaptation framework and ultimately a constructive-oriented dialogue. Such an approach has the potential for co-

creation of knowledge and establishment of joint understanding and consensus building on complex transformative nexus adaptation (Norstrom et al., 2020), such as the CWH nexus.

- The co-developed pathways are considered socially robust solutions for sustainable futures on CWH, a necessity for future learning, co-creation of knowledge, and collaborative action.
- Debate on assumptions, such as socio-economic factors that influence choices at personal, organisational, and analytical levels, formed a consensus among the 5 professional groups at the workshop; in addition, the community provided a common ground for debate, enrichment, reflection and strengthening, hence transformation. The use of animations, agreed upon a priori during the ToC and community workshop, served as the basis for convergence on conflicting perceptions. ToC and community workshops' participants and narratives produced discussions based on Google maps/territory pathways/routes and iceberg metaphors.

5.7 Summary

In this chapter, it was posited that decision-makers are likely to encounter deep uncertainty when assessing a community's vulnerability to changing climate patterns that may be experienced decades from now. The vulnerability will also arise from interlinked water development, land-use planning, and urbanisation patterns that impact water demand and supply dynamics in a changing climate over several decades. The nexus framework is essentially a polycentric governance approach, which is recommended as an appropriate analytical lens for overcoming silo planning's drawbacks. Effective participation is inherently integral to governance and transformative imperatives.

These observations are largely informed by the justice lens in which inclusion of voices, knowledge, and experiences of marginalised communities is necessary for enhancing the relevance of development and adaptation initiatives, operationalising resilience concepts, as well as addressing cognitive failure among actors in the adaptation space due to professional under-development, lack of knowledge and experiences.The TSP tools used in this study have largely overcome these shortcomings. Accordingly, multidisciplinary participatory processes are critical in exploring synergies, developing compromises, resolving conflicts of interest and facilitating productive dialogue within the C-W-H nexus adaptation framework. Such an approach has the potential for co-creation of knowledge and establishment of coherent understanding and consensus building for complex, transformative nexus adaptation needs, such as in the CWH nexus. The TSP tool used here, has several strengths, hence, it contributes to transformative adaptation planning that consider citizen science for no regret water planning scenarios and more aggressive climate mitigation and adaptation strategies that mitigate adverse health impacts associated with future “Day Zero” droughts in dryland ecosystems and South Africa in general. It is, thus worthwhile for transformative planning, especially in pursuit of Climate Resilient Development objectives that are inclusive of expert and lay knowledge frames. TSP tools is appropriate for

- Identification of historical and future planning biases;
- Providing an entry point for CRD water sector planning; and
- Integrating nexus mainstreaming into policy and institutional design.

The TSP tool is resource intensive (finances, time and human resources), however, it can inform the transformation of institutional and governance systems for no regret adaptation options in water under changing climate, with a view to enhancing the adaptive capacity of the target social systems, as well as ensuring sustainability of adaptation initiatives.

CHAPTER 6: MODELLING OF THE CWH NEXUS

6.1 Introduction

This chapter focuses on modelling CWH nexus-related diseases at the local level using secondary data. The literature in this chapter focuses on understanding the CWH nexus and South African case studies on the impacts of climate change on human health. The results focus on machine learning modelling and future projections of climate-sensitive infectious diseases in the VDM.

6.2 Understanding the CWH nexus

Climate change has remained a significant threat to global health and well-being, with South Africa no exception (Romanello et al., 2023). As the threat of climate change increases, its multifaceted impacts on natural resources, particularly water, and on public health demand urgent attention. Climate change exerts pressure on water resources, worsening existing water challenges and increasing populations' vulnerability to a range of health impacts. Climate change alters the hydrological cycle, affecting water availability and quality, which, in turn, impacts human health (Bates et al., 2008). Changes in precipitation patterns, rising sea levels, and increased frequency of extreme weather events (floods, droughts, heatwaves) directly impact water availability, quality, and access. These changes, in turn, have profound consequences for human health, including increased incidence of water-borne and vector-borne diseases, malnutrition, respiratory illnesses, and heat-related mortality (WHO, 2021). Furthermore, the impacts are not uniformly distributed, with marginalised communities and developing nations often bearing the brunt of these cascading effects (IPCC, 2022).

Vulnerable and low-income communities are extremely affected, as revealed by growing evidence of low resilience and inadequate capacity for adaptation (Wright et al., 2021). Climate change overtakes negative socio-economic situations, which relate to factors including poverty, malnutrition, limited access to medical facilities, and other stressors such as human

immunodeficiency virus/acquired immunodeficiency syndrome (HIV/AIDS), natural disasters, the privatisation of resources, and geopolitical conflicts. As global heating exceeds 1.5°C, South Africa experiences changes in climatic conditions, including higher ambient temperatures, more hot days, stronger heat waves, heavy rainfall, flooding, drought, air pollution, and dust storms (USAID, 2022). These have triggered profound alterations in environmental and human health conditions. This chapter report aims to model the relationship between climate change and health, with a focus on selected climate sensitive diseases.

The interconnections between climate change, water resources, and health form what is known as the "CWH nexus. The CWH recognises the interconnectedness of these three critical domains and emphasises the need for integrated approaches to address these multiple complex challenges. The CWH nexus is a crucial focus area for no-regret adaptation pathways. The interconnectedness of these three elements highlights the need for a holistic and integrated approach to adaptation. In light of these interconnected challenges, it is essential to develop no-regret adaptation pathways that address the climate change-water-health nexus. These pathways must be sustainable, inclusive, and adaptable to uncertain future scenarios. The components of the CWH nexus are defined as follows:

Climate (C): This component encompasses the long-term changes in temperature, precipitation, humidity, wind, and other meteorological factors. It includes both gradual changes, such as rising global temperatures, and extreme weather events, which are becoming more frequent and intense, due to climate change (IPCC, 2021). Relevant indicators include average temperature, precipitation, frequency and intensity of heatwaves, droughts, and floods.

Water (W): This component encompasses both the quantity and quality of water resources. Quantity refers to the availability of water for various uses, including drinking, sanitation, agriculture, and industry. Quality refers to the physical, chemical, and biological characteristics of water, which determine its suitability for different purposes. Relevant indicators include water

availability per capita, groundwater levels, surface water quality, and contamination levels (WWAP, 2019).

Health (H): This component encompasses the physical, mental, and social well-being of individuals and communities. Climate and water-related health impacts can be direct, such as heatstroke or waterborne diseases, or indirect, such as malnutrition resulting from drought-induced crop failures or mental health issues stemming from displacement due to floods. Relevant indicators include morbidity and mortality rates for water-borne diseases, malnutrition prevalence, heat-related illnesses, and mental health indicators (WHO, 2022).

- **Climate change as the driving force**

Climate change, primarily driven by anthropogenic greenhouse gas emissions, acts as the principal driver within the CWH nexus. The Intergovernmental Panel on Climate Change (IPCC) has unequivocally established the link between human activities and observed warming trends (IPCC, 2021). These changes manifest in various ways, including rising temperatures, altered precipitation patterns, increased frequency and intensity of extreme weather events (floods, droughts and heatwaves), and sea-level rise (IPCC, 2022). These climatic shifts exert significant pressure on water resources, thereby impacting human health.

- **Water resources: the connecting element**

Water resources serve as the central connecting element within the CWH nexus. Climate change significantly impacts both the quantity and quality of available water resources. Changes in precipitation patterns can lead to increased water scarcity in some regions and exacerbate flood risks in others (Bates et al., 2008). Rising temperatures increase evaporation rates, further stressing water supplies and impacting water quality, through processes such as eutrophication (Kundzewicz et al., 2007). Furthermore, extreme weather events can damage water infrastructure and contaminate water sources, posing significant threats to public health.

- **Human health: the vulnerable recipient**

Human health is highly vulnerable to the impacts of climate change, mediated through changes in water resources. The World Health Organization (WHO, 2021) recognizes climate change as one of the most significant threats to global health in the 21st century. The pathways (Figure 6.1) through which climate and water affect health are diverse and complex. The CWH nexus is characterized by complex feedback loops and interactions that can amplify or dampen the impacts of climate change. For instance, deforestation, driven by land-use change for agriculture and urbanisation, can exacerbate climate change by reducing carbon sequestration and increasing greenhouse gas emissions. This, in turn, can further impact water resources and human health. Similarly, poor sanitation and hygiene practices can increase the burden of waterborne diseases, further stressing healthcare systems already grappling with the impacts of climate change.

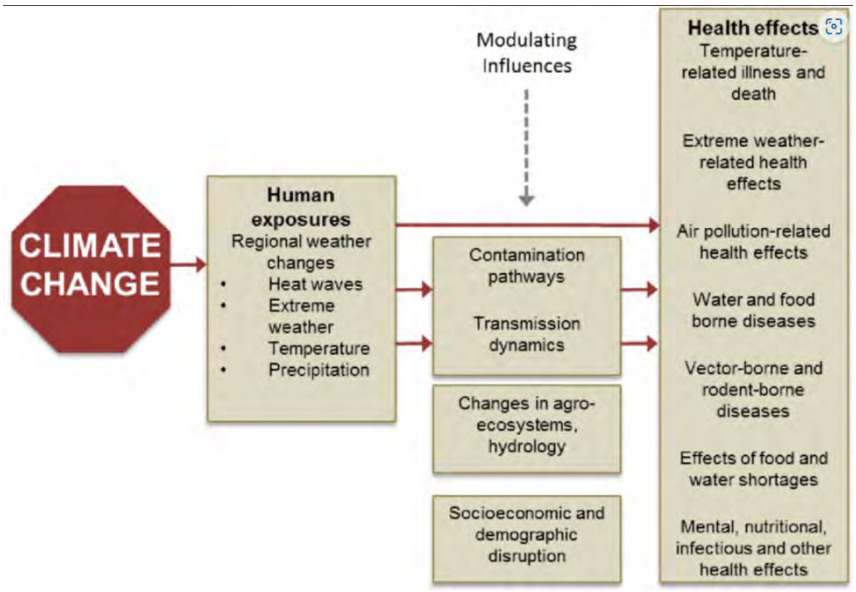


Figure 6.1: The pathways through which climate is a driving force impacting water and health

6.3 South African case studies on the impacts of climate change on human health

The impacts of climate change on human health are highly variable, and this variability depends on characteristics such as individuals' behaviour, age, gender, race, and economic status. These variables include geographic region, population sensitivity, the extent and duration of exposure

to climate change, and a society's capacity to adapt to these changes, all of which greatly influence the impact of climate change on human health. Climate change often worsens property damage, health risks, and financial instability in informal settlements, making the developing world the most vulnerable (Giri et al., 2021). The developing nations are acutely exposed to the impacts of climate change, largely due to their limited adaptive capacity and inadequate resilience to extreme weather events. Potential hazards and unfavourable impacts as consequences of climatic changes with significant environmental conditions are: increased heatwaves, melting of polar ice caps, glaciers, sea level rises, intensifying of extreme weather events (drought, flood, tsunami and hurricane), loss of biodiversity, as well as ecosystem disruptions (Jha and Dev, 2024). Figure 6.2 gives examples of health impacts of climate change and extreme weather events in different parts of South Africa.

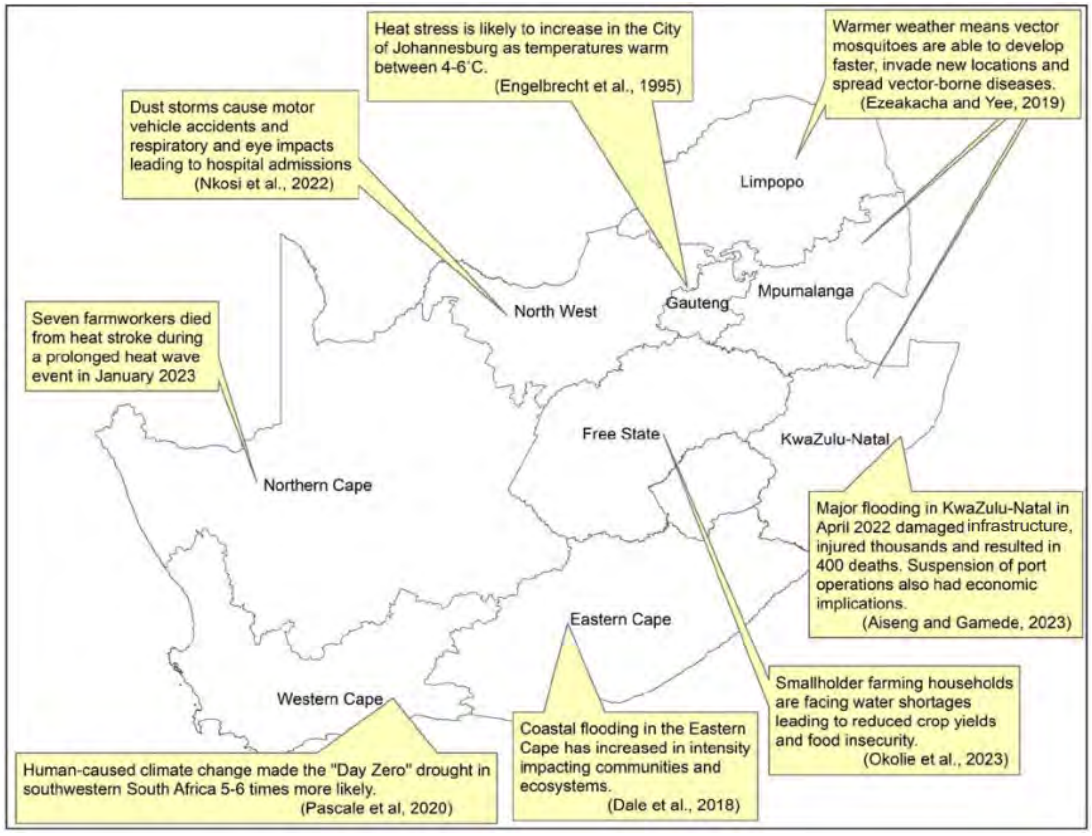


Figure 6.2: Illustrations of climate change and extreme weather events and their health impacts, around South Africa

Little is known about disease vectors in South Africa, including which vectors may be more vulnerable to the impacts of climate change (DEA, 2013). By 2050, under a high emissions scenario, about 300,000 people annually are projected to be at risk of malaria, an increase from the baseline of 1961 and 1990 (Figure 6.3) (WHO, 2015). Malaria transmission in the Limpopo Province has been shown to be seasonal, being distinctively limited to the rainy, hot summer months. In the year 2017, about 27 500 cases of malaria were reported in the Limpopo Province with the Mopani and Vhembe Municipality districts having the highest number of cases reported. Both the malaria parasite and its vector, the mosquito are highly climate-sensitive (Abiodun et al., 2019). Recently, malaria cases have been identified in regions of the Limpopo Province where they were not previously found - climate change is suspected to be the cause. Research conducted by Kabanda and Nenwiini (2016) on the spread of malaria in the Limpopo Province shows that temperature has the greatest significance, followed by rainfall. Rainfall creates a favorable environment for mosquito breeding, while humidity and temperature together influence mosquito survival rates. Increased temperatures result in increased mosquito populations because they shorten the development time of vector-borne pathogens and reduce the required incubation period (Ayanlade et al., 2022).

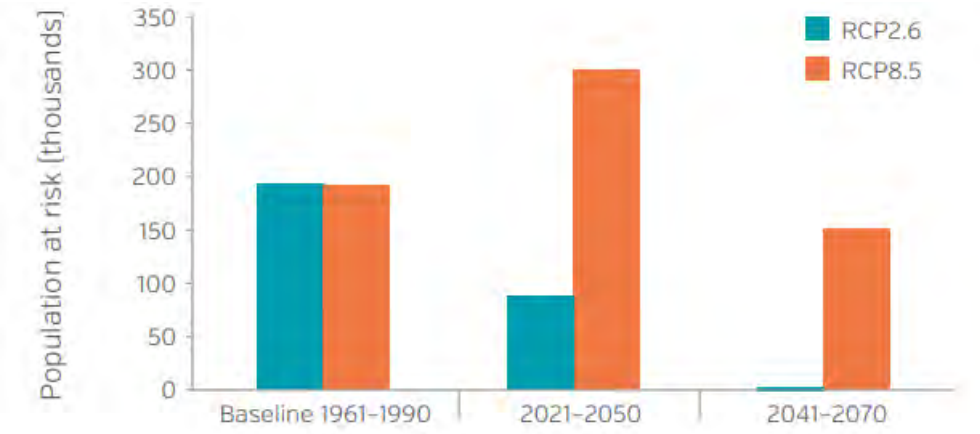


Figure 6.3: Projected population at risk of malaria in South Africa (WHO, 2015)

Any attempts to address the impact of climate change on disease prevention must be multidisciplinary. The DoH, in partnership with DFFE, utilises various resources, including developing national guidelines, collaborating with international organisations, narratives, and theoretical analysis, to map the impact of climate change on human health, along with mitigation measures and adaptation strategies. These efforts have also been supported by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) which assists the South African National Department of Health (NDoH) and South African National Department of Forestry, Fisheries and the Environment (NFFE), in formulating responses (adaptation strategies) to climate change in the health sector.

The South African Medical Research Council's (SAMRC) Environment and Health Research Unit conducted and gathered studies on potential research key areas, in the climate change and health domain. The studies gathered information from international and national publications and from institutional research experiences, thereby providing an up-to-date summary of research findings and future research priorities. The spread of poverty and inequality among local communities in South Africa has contributed to vulnerability to climate change (Chersich et al., 2018). The SAMRC, has emphasised the issue of the link between climate change and human health within vulnerable communities, such as rural and urban informal settlements (Khosi et al., 2015). The increase in extreme temperatures in South Africa is evident in the Lowveld of Limpopo and Mpumalanga, the coastal and northern areas of KwaZulu-Natal, and the Northern Cape. In 2016, a heatwave with a maximum temperature of 40 °C led to the death of 11people in the Northwest province, with the elderly being at risk. Heat waves also broke out in about 21 cities and towns in South Africa. Similarly, provinces such as Gauteng, Northwest, and KwaZulu-Natal have recorded temperatures 12 times higher than the normal record in 2018.

The South African Environmental Health Research Unit has conducted studies on temperature in major South African areas, including schools, health facilities, and workplaces. The findings

showed that indoor temperatures are higher than outdoor ones, with places frequently exceeding national standards and international guidelines. Studies showed that indoor classroom temperatures varied from 21°C at night to 34°C during midday in late summer months, in schools in Johannesburg (Bidassey-Manilal et al., 2018). Outdoor workers who are exposed to heatwaves were also assessed. The reports showed that exposure of road construction workers to temperatures frequently exceeding 40°C in Upington, Northern Cape, has heat-related health effects, including irritability, exhaustion, and sleeplessness, that impair productivity and output during hot weather. Other impacts of high heat on workers include excessive sweating, itchy skin, fatigue, blisters, headaches, dizziness, backache, dehydration, strained eyes, and exhaustion. Pre-existing chronic health conditions, such as hypertension and diabetes, were aggravated due to the negative health effects of climate change on the workers.

The Environmental Health Research Unit also identified Rustenburg as one of the hottest areas, due to its susceptibility to rising temperatures. The National Department of Health's climate change and health adaptation plan recommended implementing the heat-health vulnerability assessment tool in hot zones across all rural areas of South Africa, following its successful implementation in Rustenburg. This vulnerability assessment tool is a simple model for identifying the groups and settings at the highest risk of heat exposure and the impact on their health. Further recommendations for adaptation plans were presented to lessen or avoid vulnerability, including housing improvements, infrastructure improvements, and adaptation capacity for communities (Chersich and Wright, 2019; Paz et al., 2016). In addition, SAMRC recently designed research to investigate the impact of climate change on human health, violence, and mental health in homes and schools, in rural parts of South Africa. The research was designed to be conducted in one of the ten hottest towns in South Africa, Thohoyandou, in rural Limpopo. This aimed to develop and model interventions to address the connections among heat, violence, and mental health in schools and homes, and to assess the feasibility, acceptability, and potential effects of heat. The approach applied included characterising the 10-year climate shift, thereby deepening local

communities' understanding of major climate changes and the local concerns correlated with these communities' health (SAMRC, 2022).

The Japan International Cooperation Agency collaborated with South Africa to improve efforts and develop an early warning system for a wide range of infectious diseases that depended on forecasting climate (SATREPS, 2018). This was achieved through the Infectious Diseases Early Warning System (IDEWS) - a sophisticated, climate-based outbreak prediction model that incorporates environmental and climatic variables. This model used temporal patterns of temperature, rainfall, and sea surface temperature to predict variations in malaria prevalence and the geographical extent of the disease outbreak (Behera et al., 2018). A study in Cape Town showed that monitoring ambient temperature can predict spikes in the occurrence of diarrhoeal diseases, allowing adequate preparation for increased hospital admissions and outpatient visits (Musengimana et al., 2016). Further applications of the infectious disease, health, and climate information were studied within multiple-risk systems, including the South African Risk and Vulnerability Atlas (SARVA). This spatial record permits the visualisation of drivers, exposures, vulnerabilities, and risk through various systems. This database provides a comprehensive list of practical climate services for the agricultural sector. This heat-health warning system depends on a sophisticated meteorological system with lead time and functionality to raise alarms for the public and policy and decision-makers when areas are approaching extreme heat events (Chersich and Wright, 2019).

6.4 CWH modelling methodology

6.4.2 Lagged correlation analysis and multivariate negative binomial regression statistical modelling approaches

To explore temporal associations between climatic conditions and infectious diseases' incidences, a lagged correlation analysis was conducted for monthly malaria, diarrhoea, and bilharzia case

counts for the VDM, over the period 2003–2025. Disease surveillance data were analysed alongside monthly rainfall, maximum temperature, and relative humidity derived from ERA5-Land reanalysis. Lag periods of 0 to 3 months were applied to climatic variables to reflect plausible delays between environmental exposure and observed disease outcomes, including vector population dynamics, pathogen development, and human exposure pathways.

Spearman's rank correlation coefficient (ρ) was used to assess the strength and direction of associations between climatic variables and disease incidence at each lag interval. This non-parametric approach was selected due to the non-normal distribution and over-dispersion characteristic of routine disease surveillance data. For each disease-climate pair, correlation coefficients and corresponding p-values were calculated across all lag periods, enabling identification of both immediate and delayed climatic influences on transmission. Lag structures that demonstrated the strongest and most statistically robust associations were subsequently used to inform predictor selection in multivariate regression models.

Monthly case counts of malaria, diarrhoea, and bilharzia in the VDM were modelled using a multivariate negative binomial regression framework to quantify the influence of climatic variability on disease incidence. Disease surveillance data for 2003–2025 were integrated with monthly rainfall, maximum temperature, and relative humidity, derived from the ERA5-Land reanalysis dataset. Lagged climatic predictors were incorporated to account for delayed responses associated with vector development, pathogen incubation, and exposure pathways, with lag structures informed by prior lagged-correlation analyses.

Overdispersion in disease case counts was assessed by comparing the mean and variance for each outcome variable, revealing substantial deviation from the Poisson regression assumption of equi-dispersion. Consequently, Negative Binomial generalized linear models with a log-link function were adopted as the primary analytical approach, while Poisson models were fitted for

comparison only. Model parameters were estimated using maximum likelihood methods and interpreted as incidence rate ratios (IRRs) with 95% confidence intervals, representing the proportional change in expected disease incidence associated with unit changes in climatic predictors.

6.4.1 Data required for the nexus modelling

The infectious disease dataset was obtained from the Limpopo Provincial Department of Health and comprised reported cases of malaria, bilharzia, and diarrhoeal diseases for the VDM. The dataset covered the period 2003–2025; however, temporal coverage was not uniform across the three diseases, with varying data availability between conditions. The data were provided at the district level only and were not disaggregated by local municipality or health facility. Consequently, the analysis was limited to a district-scale assessment; intra-district spatial heterogeneity in disease occurrence could not be evaluated. Despite this limitation, the dataset was considered suitable for examining temporal variability and climate–disease relationships at the district scale.

Monthly climate predictors (variables) used in the study included rainfall, relative humidity and maximum temperature. For the present-day period (2003-2025), the ERA5-Land dataset was selected for the study. Built on the ERA5-interim Framework, ERA5-Land incorporates improved precipitation inputs and an updated land surface scheme (HTESSEL), offering more accurate estimates of key climate variables. ERA5-Land enhances the spatial resolution of the original ERA5 reanalysis product, achieving a native resolution of 9km on a reduced Gaussian grid. ERA5 products are updated daily with a latency of about 5 days (Hersbach et al., 2020).

The ERA-Land Climate data were processed using Google Earth Engine, where the ERA5-Land Image Collection was spatially clipped to the VDM boundary. An area-averaged approach was applied to compute district-mean values, for each climatic variable, at each time step. This

approach involved calculating the spatial mean of all grid cells falling within the district boundary, thereby producing a representative district-scale climate signal. The resulting time series were exported as comma-separated values (CSV) files for subsequent statistical analysis and modelling. These moderate-resolution indicators allowed precise environmental characterization to support targeted infectious disease modelling.

Future climate projections were obtained from the NASA Global Daily Downscaled Projections for CMIP6 (GDDP-CMIP6) dataset (Thrasher et al., 2022), accessed via the Google Earth Engine (GEE) platform. The GDDP-CMIP6 dataset provides bias-adjusted, statistically downscaled daily climate variables from global climate models (GCMs) participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6). The dataset has a native spatial resolution of approximately 0.25° (~25 km), making it suitable for regional- and district-scale climate impact assessments. Climate projections were extracted for two Shared Socioeconomic Pathways (SSP) Scenarios, namely SSP2-4.5, a medium stabilization scenario, and SSP5-8.5, a high emission scenario (Riahi et al., 2017; Taylor et al., 2012). These scenarios were selected to represent a plausible range of future greenhouse gas trajectories and to assess climate-related risks under both moderate and extreme forcing conditions (Figure 6.4). The daily climate data were then aggregated to monthly time steps to align with the temporal resolution of the infectious disease records. Climate projections were analysed across three future periods: near term (2021-2040), mid-term (2041-2060) and long term (2081-2100). A multi-model ensemble was constructed using 10 CMIP6 Global climate models available within the GDDP-CMIP6 archive (Table 6.1). The use of multiple models reduces uncertainties associated with individual model structures and improves robustness of projected climate signals. Climate data were initially processed and exported per model, with ensemble statistics computed during post-processing.

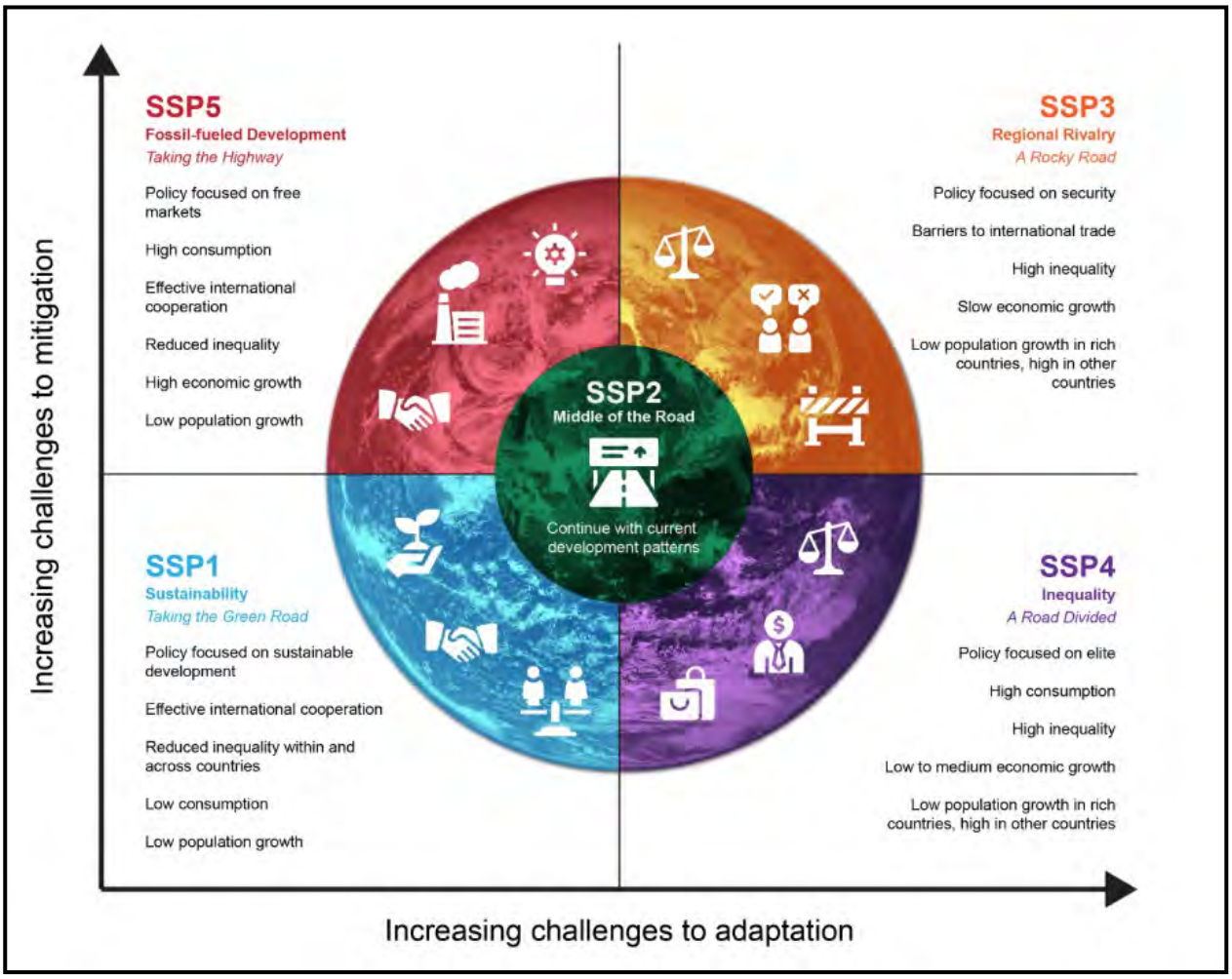


Figure 6.4: SSPs and associated challenges to mitigation and adaptation

Table 6.1: Details of the selected 10 Global Climate Models in CMIP6

Model	**Institute**	**Resolution (in degrees)**	**References**
ACCESS-CM2	Commonwealth Scientific and Industrial Research Organisation	1.88 × 1.25	Dix et al. (2019)
EC-EARTH3	EC-EARTH consortium	0.70 × 0.70	EC-Earth(2019a,2019b)
EC-EARTH3-Veg	EC-EARTH consortium	0.70 × 0.70	EC-Earth (2019b,2019c)
FGOALS-g3	Chinese Academy of Sciences Flexible Global Ocean–Atmosphere-Land System Model	2.00 × 2.00	Li et al. (2019), Li (2020)
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (GFDL)	1.25 × 1.00	Krasting et al. (2018)
INM-CM4-8	Institute of Numerical Mathematics	2.00 × 1.50	Volodin (2021)

INM-CM5-0	Institute of Numerical Mathematics	2.00 × 1.50	Volodin (2020)
IPSL-CM6A-LR	Institute Pierre-Simon Laplace (IPSL)	2.50 × 1.26	Boucher et al. (2020)
MPI-ESM1-2-LR	Max Planck Institute	1.88 × 1.88	Mauritsen et al. (2019)
NorESM2-MM	NorESM Climate Modelling Consortium	0.90 × 1.30	Bentsen et al. (2023)

6.4.3 Machine learning-based modelling and future projections of climate-sensitive infectious diseases

- **The Extreme Gradient Boosting Model fitting**

The Extreme Gradient Boosting (XGBoost) approach was applied to model the nonlinear and multivariate relationships between climatic factors and malaria incidence. XGBoost is a sophisticated ensemble method that integrates multiple weak decision tree models sequentially (Chen and Guestrin, 2016). This process involves optimizing predictive accuracy using gradient descent, where each new tree corrects the errors of previous trees. Additionally, regularization techniques are incorporated to prevent overfitting. Mathematically, XGBoost optimizes the following objective function:

$$\text{Obj}(\theta) = \sum_{i=1}^{n} l(\hat{y}_i, y_i) + \sum_{k} \Omega(f_k) \quad (6.1)$$

where $l(\hat{y}_i, y_i)$represents the loss function, measuring the discrepancy between observed (y_i) and predicted ($\hat{y}_i$) disease incidence, and $\Omega(f_k)$is a regularisation term that penalises model complexity by constraining the structure and weights of the individual decision trees f_k. This regularisation framework reduces overfitting while allowing the model to learn complex, non-linear relationships. Given the count-based nature of disease incidence data, a Poisson objective function was employed. Model outputs were constrained using clipping to ensure non-negative and epidemiologically-plausible predictions.

- **Hyperparameter Optimisation and Model Training**

The climate–health dataset, stored in comma-separated value (CSV) format, was imported and processed for analysis in a Google Colab environment. To preserve the temporal structure of the time-series data and avoid information leakage, the dataset was split chronologically into training (80%) and testing (20%) subsets. The training subset was used exclusively for model development and hyperparameter optimisation, while the testing subset was reserved for independent out-of-sample evaluation. Key XGBoost hyperparameters, including the learning rate, maximum tree depth, and number of boosting iterations, were optimized using a grid search. Hyperparameter tuning was conducted using 10-fold cross-validation on the training data only, with model performance assessed using mean squared error. This approach ensured robust model generalisation while maintaining strict separation between model calibration and prediction.

- **Model performance evaluation**

The predictive performance of the XGBoost models developed for malaria, bilharzia, and diarrhoea incidence was evaluated using a suite of complementary statistical metrics, suitable for continuous health outcomes. Mean absolute error (MAE) was used to quantify the average magnitude of prediction errors without considering their direction and is defined as:

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n} | y_i - \hat{y}_i \quad (6.2)$$

Where y_i is the actual observed value, $\hat{y}_i$ is the predicted value, and n is the total number of observations. The mean squared error (MSE) and its square root, the Root Mean Squared Error (RMSE), were used to penalise larger prediction errors more strongly, thereby capturing both the variability and magnitude of deviations between observed and predicted disease cases. Equations 6.3 and 6.4 were used to calculate the MSE and RMSE, respectively.

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (6.3)$$

$$\text{RMSE} = \sqrt{\text{MSE}} \quad (6.4)$$

To express prediction accuracy in relative terms, mean absolute percentage error (MAPE) was calculated using Equation 6.5, providing an intuitive percentage-based measure of model error, relative to observed incidence values.

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{y_i} \right| \times 100 \quad (6.5)$$

Model explanatory power was further assessed using the coefficient of determination (R^2), which quantifies the proportion of variance in malaria, bilharzia, and diarrhoea incidence explained by the climatic predictors. Together, these performance metrics provide a comprehensive assessment of model accuracy, robustness, and explanatory capability, allowing for a nuanced evaluation of the suitability of the XGBoost framework for predicting climate-sensitive infectious diseases in the VDM.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (6.5)$$

Where $\bar{y}$ is the mean value.

6.5 Results on the influence of climatic factors on infectious diseases incidence, within the CWH nexus

The changes in annual rainfall indicate that VDM has become drier between 2011 and 2024 as compared to 1993 and 2010 (Figure 6.5). The magnitude of change ranges from -1 to -6 mm/year. The drying trends are more pronounced in Thulamela and Collins Chabane municipalities. Figure 6.5 indicates that VDM's climate is marked by strong annual rainfall extremes. A typical very wet day of the year brings ~40–70 mm of rain around Thulamela and Collins Chabane (Figure 6.6). This, combined with increasing maximum 1-day rainfall extreme (Rx1day) signals a shift to fewer,

but more intense rainfall events, raising risks of drought and flood cycles. Figure 6.7 indicates a warming signal detected with mean maximum temperature (Tx) increased by about +0.3 to +0.7 °C between 2011–2024 compared to 1993–2010 in VDM, which is consistent with regional climate trends. The drought and flood cycles, together with the increased warming, are likely to influence the occurrence of climate-sensitive diseases.

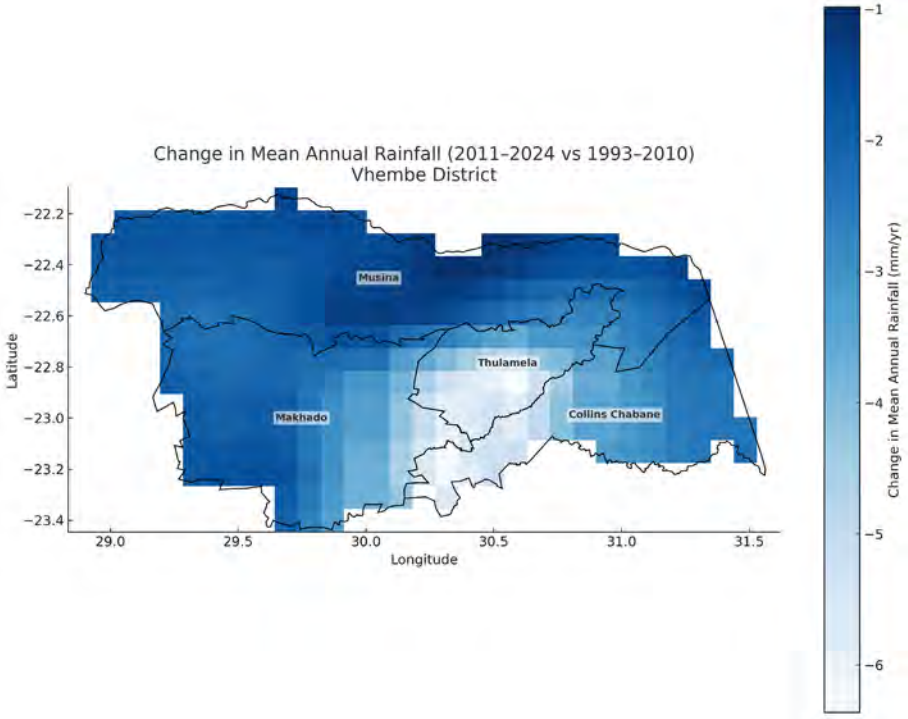


Figure 6.5: Change in mean annual rainfall

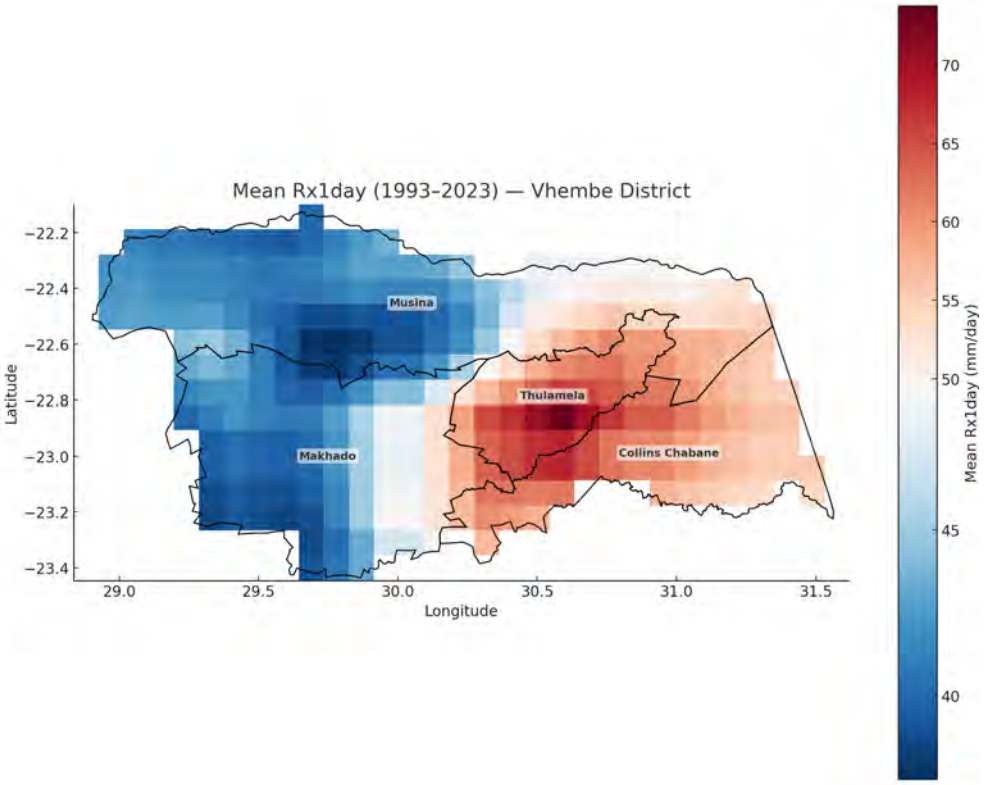


Figure 6.6: Mean Rx1day rainfall

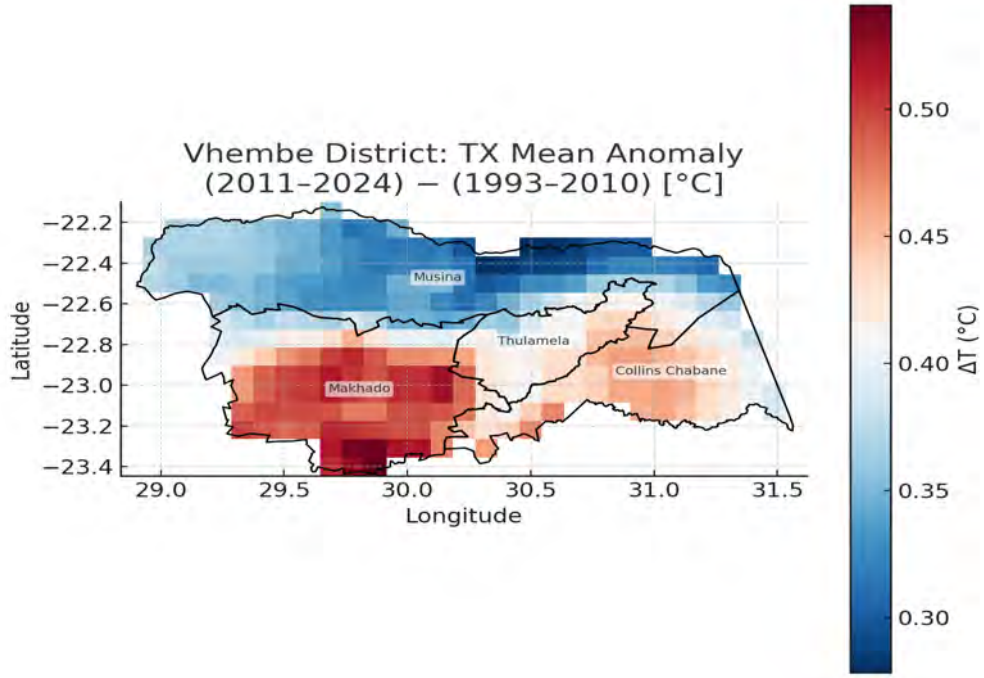


Figure 6.7: Tmax mean anomalies

Observed malaria, bilharzia and diarrhoea cases are presented in Figure 6.8. Major peaks occurred in April 2020 and May 2023, with total numbers of cases of 1771 and 796, respectively However, malaria cases declined from December 2023 but remained constant until July 2025. Thovhakale (2025) noted that case management, indoor residual spraying (IRS), and surveillance are cornerstone interventions to eliminate malaria in Limpopo Province. Significant declining trends of local transmission from 2022 to 2024, driven by intensified vector control and early case detection, were reported. These are consistent with the decline in malaria cases observed in Figure 6.8, an indication of the programme's effectiveness.

Diarrhoea cases with notably high peaks of 969, 659, and 315 occurred in January 2011, August 2015, and August 2024, respectively (Figure 6.8). There was a decline in the number of cases in July 2017, followed by consecutive peaks in September 2018, September 2019, November 2020, June 2021, September 2022, September 2023, August 2024, and September 2025. This indicated the continuation of annual peaks, linked to the end of the dry season. It is therefore imperative to improve interventions to manage the peak periods of infections. The number of diarrhoea cases remained mostly low compared to the period before July 2017. Moloko and Tshivhase (2024) noted that caregivers and guardians of children under 5 years were seemingly aware of the risk factors, treatment, and management of diarrhoea in VDM. This may be attributed to the decline in diarrhoea cases after July 2027.

There were fluctuating cases of bilharzia throughout the period of record, with notable peaks that occurred in May 2018, June 2019, April 2020, September 2021, July 2022, August 2023, and August 2025 with total numbers of cases of 154, 177, 140, 132, 108, 111, and 115, respectively (Figure 6.8), Compared to malaria and diarrhoea cases, there was no notable reduction in bilharzia cases during these periods. This likely indicates that strategies to prevent bilharzia have not yet been successfully implemented in the study area.

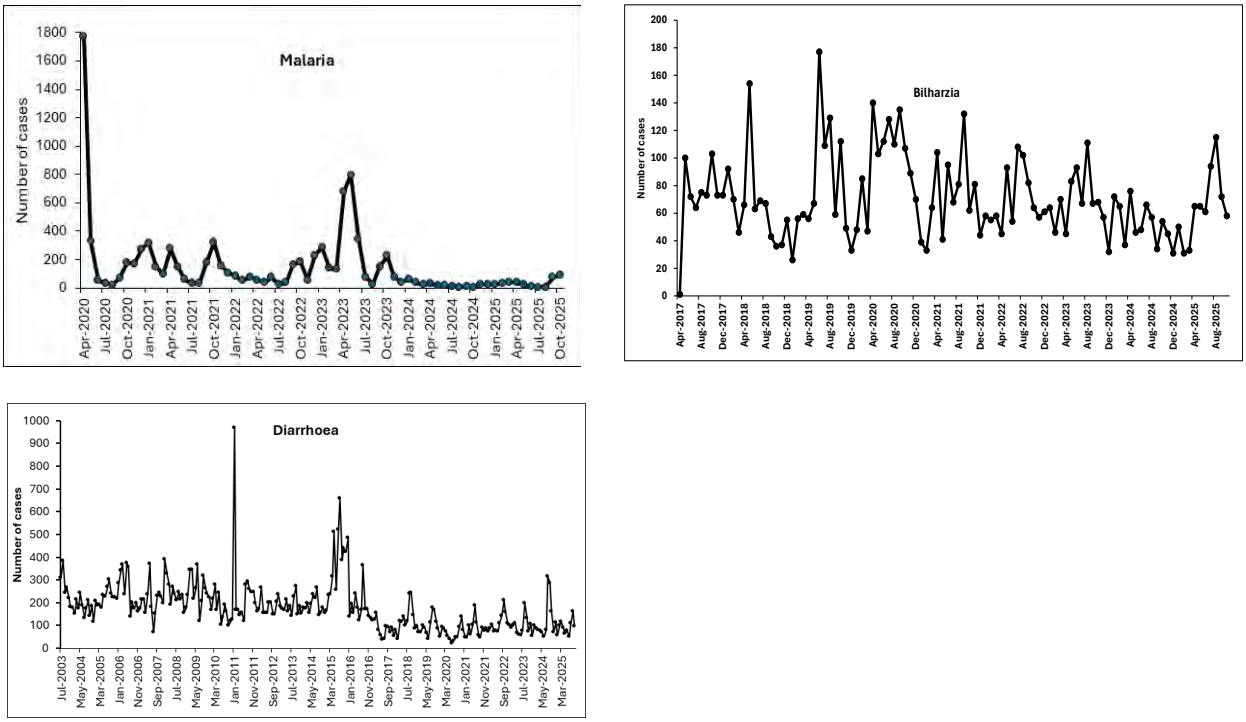


Figure 6.8: Malaria, bilharzia, and diarrhoea cases in VDM

6.5.1 Lagged climate–disease correlation analysis for malaria, bilharzia, and diarrhoea incidences

To assess the influence of climatic conditions on malaria transmission, a lagged Spearman's rank correlation analysis was performed between monthly malaria cases and three climatic variables (rainfall, relative humidity, and maximum temperature) in the VDM for the period 1997-2007. Lags of 0 to 3 months were applied to climatic variables to account for delays in breeding, parasite development, and subsequent transmission dynamics. Scatter plots were fitted with regression lines, and 95% confidence intervals were embedded to visualise the strength and direction of these associations, while the corresponding correlation coefficients (ρ) and significance levels (p-values) quantified their statistical reliability (Figures 6.9-6.12).

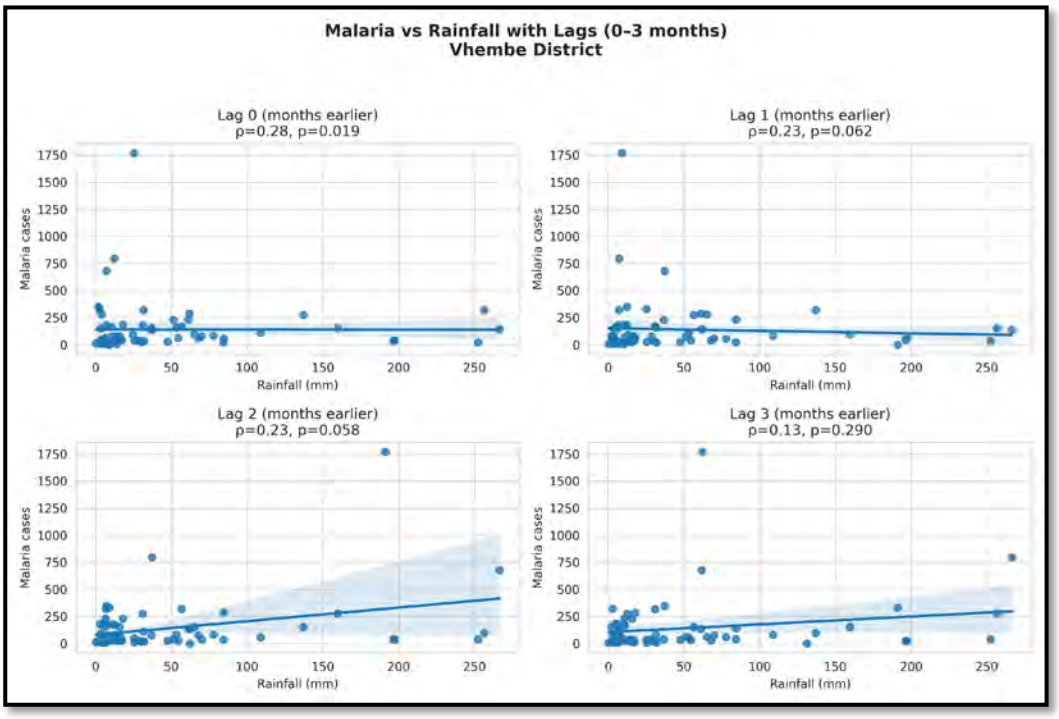


Figure 6.9: Scatter plots of monthly malaria cases against rainfall totals at lags 0–3 months in VDM (2020–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line indicates the fitted regression with a 95% confidence interval (blue shading)

The lagged Spearman's rank correlation analysis revealed a generally weak positive association between monthly rainfall totals and malaria cases in the VDM (Figure 6.9). At lag 0 (same month), rainfall exhibited a weak but statistically significant positive correlation with malaria incidence (ρ = 0.28, p = 0.019), suggesting that higher rainfall within the same month was associated with increased malaria cases. This relationship likely reflects the immediate creation of mosquito breeding habitats, following rainfall events.

At lag 1 month, the positive relationship persisted but weakened slightly and was not statistically significant (ρ = 0.23, p = 0.062), suggesting a possible short-term delayed effect of rainfall on malaria transmission that falls short of conventional significance thresholds (Figure 6.9). Similarly, at lag 2 months, rainfall maintained a weak positive association with malaria cases (ρ = 0.23), with the p-value (p = 0.058) approaching statistical significance, suggesting that rainfall may contribute

to malaria transmission, although through delayed effects, linked to vector population build-up and parasite development. By lag 3 months, the relationship between rainfall and malaria cases further weakened and became non-significant (ρ = 0.13, p = 0.290), indicating a diminishing influence of rainfall on malaria incidence, beyond a two-month period.

The lagged Spearman's rank correlation analysis showed a generally weak positive association between monthly relative humidity (%) and malaria cases in the VDM (Figure 6.10). At lag 0 (same month), relative humidity exhibited a weak but statistically significant positive correlation with malaria incidence (ρ = 0.27, p = 0.024), indicating that months with higher humidity tended to coincide with increased malaria cases. This pattern is consistent with the role of humid conditions in enhancing mosquito survival and supporting vector activity. At lag 1 month, the relationship weakened and became statistically non-significant (ρ = 0.16, p = 0.196), suggesting that any delayed influence of humidity on malaria incidence is less pronounced. At lag 2 months, the association further decreased and remained non-significant (ρ = 0.12, p = 0.334), indicating limited evidence for a sustained lagged humidity effect. By lag 3 months, the relationship was negligible (ρ = 0.02) and clearly non-significant (p = 0.882), implying that relative humidity does not exert a meaningful influence on malaria incidence beyond the same-month conditions. Overall, these results suggest that relative humidity has a modest and temporally short influence on malaria transmission in the VDM, with the strongest association occurring within the same month, and progressively weaker, non-significant relationships, at longer lags.

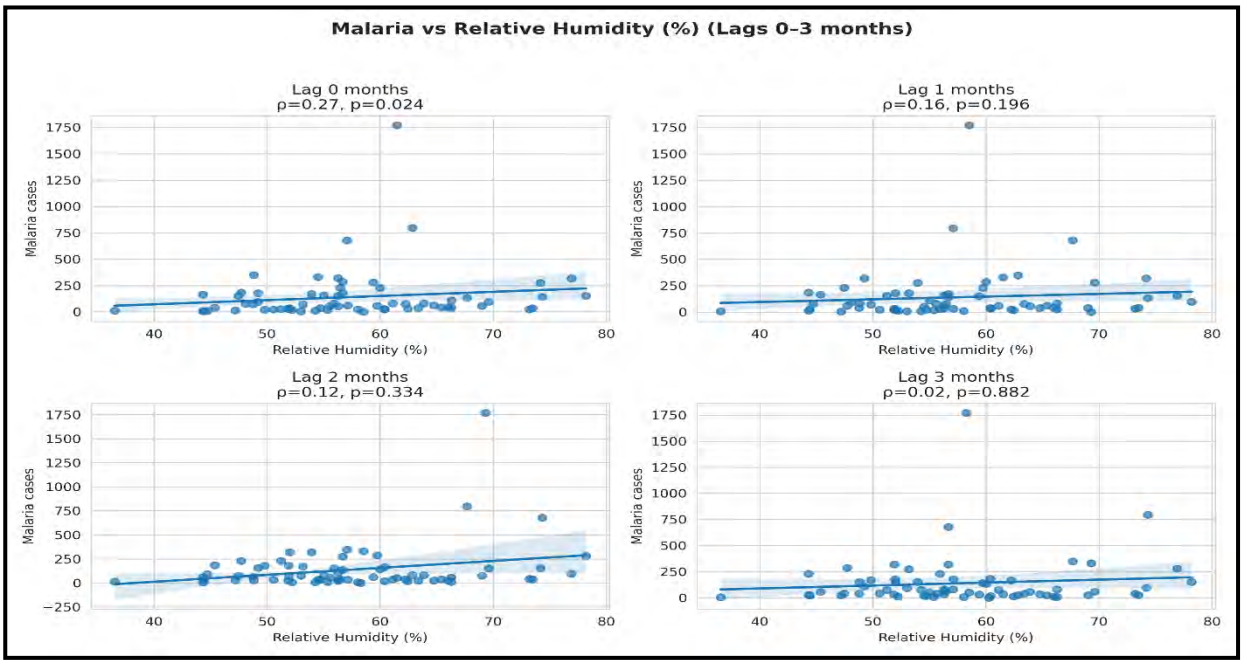


Figure 6.10: Scatter plots of monthly malaria cases against relative humidity at lags 0–3 months in VDM (2020–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line indicates the fitted regression with a 95% confidence interval (Blue shading)

The lagged Spearman's rank correlation analysis indicated a weak and temporally variable association between monthly Tmax and malaria cases in the VDM (Figure 6.11). At lag 0 (same month), Tmax showed a weak, statistically non-significant positive relationship with malaria incidence (ρ = 0.19, p = 0.118), suggesting that contemporaneous temperature conditions alone, do not strongly explain variations in malaria cases. At lag 1 month, the association strengthened and became statistically significant (ρ = 0.25, p = 0.038), indicating that higher maximum temperatures one month prior were associated with increased malaria incidence. This pattern is consistent with the role of temperature in accelerating mosquito development rates and shortening the parasite's extrinsic incubation period, thereby enhancing transmission potential after a short delay. At lag 2 months, the relationship weakened considerably and was not statistically significant (ρ = 0.09, p = 0.478), suggesting a limited sustained influence of Tmax beyond a one-month lag. By lag 3 months, the association became slightly negative and remained

non-significant (ρ = −0.06, p = 0.610), indicating no meaningful delayed effect of maximum temperature on malaria incidence at lags beyond 3 months (Figure 6.11). These findings reinforce that elevated maximum temperatures increase the malaria risks after short delays of approximately a months or two. These findings align with entomological evidence indicating that malaria transmission is highly sensitive to temperature peaks (Mordecai et al., 2019; Paaijmans et al., 2009).

Overall, the findings highlight rainfall as the most influential climatic driver of malaria in the VDM, particularly at lags of 1–3 months. This reflects the ecological processes underlying malaria transmission, where climatic conditions create a delayed but measurable impact on disease incidence. The weak influence of humidity suggests that this variable was less critical during the study period, although its role should not be disregarded under changing climate conditions.

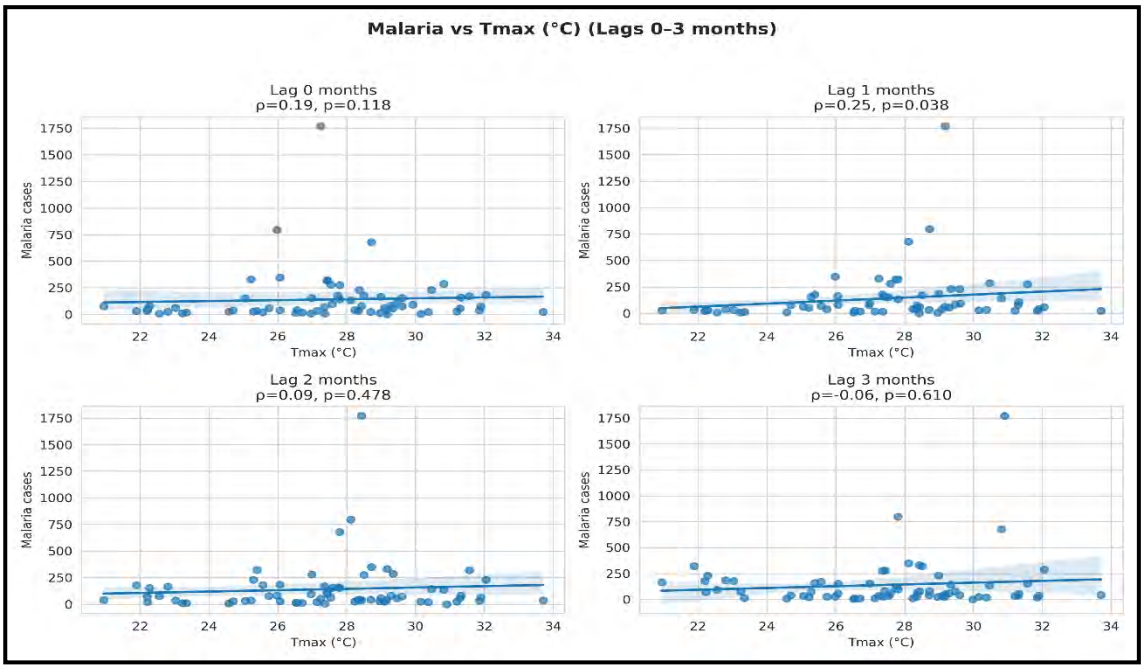


Figure 6.11: Scatter plots of monthly malaria cases against maximum temperature at lags 0–3 months in VDM (2020–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading)

The lagged Spearman's rank correlation analysis revealed a moderate negative association between monthly rainfall totals and bilharzia cases in the VDM (Figure 6.12). At lag 0, rainfall exhibited a moderate, statistically significant negative correlation with bilharzia incidence ($\rho = -0.41$, $p < 0.001$), indicating that higher rainfall in the same month was associated with a reduction in reported bilharzia cases. At lag 1 month, the negative association persisted and remained statistically significant ($\rho = -0.38$, $p < 0.001$), suggesting a short-term delayed effect of rainfall on bilharzia transmission dynamics. Similarly, at a lag of 2 months, rainfall continued to show a moderate negative, statistically significant relationship with bilharzia cases ($\rho = -0.33$, $p = 0.001$), indicating that the suppressive influence of rainfall on bilharzia transmission may persist for up to 2 months after rainfall events. This delayed effect is consistent with ecological responses of snail populations and changes in human water-contact behaviour, following wetter conditions.

By lag 3 months, the relationship between rainfall and bilharzia cases weakened substantially and became non-significant ($\rho = -0.09$, $p = 0.364$), suggesting that rainfall's influence on bilharzia incidence diminishes beyond a 2-month lag. Overall, these findings indicate that rainfall exerts a moderate but temporally limited negative influence on bilharzia transmission in the VDM, with the strongest effects occurring within the same month and up to approximately two months thereafter.

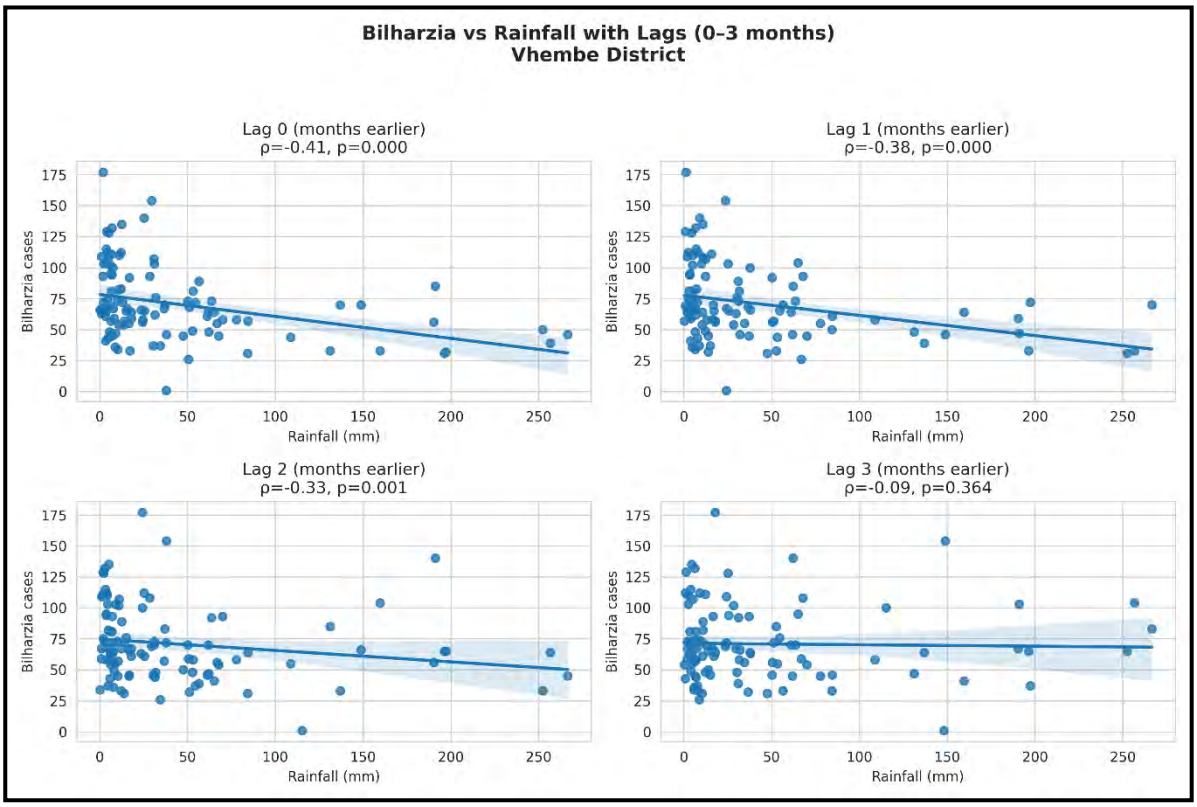


Figure 6.12: Scatter plots of monthly Bilharzia cases against rainfall at lags 0–3 months in VDM (2017–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading)

The lagged Spearman's rank correlation analysis revealed variable and temporally dependent associations between monthly relative humidity and bilharzia cases in the VDM (Figure 6.13). At lag 0, relative humidity exhibited a weak but statistically significant negative correlation with bilharzia incidence (ρ = −0.25, p = 0.010), suggesting that higher humidity conditions, within the same month may be associated with reduced bilharzia case counts. This inverse relationship may reflect unfavourable conditions for cercarial survival or changes in human water-contact behaviour, during more humid periods. At lag 1 month, the relationship between relative humidity and bilharzia cases weakened considerably and became non-significant (ρ = −0.06, p = 0.526), indicating little evidence of a short-term delayed effect of humidity on bilharzia transmission, at this timescale.

By lag 2 months, the association shifted to a weak positive relationship, although it remained statistically non-significant (ρ = 0.10, p = 0.300). This suggests that relative humidity, two months earlier, may have a limited and inconsistent influence on bilharzia incidence, with no clear evidence of a systematic delayed effect. In contrast, at lag 3 months, relative humidity showed a moderate, statistically significant positive correlation with bilharzia cases (ρ = 0.32, p = 0.001), indicating that higher humidity 3 months earlier was associated with increased bilharzia incidence. This delayed positive relationship may reflect longer-term ecological processes, including enhanced survival and proliferation of intermediate snail hosts and sustained environmental suitability that facilitates subsequent transmission.

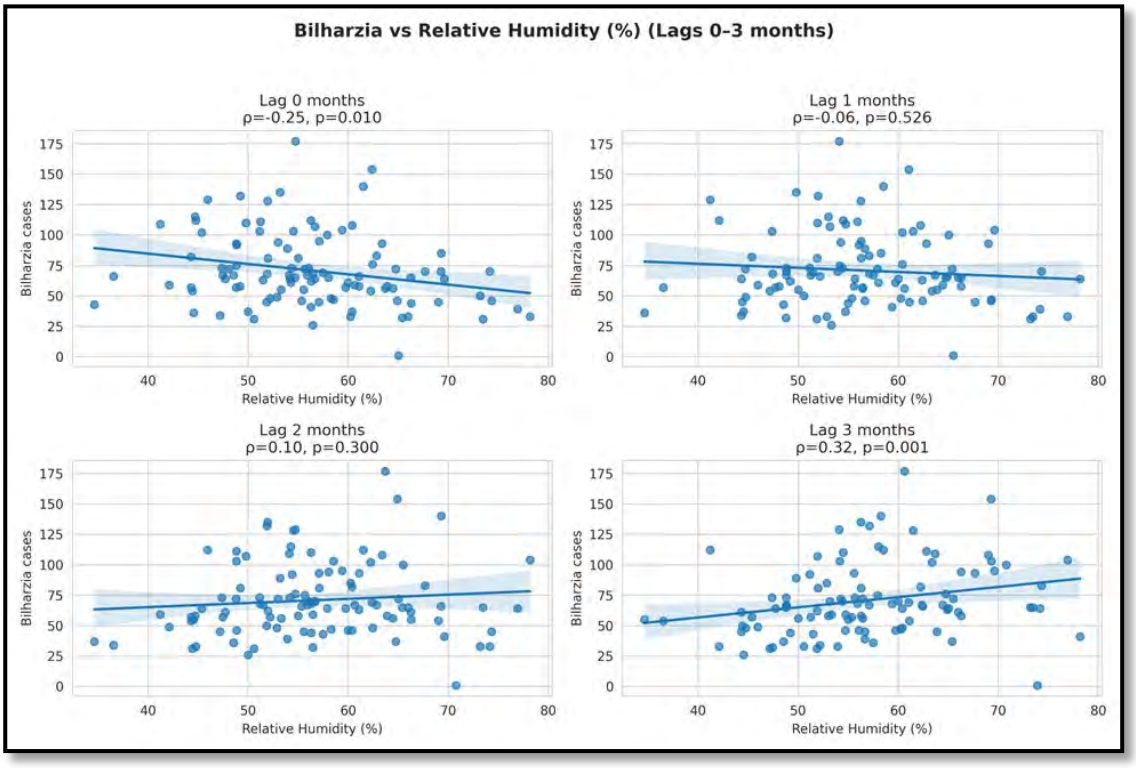


Figure 6.13: Scatter plots of monthly bilharzia cases against Relative humidity at lags 0–3 months in VDM (2017–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading).

The lagged Spearman's rank correlation analysis revealed a consistently moderate to strong negative association between monthly Tmax and bilharzia cases in the VDM (Figure 6.14). At lag 0, Tmax exhibited a moderate and statistically significant negative correlation with bilharzia incidence ($\rho = -0.38$, $p < 0.001$), indicating that higher temperatures within the same month were associated with reduced bilharzia case counts. This relationship may reflect thermal stress on intermediate snail hosts or reduced survival of schistosome cercariae at elevated temperatures. At lag 1 month, the negative relationship between Tmax and bilharzia cases strengthened further and remained highly statistically significant ($\rho = -0.50$, $p < 0.001$). This suggests a pronounced short-term delayed effect of high temperatures on bilharzia transmission, potentially linked to sustained thermal impacts on snail population dynamics and parasite development processes. Similarly, at lag 2 months, Tmax continued to show a moderate to strong negative and statistically significant association with bilharzia cases ($\rho = -0.44$, $p < 0.001$), indicating that the suppressive influence of elevated temperatures on bilharzia transmission may persist for up to two months, following periods of higher temperatures.

By lag 3 months, the negative association weakened slightly but remained statistically significant ($\rho = -0.31$, $p = 0.002$), suggesting that while the influence of Tmax diminishes over time, elevated temperatures can exert a longer-lasting suppressive effect on bilharzia incidence beyond the immediate and short-term periods. Overall, these findings indicate that maximum temperature plays a substantial, although temporally persistent inhibitory role in bilharzia transmission, in the VDM. The consistently negative relationships across all lags highlight the sensitivity of bilharzia transmission dynamics to thermal conditions, with the strongest effects occurring within one to two months following elevated temperature conditions.

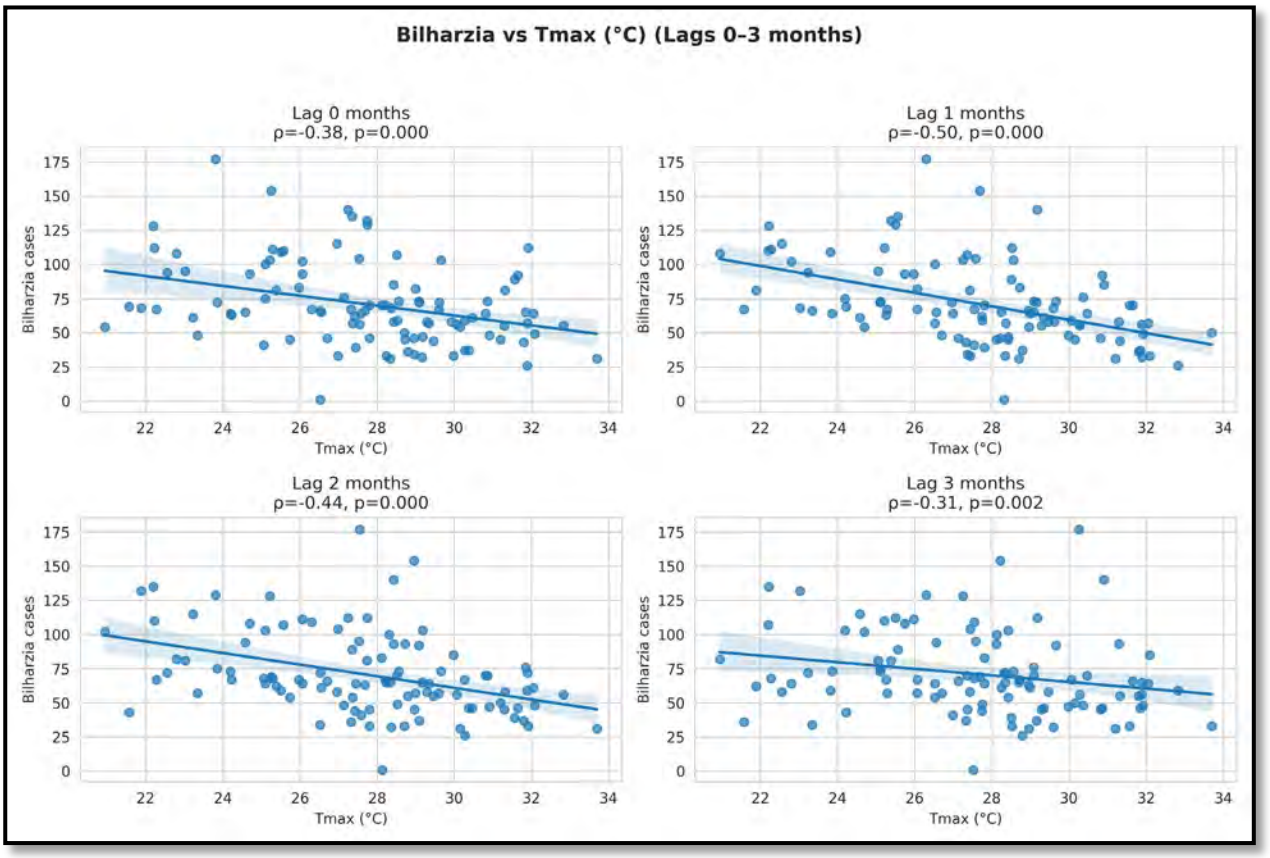


Figure 6.14: Scatter plots of monthly bilharzia cases against Tmax at lags 0–3 months in VDM (2017–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading)

The lagged Spearman's rank correlation analysis revealed a consistently weak and statistically non-significant association between monthly rainfall totals and diarrhoea cases in the VDM Municipality (Figure 6.15). At lag 0 (same month), rainfall exhibited a weak negative correlation with diarrhoeal incidence (ρ = −0.09, p = 0.148), indicating little evidence of an immediate relationship between rainfall variability and diarrhoea cases within the same month.

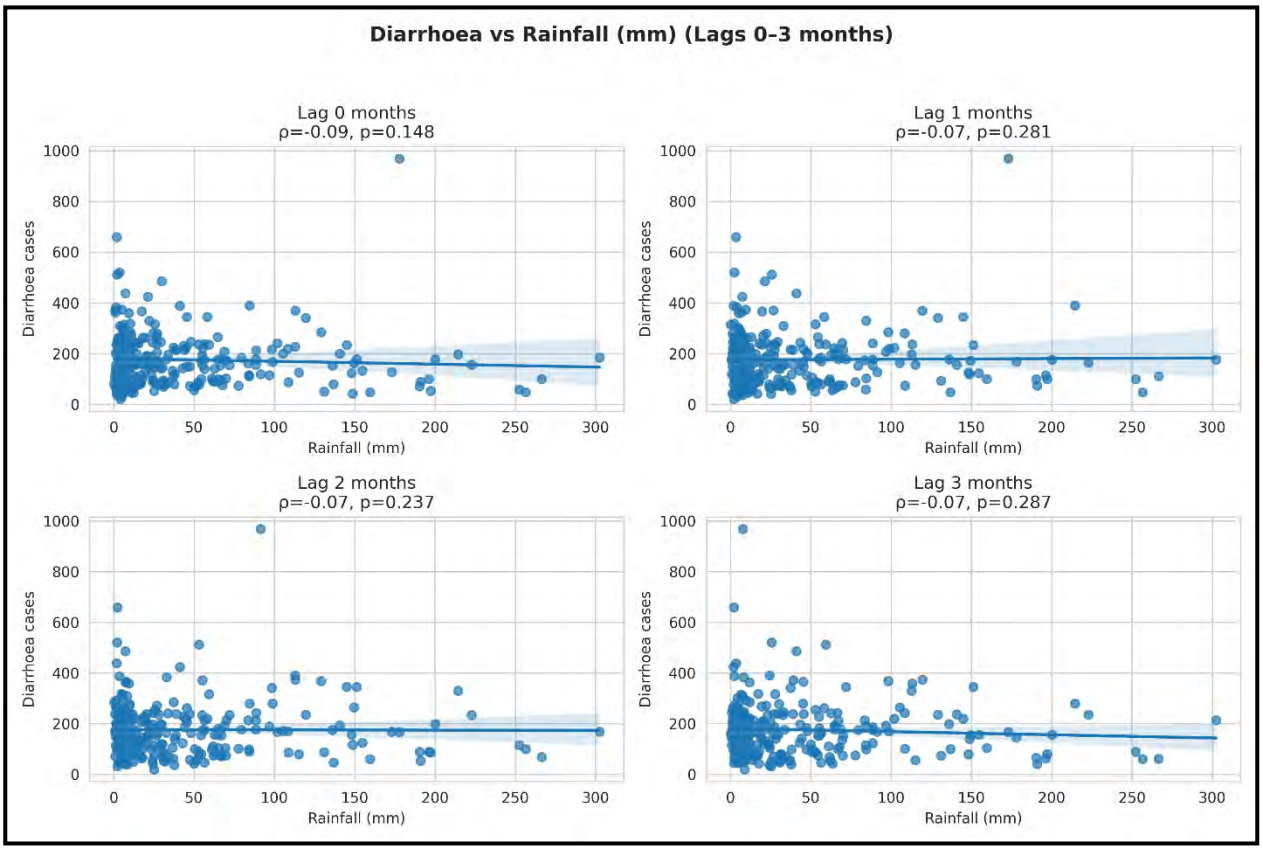


Figure 6.15: Scatter plots of monthly diarrhoea cases against maximum rainfall at lags 0–3 months in VDM (2004–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading)

At lag 1 month, the relationship remained weak and non-significant (ρ = −0.07, p = 0.281), suggesting that rainfall one month earlier does not exert a clear delayed influence on diarrhoeal transmission dynamics (Figure 6.15). This lack of significance indicates that short-term hydrological changes, following rainfall events, may not consistently translate into measurable changes in diarrhoea incidence, at the population level. Similarly, at lag 2 months, rainfall continued to show a weak negative and statistically non-significant association with diarrhoea cases (ρ = −0.07, p = 0.237), indicating that any delayed effects of rainfall on diarrhoeal incidence are minimal and inconsistent at this timescale. By lag 3 months, the negative relationship persisted but remained non-significant (ρ = −0.07, p = 0.287), further confirming the absence of a strong or

systematic delayed effect of rainfall on diarrhoeal disease occurrence, in the district. Overall, these findings suggest that rainfall plays a limited and indirect role in shaping diarrhoeal disease incidences in the VDM. The consistently weak and non-significant relationships across all examined lags imply that diarrhoeal transmission is likely influenced more strongly by non-climatic factors, such as water supply reliability, sanitation infrastructure, hygiene practices, and contamination pathways, rather than by rainfall variability alone.

The lagged Spearman's rank correlation analysis revealed a generally weak negative association between monthly relative humidity and diarrhoea cases in the VDM (Figure 6.16). At lag 0 (same month), relative humidity exhibited a weak but statistically significant negative correlation with diarrhoea incidence ($\rho = -0.21$, $p = 0.001$), indicating that higher humidity conditions within the same month were associated with reduced diarrhoea case counts. At lag 1 month, the negative association between relative humidity and diarrhoea cases persisted but weakened and was not statistically significant ($\rho = -0.11$, $p = 0.066$). This suggests a possible short-term delayed influence of humidity on diarrhoeal transmission that does not meet conventional significance thresholds, indicating limited evidence for a sustained effect, beyond the same month.

At lag 2 months, relative humidity continued to show a weak negative relationship with diarrhoea cases, which remained statistically non-significant ($\rho = -0.09$, $p = 0.158$) (Figure 6.16). This finding suggests that any suppressive influence of relative humidity on diarrhoeal incidence diminishes further with increasing lag time. By lag 3 months, the association between relative humidity and diarrhoea cases weakened further and remained non-significant ($\rho = -0.05$, $p = 0.400$), indicating little evidence of a delayed effect of relative humidity on diarrhoeal incidence, beyond the immediate period. Overall, these findings indicate that relative humidity exerts a weak and temporally limited influence on diarrhoea incidence in the VDM, with the strongest effect occurring within the same month and diminishing rapidly at longer lags. This suggests that while humidity may play a role in modulating diarrhoeal risk, its influence is likely to be secondary to

other climatic and non-climatic drivers, such as rainfall patterns, temperature, water quality, and sanitation conditions.

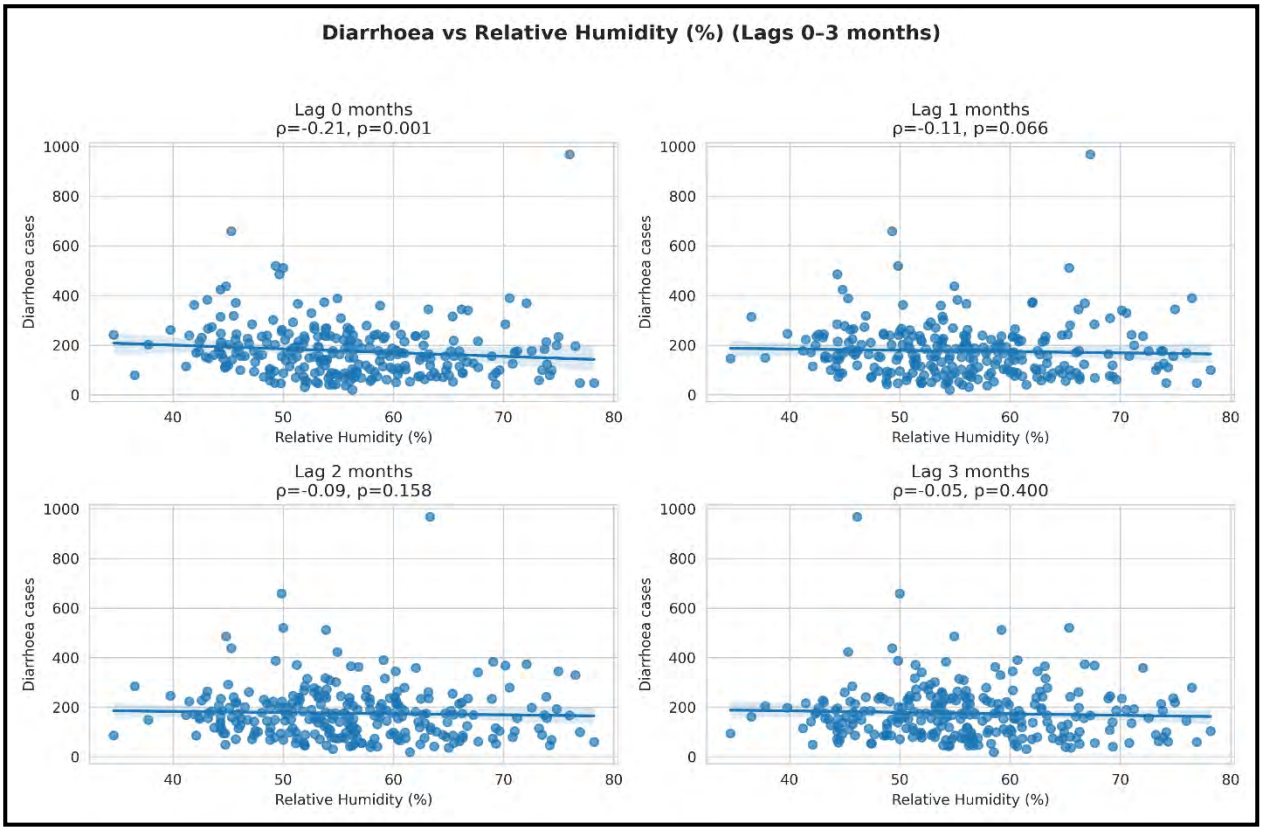


Figure 6.16: Scatter plots of monthly diarrhoea cases against relative humidity at lags 0–3 months in VDM (2004–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading).

With respect to maximum temperature (Tmax), the lagged Spearman's rank correlation analysis revealed a generally weak and inconsistent association between monthly Tmax and diarrhoea cases in the VDM (Figure 6.17). At lag 0 (same month), Tmax exhibited a very weak and statistically non-significant positive correlation with diarrhoea incidence (ρ = 0.04, p = 0.496), indicating little evidence of an immediate effect of temperature on diarrhoeal case counts, within the same month. At lag 1 month, the relationship shifted to a weak negative association, although this relationship remained statistically non-significant (ρ = −0.09, p = 0.150). This suggests a possible

short-term delayed influence of higher temperatures on diarrhoeal incidence, but one that does not meet conventional levels of statistical significance. Similarly, at lag 2 months, Tmax continued to show a weak negative relationship with diarrhoea cases, with the p-value approaching statistical significance ($\rho = -0.12$, $p = 0.052$). This near-significant result suggests that elevated temperatures may begin to exert a modest suppressive effect on diarrhoeal incidence after a delay of approximately two months, potentially reflecting indirect pathways, such as changes in pathogen survival or human exposure behaviours.

By lag 3 months, the negative association persisted at a similar magnitude, but did not reach, statistical significance ($\rho = -0.12$, $p = 0.053$) (Figure 6.17). This indicates that any delayed influence of Tmax on diarrhoeal incidence remains weak and uncertain at longer lag periods. Overall, these findings suggest that maximum temperature plays a limited and secondary role in shaping diarrhoeal disease incidence in the VDM, with no strong or consistent associations observed across the examined lag periods. The weak and largely non-significant relationships imply that diarrhoeal transmissions in the region are likely driven more strongly by other climatic factors, such as rainfall variability, as well as non-climatic determinants, including water quality, sanitation infrastructure, and hygiene practices.

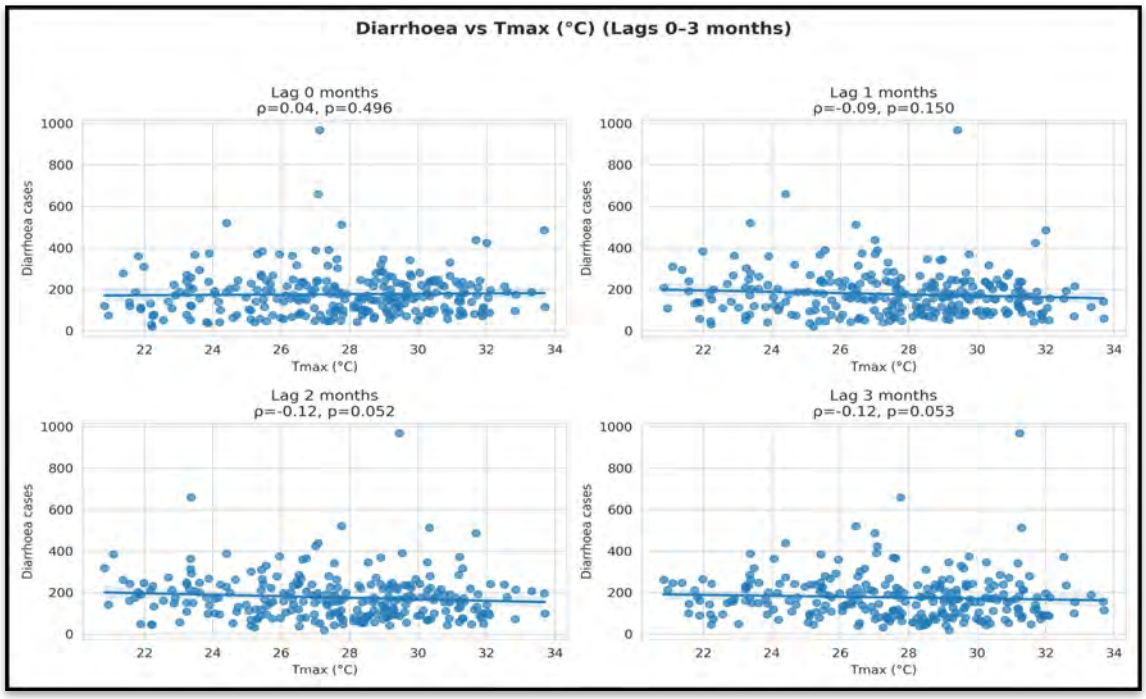


Figure 6.17: Scatter plots of monthly Diarrhoea cases against Tmax at lags 0–3 months in VDM (2004–2025). Each panel displays Spearman's correlation coefficient (ρ) and p-value; the blue line represents the fitted regression with a 95% confidence interval (blue shading).

6.5.2 Multivariate negative binomial regression modelling results on malaria, bilharzia and diarrhoea

The multivariate negative binomial regression results indicate that climatic variables were significantly associated with malaria incidence in VDM (Tables 6.2 and 6.3). Maximum temperature (Tmax) showed a strong and statistically significant positive association with malaria incidence (IRR = 1.196, p = 0.0005), while relative humidity also showed a significant positive effect (IRR = 1.050, p = 0.0146). These findings highlight the role of thermal and moisture conditions in shaping malaria transmission dynamics, which are closely linked to vector survival and parasite development. In contrast, rainfall showed a small but statistically significant negative association with malaria incidence at a zero-month lag (IRR = 0.994, p = 0.0258), reflecting the complex influence of water availability on mosquito breeding environments.

The direction and significance of the regression coefficients align with patterns observed earlier in the lagged climate–disease correlation analysis, where temperature and relative humidity exhibited stronger associations with malaria incidence at short lags, whereas rainfall showed weaker and more variable relationships. Ultimately, these results illustrate that malaria incidence in the VDM is strongly driven by temperature and humidity, while rainfall plays a more complex, temporally dependent role, highlighting the interaction among climate change, water-related processes, and health outcomes.

Table 6.2: Negative binomial regression coefficients (log scale) for malaria incidence in VDM

Variable	Coef	std err	Z	p-value
Intercept	-2.6063	1.6171	-1.6117	0.107
Rain_lag	-0.0065	0.0029	-2.2295	0.0258
Tmax_lag	0.179	0.0517	3.4604	0.0005
RH_lag	0.0488	0.02	2.4425	0.0146

Table 6.3: Incidence Rate Ratios (IRRs) from Negative Binomial regression for malaria incidence

Variable	IRR	95% CI	p-value
Intercept	0.074	0.003 – 1.756	0.107
Rain_lag	0.994	0.988 – 0.999	0.0258
Tmax_lag	1.196	1.081 – 1.324	0.0005
RH_lag	1.05	1.01 – 1.092	0.0146

The multi-variate negative binomial regression results indicate that climatic variables were not statistically significant predictors of bilharzia incidence in the VDM (Tables 6.4 and 6.5). Rainfall showed a negligible association with bilharzia incidence (IRR = 0.999, p = 0.5937), whereas

maximum temperature showed a weak, non-significant negative effect (IRR = 0.945, p = 0.1752). Relative humidity demonstrated no meaningful association with bilharzia incidence (IRR = 1.002, p = 0.904). Overall, these findings suggest that short-term climatic variability alone does not significantly explain bilharzia transmission dynamics in the study area, indicating that non-climatic factors, such as freshwater contact behaviour, snail habitat persistence, and water and sanitation conditions, may play a more dominant role.

Table 6.4: Negative binomial regression coefficients (log scale) for Bilharzia incidence

Variable	Coef	std err	z	p-value
Intercept	5.7572	1.3422	4.2893	0.0
Rain_lag	-0.0013	0.0025	-0.5335	0.5937
Tmax_lag	-0.0566	0.0418	-1.3558	0.1752
RH_lag	0.0019	0.0157	0.1207	0.904

Table 6.5: Incidence Rate Ratios (IRRs) from Negative Binomial regression for Bilharzia incidence

Variable	IRR	95% CI	p-value
Intercept	316.47	22.795 – 4393.706	0.0
Rain_lag	0.999	0.994 – 1.004	0.5937
Tmax_lag	0.945	0.871 – 1.026	0.1752
RH_lag	1.002	0.971 – 1.033	0.904

The multivariate negative binomial regression analysis indicates that none of the climatic variables examined were statistically significant predictors of diarrhoeal disease incidence in the VDM (Tables 6.6 and 6.7). Rainfall exhibited a weak positive association with diarrhoeal incidence (IRR = 1.001, p = 0.5695), indicating a negligible increase in cases as rainfall increased. Maximum temperature showed a weak and non-significant negative effect (IRR = 0.986, p = 0.5655), while

relative humidity was also negatively associated with diarrhoeal incidence, but remained statistically insignificant (IRR = 0.990, p = 0.3246). Overall, these findings suggest that short-term climatic variability alone does not significantly explain diarrhoeal disease incidence in the study area, highlighting the likely of the essential role of water quality, sanitation infrastructure, hygiene practices, and exposure pathways in shaping diarrhoeal disease dynamics.

Table 6.6: Negative binomial regression coefficients (log scale) for Diarrhoea incidence

Variable	Coef	std err	z	p-value
Intercept	6.0722	0.7891	7.6947	0.0
Rain_lag	0.001	0.0017	0.5689	0.5695
Tmax_lag	-0.0141	0.0245	-0.5746	0.5655
RH_lag	-0.01	0.0101	-0.985	0.3246

Table 6.7: Incidence Rate Ratios (IRRs) from negative binomial regression for diarrhoea incidence

Variable	IRR	95% CI	p-value
Intercept	433.624	92.342 – 2036.223	0.0
Rain_lag	1.001	0.998 – 1.004	0.5695
Tmax_lag	0.986	0.94 – 1.035	0.5655
RH_lag	0.99	0.971 – 1.01	0.3246

6.5.3 Predictive modelling of infectious diseases using XGBoost

Following the lagged correlation and multivariate regression analyses an Extreme Gradient Boosting (XGBoost) model was implemented to quantify the predictive relationship between climatic variables and infectious diseases' (diarrhea, malaria and bilharzia) incidences within the VDM. This machine learning approach enables the modelling of non-linear interactions and complex dependencies that are not fully captured by traditional correlation methods.

- **Present-Day XGBoost prediction of malaria incidences**

The present-day results, between observed and XGBoost-predicted malaria cases, demonstrate that the model effectively captures the temporal variability and seasonal structure of malaria incidence in the study area (Figure 6.18). The predicted values generally follow the timing of observed peaks and troughs, indicating that the model successfully learns climate-driven signals governing malaria transmission dynamics. This alignment suggests that climatic drivers embedded in the model, together with temporal information, are sufficient to reproduce relative changes in malaria risk. Despite reproducing seasonal patterns, models consistently overestimate the magnitude of observed malaria cases, even after clipping was applied to constrain extreme predictions. This behaviour is consistent with insights from the SHAP summary analysis (Figure 6.19), which indicates that maximum temperature at a one-month lag (Tmax_lag1) is the dominant driver of model output, followed by lagged malaria incidence and rainfall. The XGBoost model is most effective at identifying relative malaria risk, seasonal timing, and climate sensitivity, rather than providing precise estimates of disease burden. The prominence of lagged malaria incidence highlights transmission persistence, while the secondary role of rainfall and humidity reflects their indirect modulation of vector habitats' suitability.

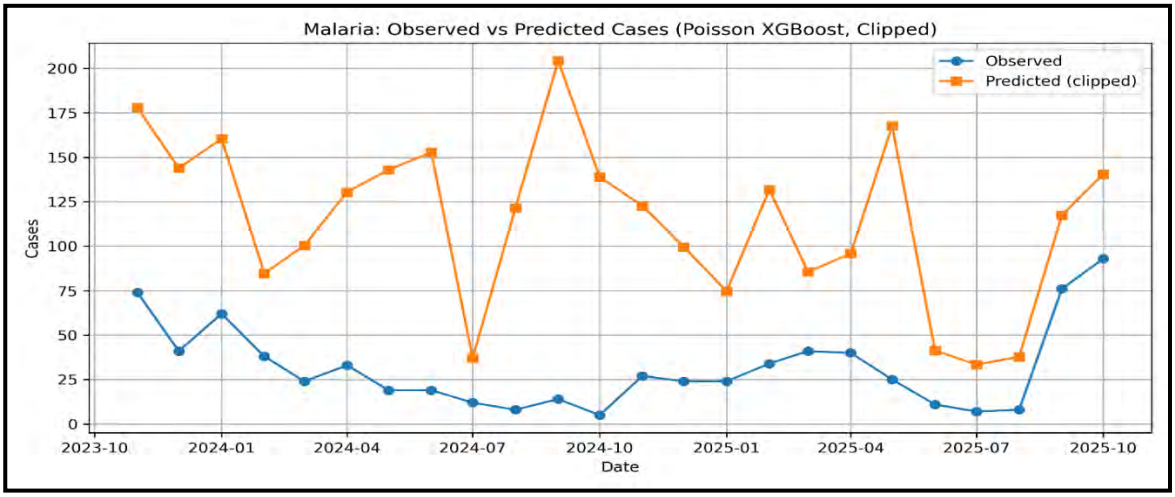


Figure 6.18: Observed and XGBoost-predicted monthly malaria cases for the present-day period

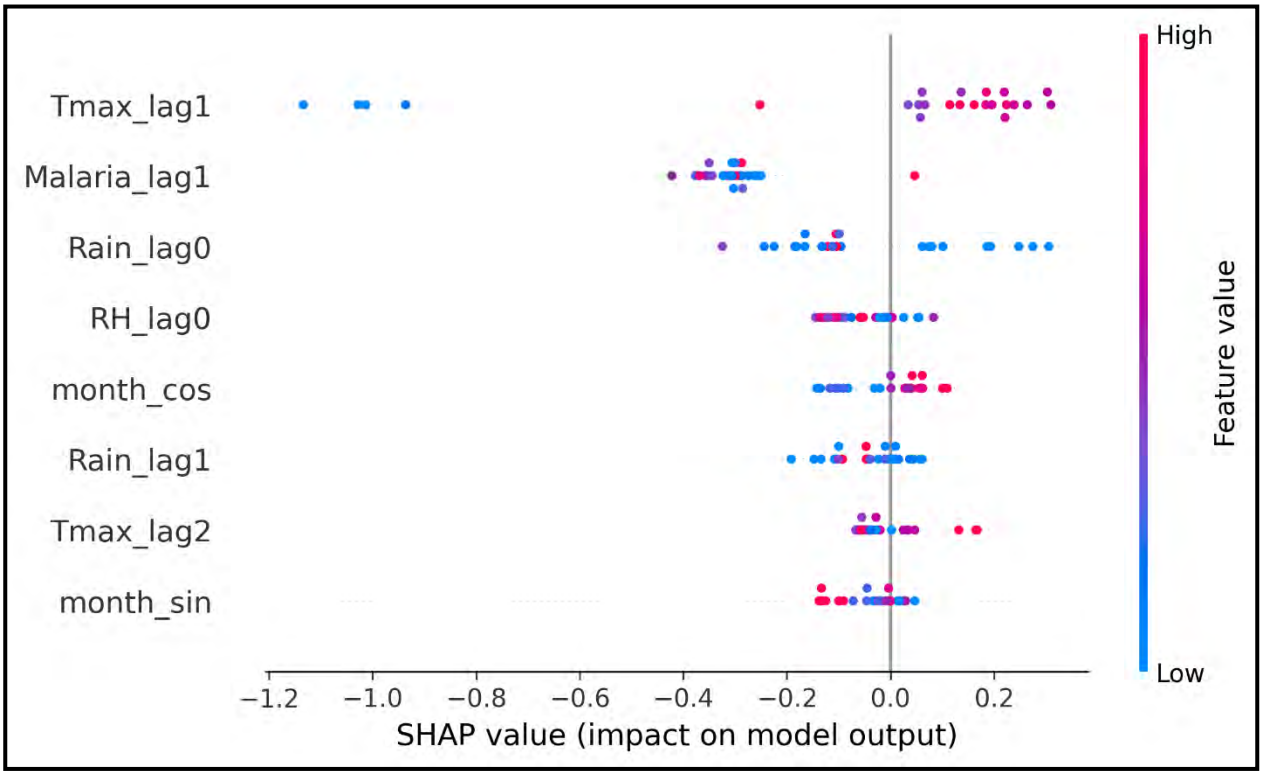


Figure 6.19: SHAP summary plot illustrating the contribution of climatic predictors to XGBoost model predictions of present-day malaria incidence

- **Present-Day XGBoost Prediction of Bilharzia Incidence**

The comparison between observed and XGBoost-predicted bilharzia cases indicates that the model captures the overall temporal variability of bilharzia incidence in VDM (Figure 6.20). Predicted values follow the timing of observed increases and decreases, suggesting that the model captures climate-related signals associated with seasonal changes in transmission. The model reproduces relative fluctuations in bilharzia risk, indicating its ability to represent climate-enabled variability, rather than exact case counts. The SHAP summary analysis (Figure 6.21) identifies maximum temperature at a one-month lag (Tmax_lag1) and recent rainfall (Rain_lag0 and Rain_lag1) as the most influential predictors. These variables primarily affect environmental suitability for intermediate snail hosts rather than directly controlling transmission intensity. The

moderate contribution of lagged bilharzia incidence further indicates persistent transmission, while the weaker influence of relative humidity and seasonal terms suggests indirect modulation of risk rather than strong short-term climatic forcing.

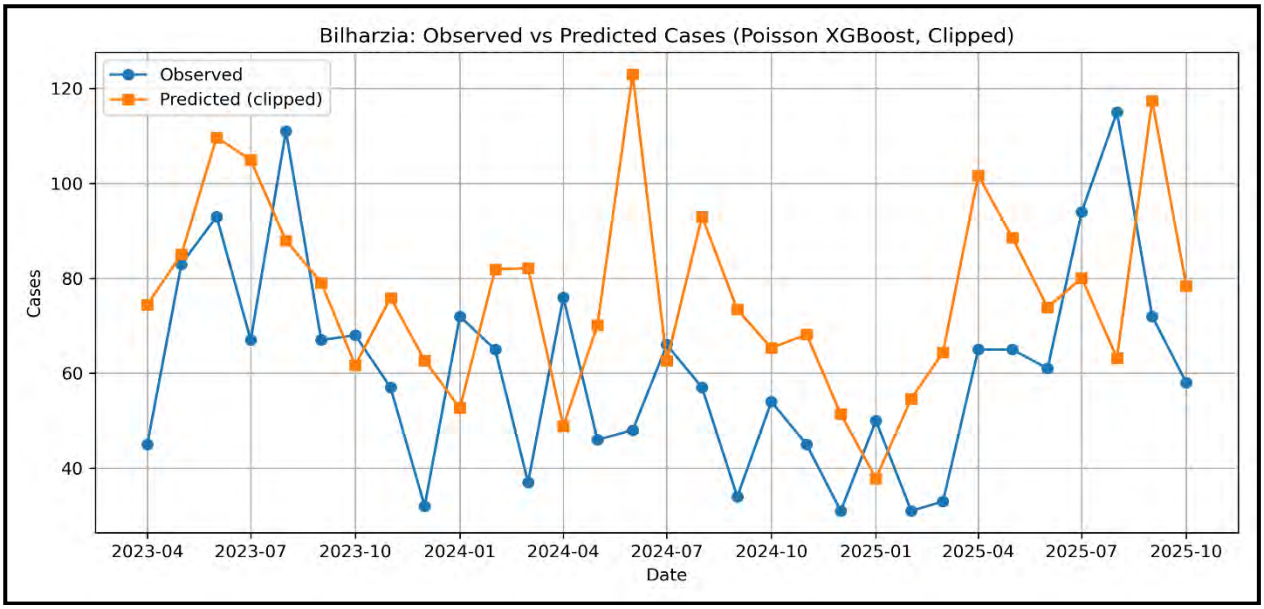


Figure 6.20: Observed and XGBoost-predicted monthly bilharzia cases for the present-day period

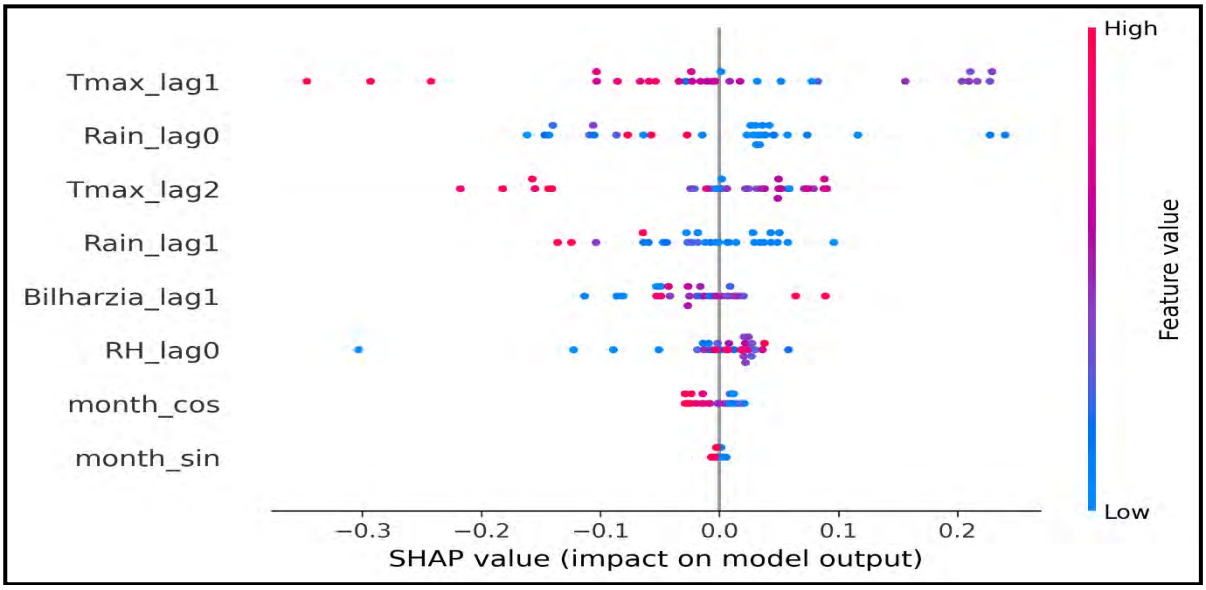


Figure 6.21: SHAP summary plot showing the contribution of climatic predictors to XGBoost model predictions of bilharzia incidences

- **Present-Day XGBoost Prediction of Diarrhoea Incidences**

The model captured the overall temporal variability and episodic peaks in diarrhoeals across the study period (Figure 6.22). Model predicted values generally align with the timing of observed rain increases and declines, particularly during periods characterised by heightened variability, indicating that the model successfully learns climate-related and seasonal signals, influencing diarrhoeal transmission. While short-term fluctuations were reproduced reasonably well, discrepancies in peak magnitudes remain evident, hence, reflecting the complex and event-driven nature of diarrhoeal disease dynamics.

The SHAP summary analysis provides insight into this behaviour, identifying lagged diarrhoeal incidence (Diarrhoea_lag1) as the dominant contributor to model output, highlighting strong temporal persistence in transmission dynamics (Figure 6.23). Relative humidity at zero lag (RH_lag0) and rainfall at one-month lag (Rain_lag1) also show notable influence, suggesting that moisture conditions and antecedent rainfall events modulate diarrhoeal risk by affecting pathogen survival, water contamination, and exposure pathways. Temperature variables (Tmax_lag1 and Tmax_lag2) and seasonal components contribute more modestly, primarily refining seasonal timing, rather than driving large changes in predicted incidences.

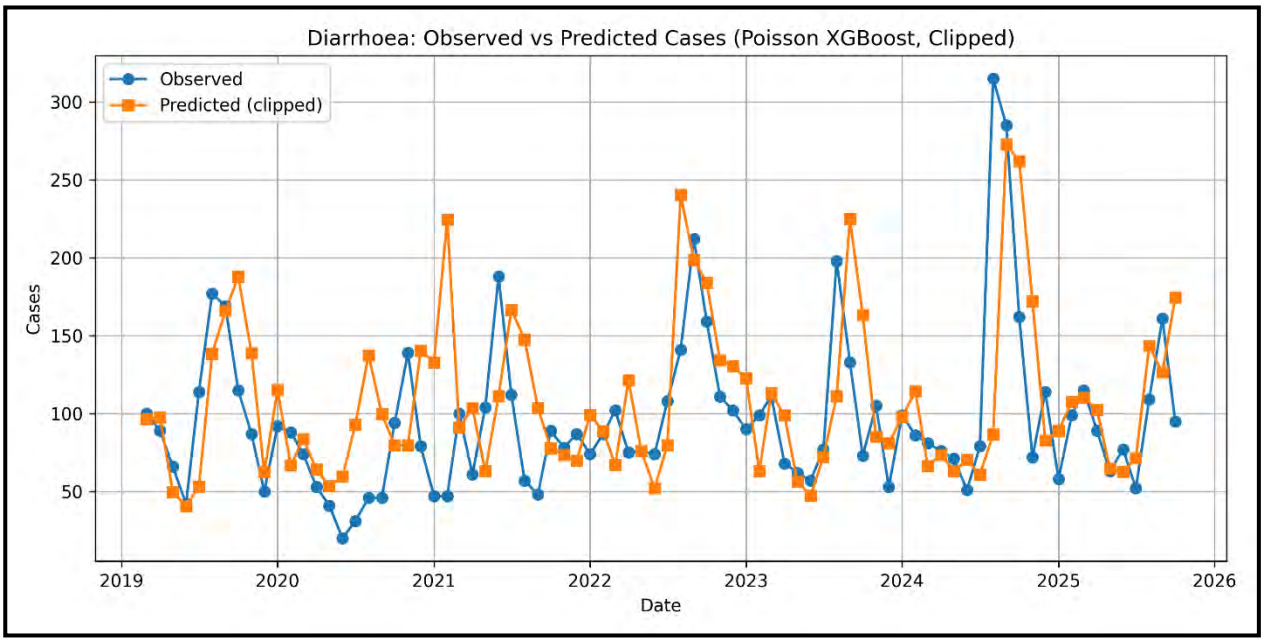


Figure 6.22: Observed and XGBoost-predicted monthly diarrhoea cases for the present-day period

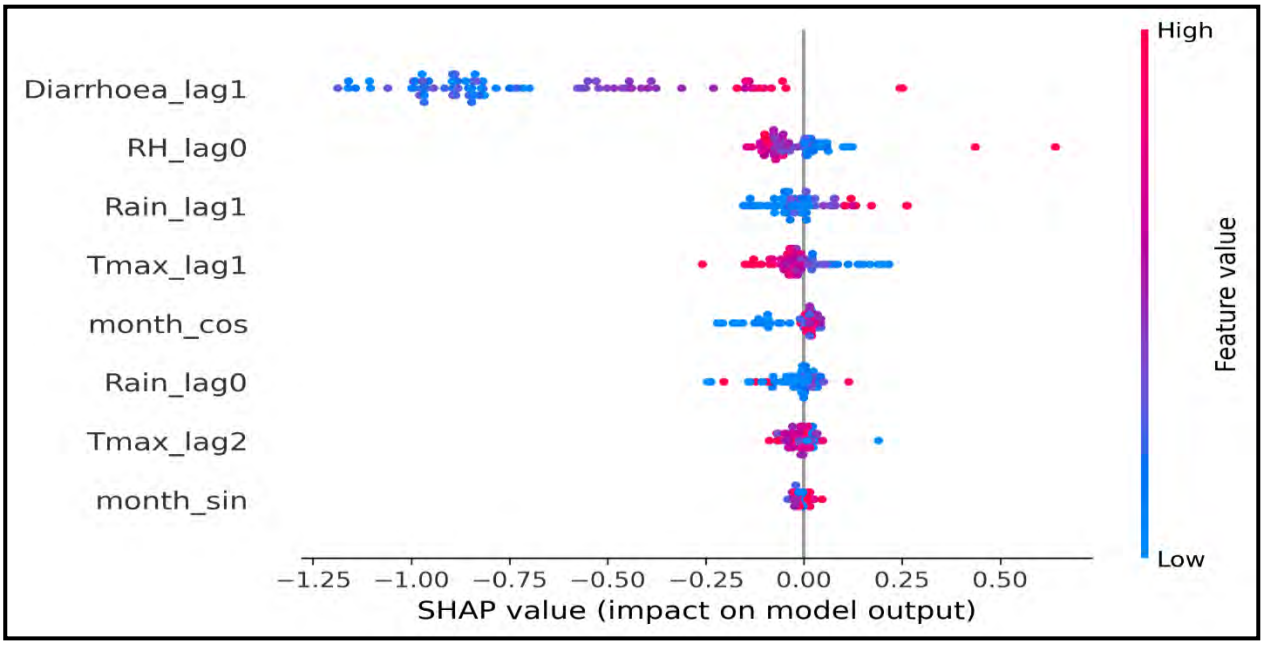


Figure 6.23: SHAP summary plot illustrating the contribution of climatic predictors to XGBoost model predictions of diarhoea incidences

6.5.3 Interpretation of XGBoost model performance across diseases

The performance metrics indicate substantial variation in XGBoost predictive skill across malaria, diarrhoea and bilharzia. Malaria exhibits the highest error levels, with large MAE (82.73) and RMSE (93.23) values, reflecting considerable discrepancies between observed and predicted case counts (Table 6.8). This is reinforced by the extremely high MAPE (476.31%) and strongly negative R^2 (–15.223), indicating that the malaria model performs substantially worse than a simple mean-based benchmark. The poor predictive performance observed for malaria may be partly influenced by limitations in the disease-reporting record, including a shorter effective reporting period (2020-2025). Malaria incidences are highly sensitive to changes in diagnostic practices, vector-control interventions, and reporting systems, thereby decoupling observed case counts from underlying climatic suitability. These results suggest that, while the model captures temporal patterns, climate-only predictors are insufficient to accurately reproduce absolute malaria-incidence reports, likely due to strong influences from non-climatic factors such as vector control interventions, immunity, and surveillance practices.

Table 6.8: Performance metrics of XGBoost models for predicting present-day infectious diseases' incidences

Metric	Malaria	Diarhoea	Bilharzia
MAE	82.73	37.34	25.50
MSE	8692	2926.80	880.84
RMSE	93.23	54.10	29.68
MAPE (%)	476.31	47.61	49.33
R^2	-15.223	-0.155	-0.881

In contrast, the diarrhoeal disease model shows moderate predictive performance, with lower MAE (37.34) and RMSE (54.10) values relative to malaria. The MAPE (47.61%) indicates improved proportional accuracy, although the slightly negative R^2 (–0.155) suggests that the model still struggles to outperform a baseline mean predictor. Failures introduce variability that is only partially captured by climatic drivers. Bilharzia demonstrates the lowest error metrics among the three diseases, with comparatively small MAE (25.50) and RMSE (29.68) values, indicating closer alignment between observed and predicted cases. However, the negative R^2 (–0.881) indicates that, despite a reduced error magnitude, the model does not fully explain the variability in bilharzia incidence. This suggests that while climatic and hydrological conditions contribute to bilharzia risk, transmission dynamics remain strongly mediated by water-contact behaviour, ecological persistence of snail hosts, and sanitation conditions. Overall, these results confirm that the XGBoost models are more effective at capturing relative variability and climate-sensitive risk signals than at predicting absolute diseases' burden, supporting their use for scenario-based projections, rather than precise case forecasting.

6.5.3 Climate change driven XGBoost projections of infectious disease incidence under SSP2-4.5 and SSP5-8.5

The XGBoost projections indicate persistent strong variability in malaria incidences across the near- (2021–2040), mid- (2041–2060), and long-term (2081–2100) periods, under both SSP2-4.5 and SSP5-8.5 scenarios (Figures 6.24-6.26). Across all horizons, recurrent peaks and troughs are maintained, suggesting that the climatic drivers embedded in the model continue to govern the timing and intra-annual dynamics of malaria transmission, under future climate conditions. While both scenarios display similar recurring patterns, SSP5-8.5 generally exhibits higher and more frequent extreme peaks, particularly in the near- and mid-term projections, reflecting enhanced climatic suitability for malaria transmission, under higher-emissions pathways.

Even though the amplitude of predicted peaks varies across time horizons, there is no clear monotonic increase in baseline malaria incidence from the near- to long-term periods, indicating that climate change may primarily influence variability and extremes rather than steady increases in mean incidence. The persistence of pronounced peaks under SSP5-8.5, in the long-term highlights the potential for episodic surges in malaria risk, even if average conditions remain comparable across scenarios. These findings may suggest that future malaria risk in the study area is likely to be characterised by heightened climate-driven variability and occasional extreme transmission periods, rather than uniform increases in diseases' burden. Consequently, the XGBoost projections should be interpreted as indicators of changing seasonal risk patterns and extreme-event sensitivity, with important implications for climate-informed early warning systems and adaptive public health planning.

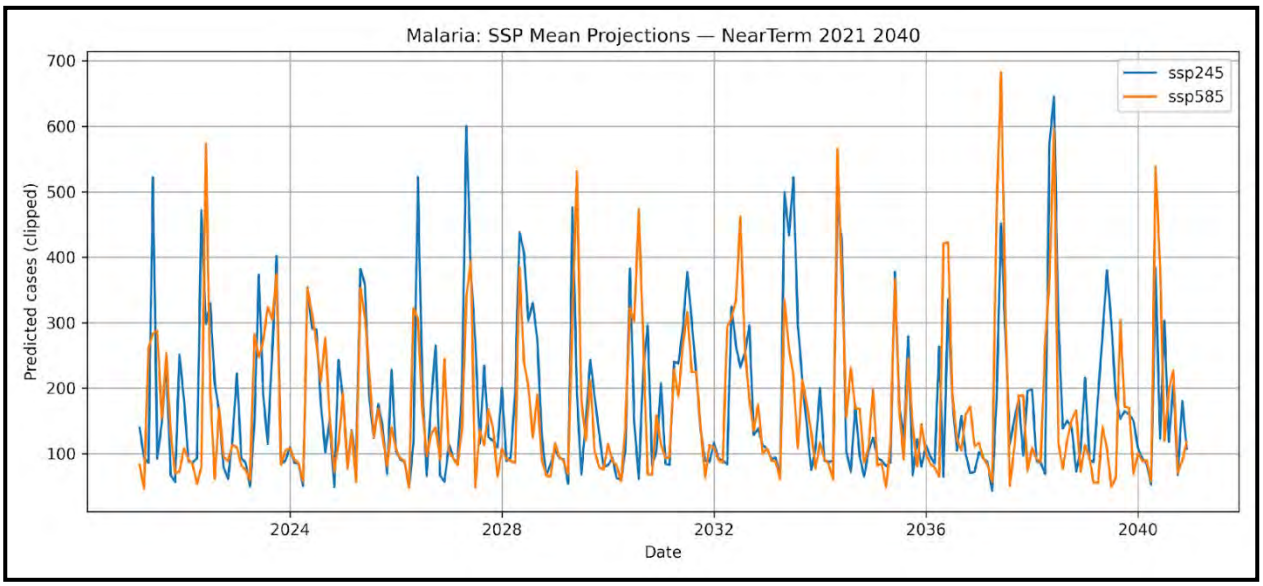


Figure 6.24: XGBoost-Projected mean monthly malaria incidence under SSP2-4.5 and SSP5-8.5 scenarios for the near-term period (2021–2040)

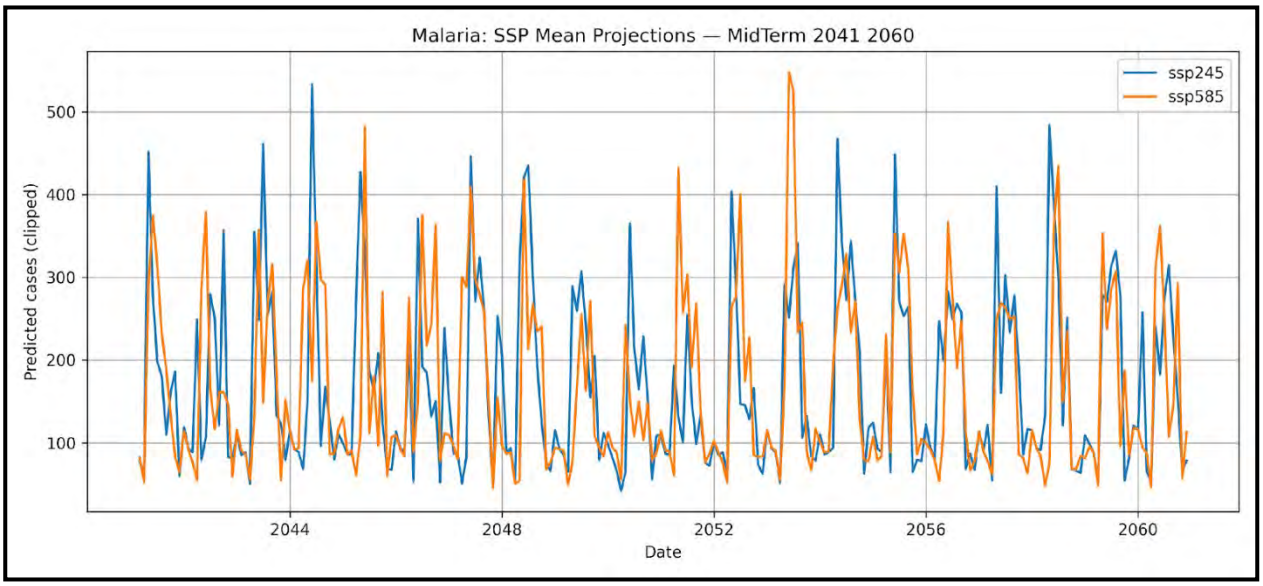


Figure 6.25: XGBoost-projected mean monthly malaria incidences under SSP2-4.5 and SSP5-8.5 scenarios for the mid-term period (2041–2060)

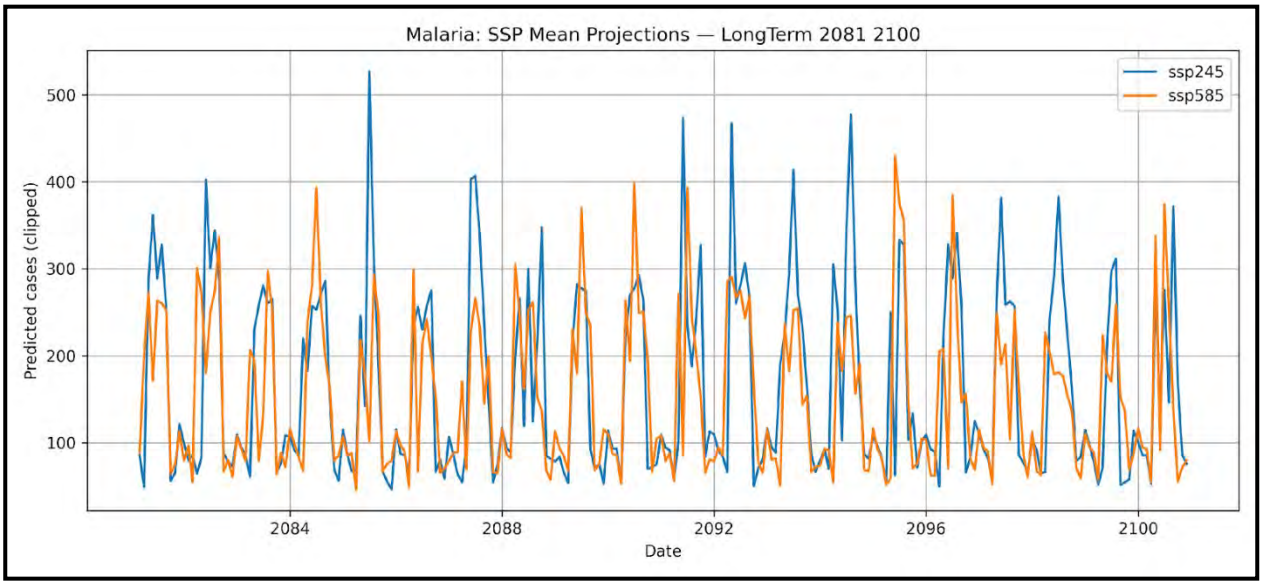


Figure 6.26: XGBoost-projected mean monthly malaria incidences under SSP2-4.5 and SSP5-8.5 scenarios for the long-term period (2081–2100)

The XGBoost projections of bilharzia incidences show a persistent and well-defined cycle across the near-term (2021–2040), mid-term (2041–2060), and long-term (2081–2100) periods under both SSP2-4.5 and SSP5-8.5 scenarios (Figures 6.27-6.29). Recurrent annual peaks and troughs are

maintained throughout all time horizons, indicating that the climatic drivers embedded in the model continue to regulate the timing of bilharzia transmissions, under future climate conditions. Both scenarios display similar seasonal structure, however, SSP5-8.5 generally exhibits greater peak variability in the near- and mid-term periods, reflecting enhanced hydrometeorological variability that may influence freshwater habitats' suitability for intermediate snail hosts.

Differences in peak magnitude between years indicate the influence of interannual climate variability, likely mediated through year-to-year fluctuations in rainfall intensity and freshwater persistence. Within the CWH nexus, these results reinforce the notion that bilharzia risk remains strongly governed by water availability, ecological persistence of snail habitats, and human water-contact behaviour, with climate acting as an indirect enabling factor. Consequently, XGBoost projections for bilharzia should be interpreted as indicators of future climate-sensitive transmission potential and variability, rather than precise forecasts of the disease's burden.

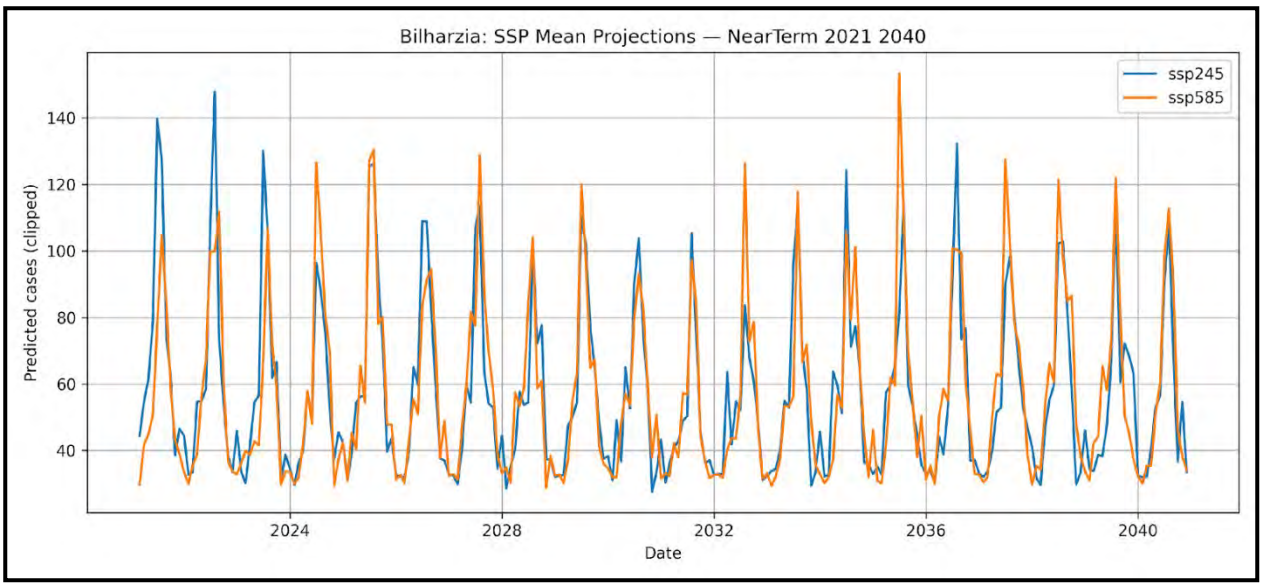


Figure 6.27: XGBoost-projected mean monthly bilharzia incidences under SSP2-4.5 and SSP5-8.5 scenarios for the near-term period (2021–2040)

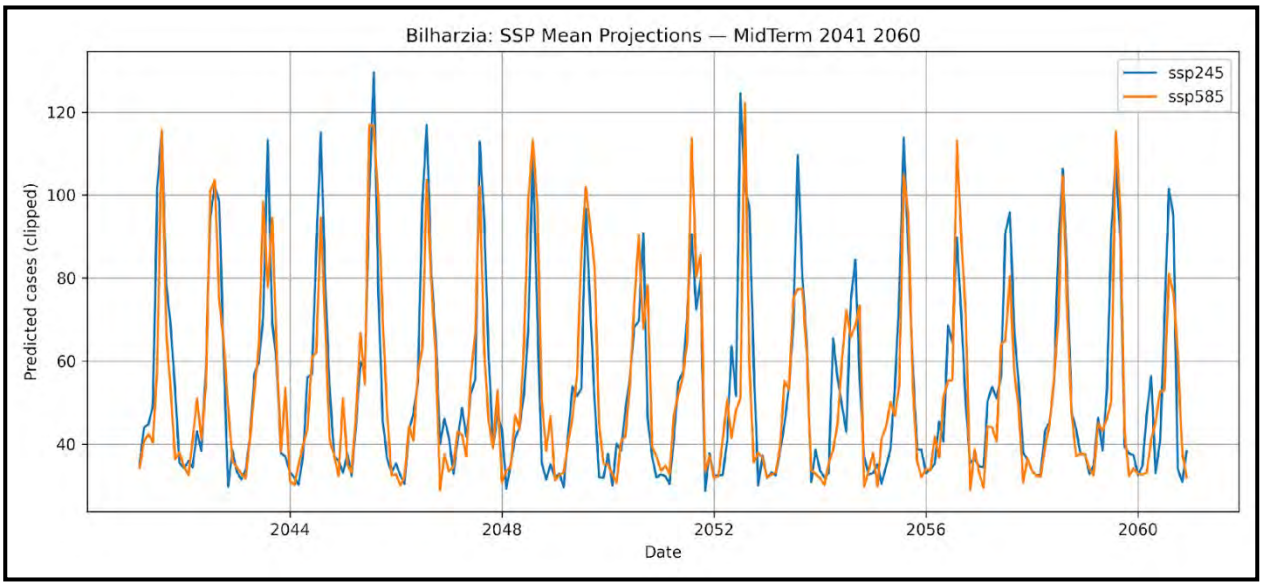


Figure 6.28: XGBoost-projected mean monthly bilharzia incidences under SSP2-4.5 and SSP5-8.5 scenarios for the mid-term period (2041–2060)

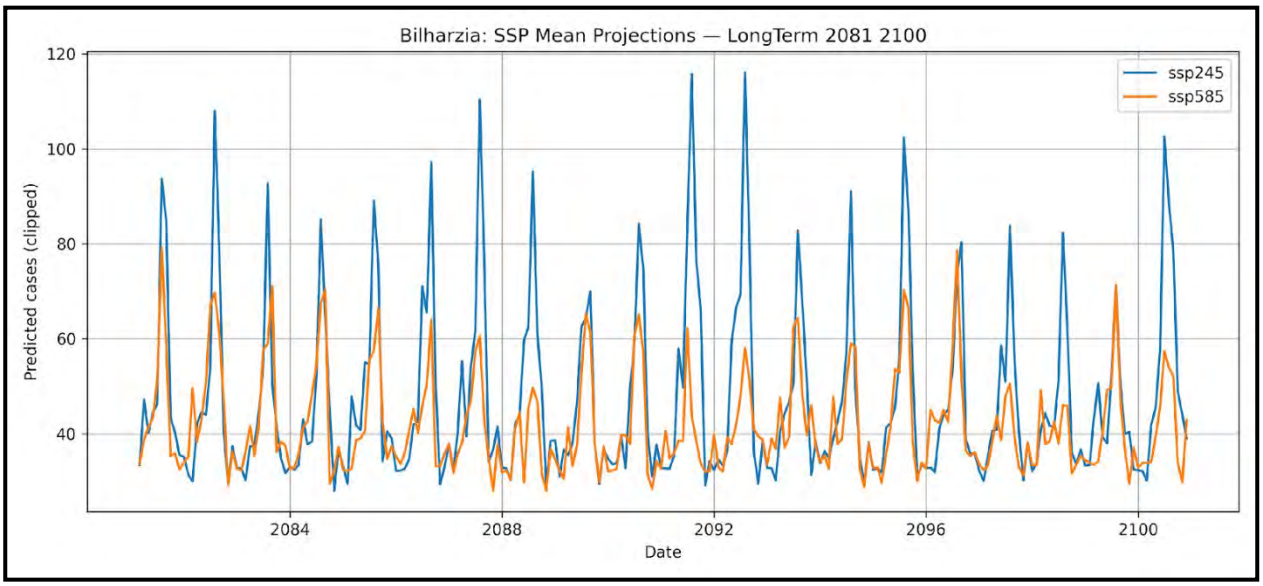


Figure 6.29: XGBoost-projected mean monthly bilharzia incidences under SSP2-4.5 and SSP5-8.5 scenarios for the long-term period (2081–2100)

The XGBoost projections of diarrhoeal disease incidences reveal pronounced peaks (Figures 6.30-6.31) occurring irregularly across both the mid-term (2041–2060) and long-term (2081–2100) periods under SSP2-4.5 and SSP5-8.5 scenarios, compared to bilharzia and malaria. Variability is

evident, although the timing and magnitude of extreme peaks vary substantially between years, indicating that diarrhoeal risk is driven more by short-term exposure and contamination events, than by gradual climatic suitability. Across both future horizons, substantial overlap is observed between SSP2-4.5 and SSP5-8.5 projections, with scenarios' divergence becoming most apparent during extreme incidence spikes, rather than during baseline conditions. This contrasts with the clearer scenario separation observed for malaria and suggests that future diarrhoeal risk may be governed more by threshold exceedance and infrastructure vulnerability, rather than by emissions pathway alone. Within the CWH nexus, these findings highlight that diarrhoeal disease outcomes are strongly shaped by water contamination pathways, sanitation resilience, and hygiene conditions, with climate change acting primarily as an external stressor that amplifies short-term outbreak potential. Consequently, XGBoost projections for diarrhoeal incidences should be interpreted as indicators of episodic outbreak risk and shock sensitivity, rather than as predictors of sustained changes in mean disease incidence.

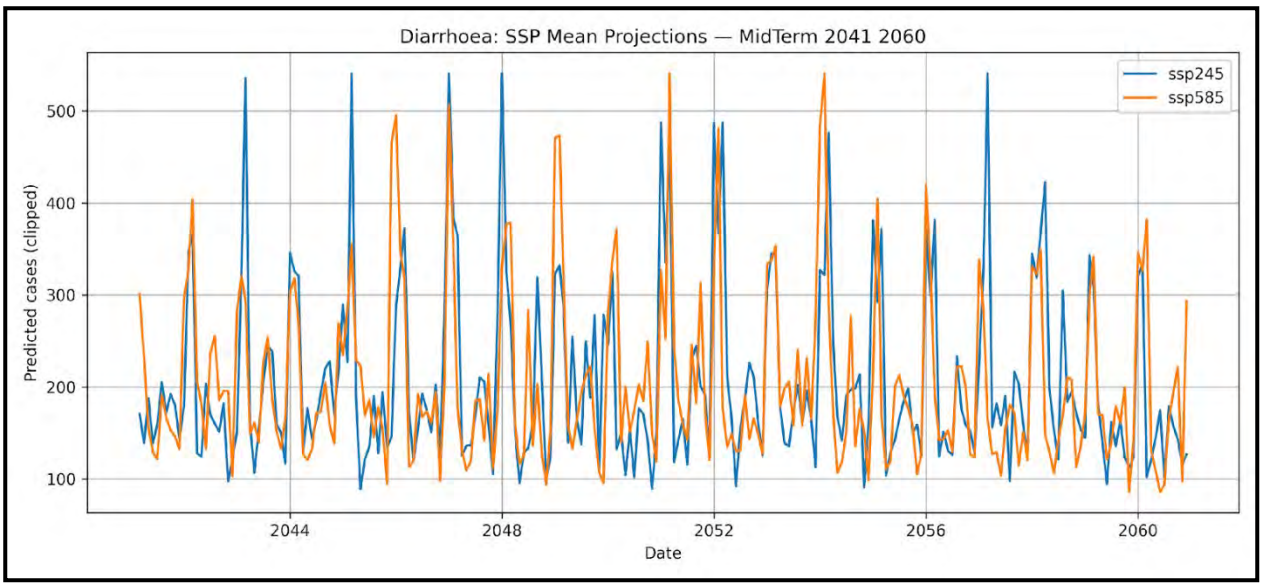


Figure 6.30: XGBoost-projected mean monthly diarhoea incidences under SSP2-4.5 and SSP5-8.5 scenarios for the mid-term period (2041–2060)

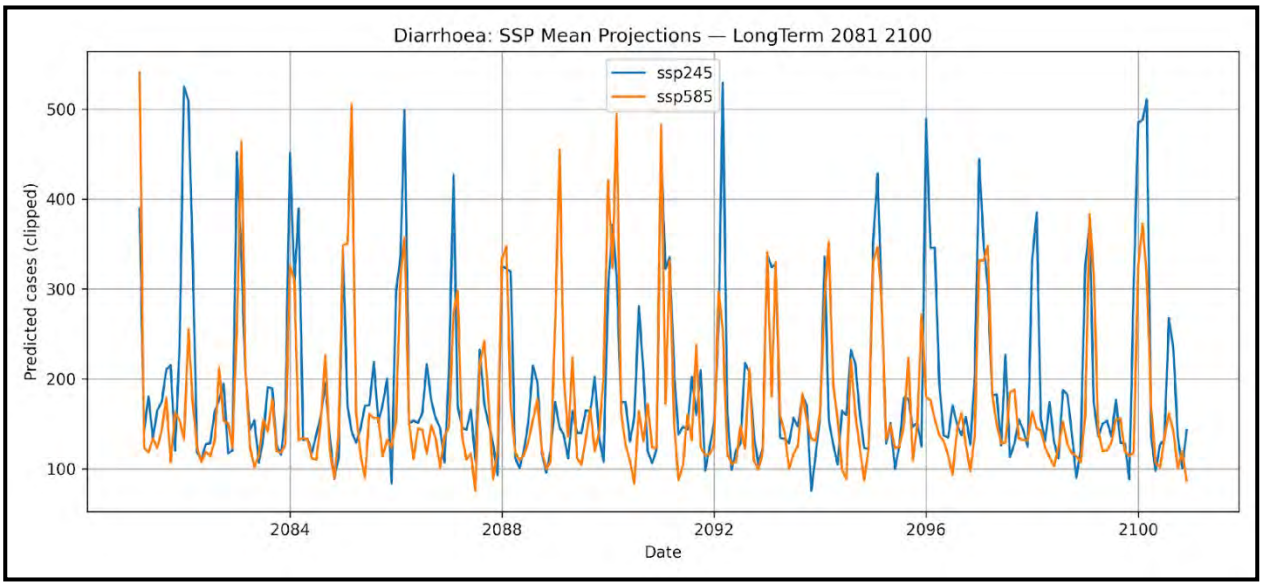


Figure 6.31: XGBoost-projected mean monthly diarrhoea incidences under SSP2-4.5 and SSP5-8.5 scenarios for the near-term period (2081–2100)

CHAPTER 7: INNOVATIONS, COLLABORATIVE LEARNING AND CO-PRODUCTION OF NO REGRET ADAPTATION STRATEGIES AND CRD IN THE WATER SECTOR

7.1 Introduction

This chapter discusses concepts and tools for exploring pathways for innovation in transformative adaptation planning. It also analyses broad innovations for collaborative learning and co-production of no regret adaptation strategies and CRD in the water sector. The chapter discusses emerging gaps and opportunities, as well as innovations in collaborative learning and co-production.

7.2 Overview of innovations theory and practice

Innovations are central instruments of sustainability policies, and they project future visions onto technological solutions and enable win-win framings of complex sustainability issues. Innovation cover a broad spectrum of dimensions across technological, institutional, and behavioural changes, as well as being responsive social systems, which in turn influence the effectiveness of smart technologies, such as carbon capture and storage initiatives (Steffen et al., 2018). Innovation can also be framed as policy alternatives for addressing a particular objective (Buschmann and Oels, 2019) and, in general are inclusive of changes in processes, practices, structures, and institutions at individual, organizational, and technological levels (Newell et al., 2021; Otto et al., 2020; Douthwaite and Hoffecker, 2017).

Primarily, innovation involves organizing knowledge to create new products, processes, or ideas that drive social change. It is a creative cycle in adapting to change and for producing goods and services within an organization or community (Douthwaite and Hoffecker, 2017). Due to the understanding of institutional-human behaviour interplay (community-based learning labs), (Seto et al., 2016), it is argued that cross-sector linkages and membership to local institutions are

potentially critical in the innovation ecosystem as they both mediate capabilities and accumulation of knowledge and diffusion of ideas and solutions to Day-Zero water risks as avenues for collaborative learning and innovation. Community-based disaster reduction innovation platforms (CBDRR-IPs), hence, are suggested as avenues for collaborative learning, co-designing of innovations, and amplification of these across regimes.

In this report, innovation is conceptualised from a system transformation perspective, in the context of climate change extremes on water and its chain impacts on hygiene, sanitation, as well as the quantity and quality of water. The report does not focus on specific innovations *per se*, but rather, as suggested by Malmström et al. (2025), focuses on intentional responses. Intentional responses are, herein referred to as public policy responses as well as autonomous action by individuals, communities, or businesses towards addressing the climate-related challenges on water-health-sanitation-hygiene (WAHSH) outcomes in Day-Zero adaptation planning. Implicitly, the focus is on systemic societal impacts of policies with a view of supporting innovation for mitigating climate related risks on water resources and livelihoods. We advocate for transformative collaboration and co-designing of WAHSH innovation through CBDDR-IPs as key to DayZero adaptation initiatives.

7.3 Concepts and tools for exploring pathways for innovation in transformative adaptation planning

This section elaborates and operationalizes various aspects of innovation from a CBDRR perspective and in the context of transformative adaptation planning for Day Zero water scenarios. The following section highlights the concepts used in the investigation in general and the conceptualization of innovation from a citizen science and justice lenses' perspective. The study adopted and adapted Temmer et al. (2024) main transformation topologies to delineate the scope and meaning of innovation using the interaction of water availability, sanitation and hygiene

outcomes (herein referred to as CWH nexus) as a baseline to conceptualizing complexity in adaptation planning.

Systemic risks and complexity

Systemic risks such as the effect of climate related droughts and floods on water borne diseases impact societies individually and collectively in terms of incurred losses, experienced disruptions, collapse, damage to systems or its subsystems (Hochrainer-Stigler, 2020). Health, as a crucial facet of this nexus, is intricately linked to the availability and quality of water, the energy required for sustenance, and the nutritional aspects of food production, hence the need for a holistic understanding of these interdependencies is critical as well as being integral to strategic planning in the pursuit of sustainability and no regret adaptation planning (Mutanga et al., 2024).

Nexus lenses on water, climate change, health, as well as governance, policy, and institutional frameworks are, thus systemic in nature and considered critical in the design of no regret adaptation measures. Understanding system interdependencies has the potential to inform how systemic risks are induced as well as the design and implementation of transformative change. Accordingly, developing and implementing context-specific solutions should be rooted in local knowledge as part of a system-of-systems approach for addressing unique challenges and opportunities to deepen the climate crisis and other global change in general (Hochrainer-Stigler et al., 2024).

In this report, vulnerability of communities to health risks-climate change nexus is conceptualised through water quality, sanitation, and hygiene pathways and complex systems. Systems-of-systems approaches for short-term risk analysis aim to reduce the risk of cascading adaptation failures, allow for more effective responses, and improve coordination. For long-term planning, systems of-systems approaches, and adaptation planning actors, take a holistic view and explore

strategic adaptation interventions across critical sectors for effective adaptation on any WAHSH component.

Contextualised visions as innovations

Lived experiences, needs, priorities, and cultural aspirations influence innovations. Operationalising such visions to standard assumptions through multi-criteria objective analysis, can facilitate the emergence of robust and unbiased no regret adaptation pathways, herein termed as "innovations". Effective adaptation requires co-production of knowledge with the robust engagement of scientists and local communities (Klenk et al., 2017). Co-produced visions, goals, and strategies can involve perspectives across multiple sectors, scales, and communities to gather the full range of ideas, innovations, and possible actions to address trade-offs and inform transitions toward CRD.

Innovation

An idea, good, service, process, or procedure is considered to be novel in solving a given problem or exploiting an opportunity (Nair et al., 2016) which addresses technological, institutional, behavioural, social, cultural, and indigenous issues (Otto et al., 2020; Steffen et al., 2020; Douthwaite and Hoffecker, 2017). Innovation can take many forms, such as:

- Idea to solve societal problem, which in this case, is the need for transformative adaptation solution to DayZero risks in the water sector;
- Conceptualisation and framing of a problem;
- Implementation approach;
- Process or product, such as a policy, or structure for policy learning, and
- Software and hardware.

Transformation

Transformation largely involves reimagining social, economic, and environmental systems, changing policies and regulations, promoting behavioural changes, and fostering innovation and technological advancements, to tackle root causes of challenges and promote sustainability and equity (Hochrainer-Stigler et al., 2024). Transformative adaptation in the water sector aims at ensuring just and minimum access to clean and safe water for sanitation and hygiene, as well as livelihood support. In this report, the transformation towards ensuring minimum access to water for hygiene, sanitation (considered part of health), and livelihoods under various Day-Zero scenarios is considered as part of WAHSH innovation. In essence, we have conceptualised transformative innovation pathways as ideas and practices, governance trajectories or policies that ensure minimum water access beyond mere survival as well as providing of dignified life - access to sanitation and pursuit of desired livelihood activities, food production and utilization. These in essence facilitate one escaping from water crisis-triggered poverty traps.

Systemic transformations of underlying drivers of water security dynamics (availability, access and cost) and reducing vulnerability to harm from climate change induced water-borne related diseases, while ensuring everyone lives within safe corridors or sustainability of the water resources and ecosystems in a changing climate, is the focus of innovation lenses adopted in this report. The focus, however, is only on 3 broad governance pathways as “innovation”, hence no specific innovation is explicitly given, as this requires context-specific code-signing processes, policy experimentation, and validation of many such innovations, on the effect of water sensitive sanitation and hygiene practices on water demands and their chain impact across competing uses.

7.4 Analytical approach

The analytical approach used largely borrows from existing analytical frameworks on structuration theory /structures and agency (Giddens, 1984) and multi-level perspective (MLP) on innovations (Geels, 2019; 2005), as well as innovation labs, system, transition and complex systems, policy

experimentation and synergy theories (Hanson et al., 2003). In so doing, this report presents an assessment of gaps and opportunities for transformation and resilience building to anticipated Day Zero risk planning under uncertainty, in VDM, Limpopo Province, Republic of South Africa. Dorst's (2015) nine-part "frame creation process model" as outlined hereunder was adapted in the framing process:

- **Archaeology**: analysing the problem in depth while considering earlier attempts to solve it;
- **Paradox**: investigating the challenges in addressing the problem;
- **Context**: exploring key actors of the problem and their environment, that is, their behaviors;
- **Field**: examining the broader landscape, surrounding the problem (context);
- **Themes**: analysing and articulating deeper factors at play in the field;
- **Frames**: investigating implications of possible actions, given the themes and envisaged outcome;
- **Futures**: "thinking forward" to see if the frame will lead to viable solutions - back casting and storytelling tools were used;
- **Transformation**: critically evaluating different solutions and their feasibility over time. This was based on the assumptions that the team co-developed the solutions, at the expert and community levels; and
- **Integration**: ensuring frames and solutions can be well integrated into stakeholder organizations; hence, co-designing at the community level is recommended for future elaboration.

The workshops adopted the decision-to-practice learning steps by Brown (2008), to interactively integrate knowledge cultures in answering research questions. The FGDs and KIIs following the adaptation pathways (Wise et al., 2014; Werners et al., 2021a) were the primary data collection tools. Community workshops (knowledge cultures from strategic, local, and holistic clusters) were

used to segregate and categorise actors to ensure representativeness and community inclusion. The analysis of the process outputs was used to understand different stakeholders' perspectives on the CWH nexus, including priority "no regret" adaptation strategies and innovations at the community level.

7.5 Data analysis

Descriptive statistics were used to analyse innovations and practices identified by the community and experts. These were backed up by the KIIs and FGD findings. Quantitative data was analysed using descriptive statistics through the Statistical Package for Social Sciences (SPSS) version 28 of the International Business Machines (IBM) Corporation. Thematic data analysis involved identifying, analysing, and reporting patterns (themes) within the data (Bryman, 2016). Data analysis using the thematic approach affords the researcher flexibility and fits different or multiple contexts. This included the use of:

- The back-casting approach to fold the future into the present "strategic intent", based on participants' lived experience and expertise. Strategic intent provided a shared platform for solutions (herein referred to as innovations) while focusing on the overall objective for Day Zero adaptation innovations. The dwelling (reflective learning/connecting/engagement) process meant investing time to understand and articulate both the problem and objective, including alternate means of coping with climate impacts on hygiene, sanitation, as well as quality and quantity of potable water at the household and community levels. These were based on several assumptions, whose meaning was jointly agreed upon, through consensus. The platform and freedom provided challenged expert views, hence dissonance on justice lenses, an emerging issue, yet neglected in adaptation policy cycles.
- The storyline referred to Quantitative Story Telling (QST), in exploring uncertainty in support of the various plausible innovations. The QST is a multi-scale nexus assessment and bio-physically grounded method for assessing dominant stakeholder narratives and

expectations; it is critical in the analysis of complex social-ecological system challenges (Di Felice et al., 2021); co-production of knowledge (Saltelli and Giampietro, 2017), as well as checking the coherence of already existing or new narratives (Di Felice et al., 2021). Divergent viewpoints such as opinions and their interpretations, expert and lay judgement, knowledge authorities, truth claims and assumptions, informed the narratives, through a complex combination of cognitive and moral principles, beliefs, values, knowledge, experience, and social-political factors (Kowarsch et al., 2017). In essence, the significant utility of QST lies in its support for citizen science and effective participation, as envisaged under the transformative approaches to planning. Segregation of FGDs based on gender and age-groups was undertaken, to ensure a truly inclusive participation and co-creative process. This enabled a nuanced knowledge sharing, as well as the addressing of potential power imbalances.

- Multi-criteria decision analysis (MCDA) based on multi-criteria objective and participatory scenario workshops were some of the collaborative tools used to navigate contested goals and viewpoints (Eames and Mcdowall, 2010). Alternatives were evaluated using a defined set of qualitative and quantitative criteria, weighted according to stakeholders' preferences and policy goals. MCDA is inherently subjective, although a consensus was reached, around the definition, meaning, and scope of the assumptions adopted, and the processes, thereby reducing potential bias in the solutions. The MCDA was anchored on the principles of "deliberative" research, which involves a representative group of individuals in processes of learning, discussion, and formulation of conclusions or recommendations (Ercan et al., 2022) that are informed by the lived experience of citizens, as well as the specialist knowledge of analysts (Blomkamp, 2018).

7.5.1 Policy design principles for conceptualising WAHSH innovations

A policy cycle usually includes identification, definition, articulation, justification, and choice, on a course deemed appropriate to solve a problem (in this instance, climate related WAHSH risks and associated innovation for transformative adaptation). The concept of "innovation" was defined to mirror the policy cycle and the summarised governance pathways for no regret adaptation. We adopted Blomkamp (2018) definition of co-designing as the active involvement of a diverse range of participants in exploring, developing, and testing responses to shared challenges. The WAHSH Day-Zero scenarios informed the conceptualisation of innovative collaborative mechanisms for learning, grounded in policy design principles, as highlighted hereunder:

- **Causation:** establishing cause-effect (action-consequences), in which case policy makers need to identify significant contributing factors, for addressing WAHSH wicked challenges.
- **Intervention:** effecting change from one state (undesirable) to another (desirable) by influencing variables which have transformative properties (information, regulatory, communicative and behavioural). The adopted assumptions enabled the incorporation of a transformative lens.
- **Evaluation:** specifying values attached to a particular policy instrument (not comparison of outcomes with objectives). It involves actions for facilitating learning within the system, by enhancing opportunities for dialogue over desired values and simulating reflection by subjects. It also involves identifying options for achieving a given result, as well as analytical and implementation strategies**.** The assumptions were matched to context specific lived experiences and expert views
- **Interaction:** this was based on Luhmann's theory of the autopoietic perspective on the self-organizing aspect of systems of communication, which constitute social life. The assumption is that, a system that organizes itself does not require order to be imposed externally, buexternally butown order through the interplay of the components of the

system. Such logic guides policy reflexivity or the ability of a system to understand its own operations in terms of more general processes in social differentiation. The extent of interaction enhances opportunities for adaptation and learning; hence, our recommendation of CBDRR-IPs as an institutional framework for simultaneously evaluating interagency coordination and transformation.

- **Coordination**: is the need to understand interagency/ intersystem conflicts (which are more procedural rather than being substantive/ relational). Process and policy products are critical in enhancing reflexivity. The centrality of national and subnational systems in adaptation planning was, thus posited as critical for interagency/ intersystem conflicts' management.

7.6 Assumptions

Debates on assumptions, such as socio-economic factors that influence choices at personal, organisational, and analytical levels, formed the logic among the 5 professional groups at the workshop, while the community also provided the bases for the debate, enrichment, reflection, and strengthening, hence transformation. The use of animations, agreed upon a priori during the ToC and community workshop, served as the basis for convergence on conflicting perceptions. ToC and community workshops' participants and narratives captured the summary of animation discussion, based on Google maps/territory pathways/ routes and iceberg metaphors**.** The team developed assumptions (what we need to do) to guide the achievement of transformative adaptation and more aggressive climate mitigation and adaptation strategies that can prevent future Day-Zero droughts in dry areas and, more broadly, inform water sector planning. Such transformative adaptation, herein termed "innovation", needs to:

a) reduce socio-economic vulnerability and build capacity to address any adaptation deficit/ challenges/ constraints;

b) address present and future disaster risk on water resources and ecosystems (including ensuring sustainability from a justice lens); and

c) build long-term social ecological resilience (the ability to anticipate, monitor, absorb, adapt, learn, and recover from any WAHSH day scenario risks).

Assumptions were operationalised as hypothetical cause-and-effect links and explanations of worldviews, beliefs, rationales, and analytical perspectives, as well as evidence that informs analyses of the problem and outcomes of a development issue being pursued (in our case, climate-resilient CWH). The promising RCP 4.5 (best scenario transformation pathways) innovations were thus evaluated against the following criteria:

- key existing policy instruments, institutions, and technologies;
- costs and risks;
- impacts and vulnerability (societal, equity and justice);
- effects on additional policy objectives, for example, the ecosystem services, health, food security and poverty reduction;
- *ante* and *ex post* analysis of each suggested adaptation goal/policies from, technical, scientific and political angles, at scale; and
- political economy - winners (who benefit) and losers (who pay) for innovation.

The transformation trajectories from Temmer et al. (2024) were adopted to recommend governance trajectories and innovations for transforming WAHSH policies and practices in adaptation planning. The trajectories are complementary in terms of envisioned scope, depth, and speed of change, as well as non-exclusive subcategories on transformation, thereby suggesting the need to consider inherent synergies and trade-offs within and between them. The three non-exclusive pathways/ governance trajectories are:

- **Big wins pathways** - in-depth and systematic public service reforms, technological projects, large scale infrastructural investments, and land-use planning that can be adapted, adopted, and implemented.
- **Small wins pathways** - rapid and system-wide/ in-depth small steps to system-wide-grassroot initiatives/experiments/startups with possibility for replication, accumulation, and ultimately system-wide amplification (transformation/scaling) of the whole system. Small wins pathways can trigger the rapid spread of small ideas/practices/solutions to a policy problem, a grassroots initiative/experiment/startup on water saving, from local contexts to the whole system through an innovation diffusion system. Small wins pathway is advisable where self-organisation already exists (Temmer et al., 2024; Avelino, 2015).
- **Rules-change pathways -** include rapid and systemwide rule change to in-depth change, by means of enacting new regulations, economic incentives, minor changes of existing schemes, as well as actor behavioural change (risk communication and communication for development approaches) over time.

7.6.1 Scope of definitions in transformation pathways and innovation

- **Adaptation support:** refers to innovation platforms, extension services and financial services/ micro financing;
- **Climate services**: include the generation, translation, and application of climate knowledge to support informed and forward-looking decision-making by individuals and organisations.
- **Nature-based services:** include green roofs, afforestation, agroforestry, and conservation agriculture. Nature-based approaches contribute to smart water objectives;
- **Rules, norms and regulatory changes**: refers to institutional and policy changes on water tenure, law revisions, drainage, accountability, and transparency;

- **Communication for development**: focuses on advocacy, cultural change, skills and awareness, water and nature, governance, policy, institutional); collective action and community planning structures;
- **Smart agriculture**: refers to reduced water use, indigenous crops, rainwater harvesting, runoff control, and use of drip irrigation. In essence, smart agriculture is part of smart-water practices
- **Smart water practices**: includes water-saving behaviour at the individual level, such as metering, use of alternative sources such as boreholes, rain/runoff harvesting, and automatic taps;
- **Technological changes**: are inclusive of awareness and use of water-sensitive (saving) technology on sanitation and hygiene, waste management, water harvesting, as well as nature-based practices;
- **Urban planning**: focuses on the use of nature-based approaches, such as tree planting, use of natural infiltration, drainage, and waste infrastructure in urban planning;
- **Indigenous knowledge systems**: make use of local knowledge in environmental conservation, water harvesting and use, disease and pest control, and others;
- **Infrastructure:** includes expanding waste management systems, expanding water storage systems, building new storage systems and investing in alternative energy sources for powering water conveyance schemes;
- **Water tenure arrangements:** refer to the rights and rules (both formal and informal) determining how individuals and groups can use water resources and the way users relate to one another (FAO, 2020). Such rights and rules can be established by formal law (legislation or judicial decisions), customary arrangements, or other instruments. It includes how water is appropriated through (a) land acquisitions; and (b) infrastructural development (c) pollution, (d) changes in cultivated crops, (e) afforestation, (f) land–atmosphere interactions (NBS), (g) a switch to more efficient irrigation systems, as well as (h) virtual water trade.

- **Empowerment:** refers to the capacity of people to make effective choices, envision alternatives, participate in decision-making, negotiate with influence, control and hold accountable institutions that affect their lives and livelihoods. Basically, it covers all the phases of the planning cycle; code signing innovations through CBDDR-IPs is a strategy in empowering communities.

7.7 Results and discussion

The section provides the results based on statistical analysis, document analysis, and MCDA; the discussions also focus on emerging issues and subsequent conceptualisation on innovation for collaborative learning.

7.7.1 Baseline context on WAHSH

Figure 7.1 presents the current (baseline) water situation in the study area. There was consensus (100% of responses) that conveyance losses, inadequate water supply, and poor governance are the main issues underlying the baseline water situation in VDM. The consensus on poor governance indicates that the respondents believe that climate impacts related to WAHSH are closely tied to governance failures. This needs to be taken into account in planning CRD and the design of WAHSH innovations. Other major concerns articulated included, environmental degradation and dilapidated water infrastructure (46.7%). These findings greatly informed the innovation pathways in the later sections. Understanding baseline conditions is essential, since innovation is based on “what is” and “what should be”.

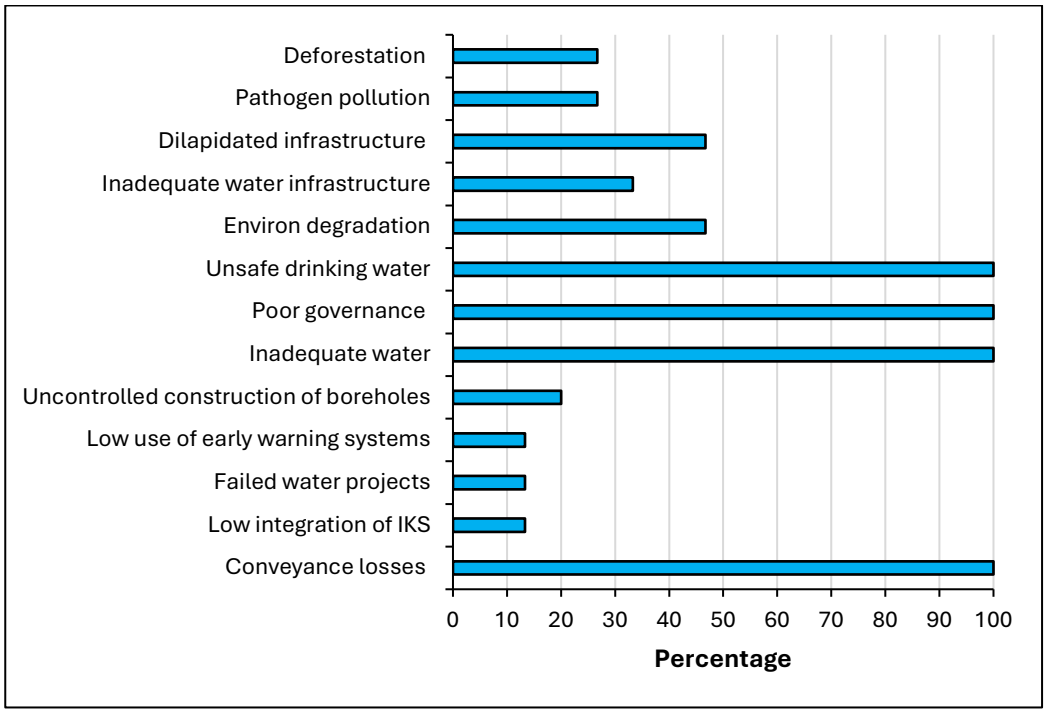


Figure 7.1: Baseline context on CWH at the household level

Some of the factors influencing the baseline context on water security are, availability, cost, and access, as are explained in Figures 7.2 to 7.5. Figure 7.2 summarises the factors that are responsible for inadequate water quantity (limited availability/poor access). Drought, which is largely climate driven (54% of the respondents), emerged as the biggest factor responsible for water insecurity at the community and household levels. Other drivers include, increasing population (15%), aging infrastructure (12%), water wastage (13%), and pollution (6%). Ageing infrastructure, pollution, and water wastage are governance factors that also contribute to water insecurity. These multifaceted, interdependent, and complex relationships among climate (drought), water, and health intersect directly and indirectly with rural and urban planning, land use, food security, and behavioural dynamics.

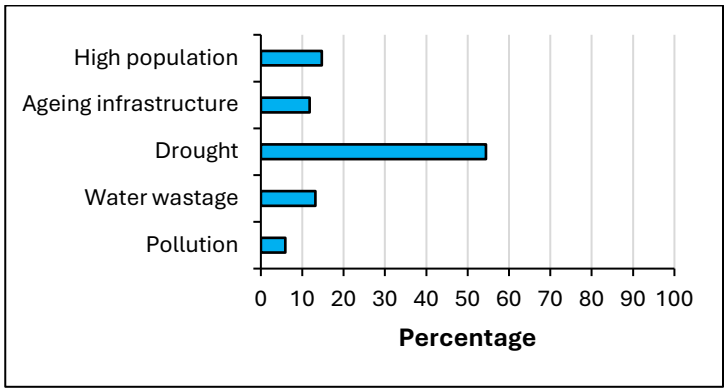


Figure 7.2: Factors causing reduction in water quantity

Identified drivers impacting water quality are livelihood-related (soil erosion (agriculture) at 6% and sand mining (9%), behavioural-related (dumping waste at 21%), and planning failures, that is failure to adhere to zoning in human settlement (about 18%). The results imply that the innovation for Day Zero water scenarios cuts across political, policy, settlement planning, behavioural, and livelihood interventions.

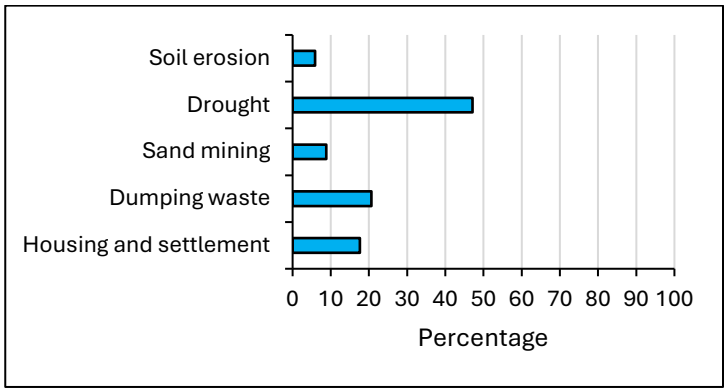


Figure 7.3: Factors causing reduction in water quality

Figure 7.4 summarises the factors influencing water borne diseases. Contamination/pollution (57%) and inadequate water treatment (22%) were the leading factors associated with water-borne diseases such as cholera. Water rationing, which is mostly a governance issue, also influences water borne disease status at the household/community levels, as indicated by 15% of respondents. Aged infrastructure (6%) has also been identified as a factor contributing to water-

borne diseases, probably through the infiltration of pathogens into water during conveyance. Several studies (Shortridge et al., 2014; Renwick et al., 2019) have illustrated that ageing/deteriorating infrastructure is associated with water-borne diseases. As systems deteriorate, main breaks, pressure losses, biofilm accumulation, and other deficiencies become more likely, potentially endangering drinking water quality and public health (Renwick et al., 2019).

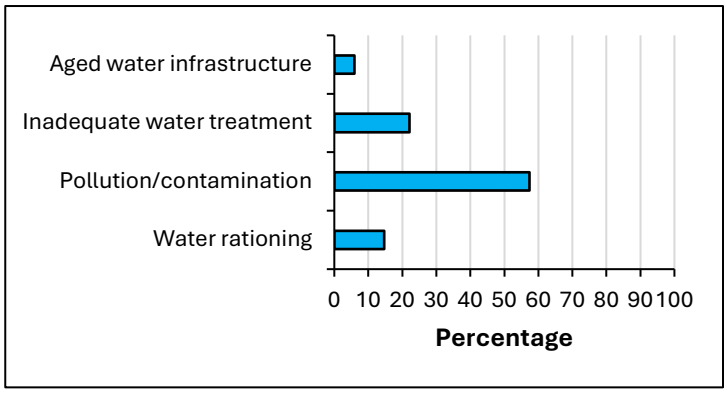


Figure 7.4: Factors responsible for water borne diseases

- **Coping strategies of current WAHSH scenarios and transformative Day Zero adaptation pathways and innovations**

A SWOT analysis of coping strategies can inform innovation pathways and reveal the policy, ecological, social, technological, legal, and political changes and innovations that are required to transform any given system. Figure 7.5 presents the coping strategies in use or recognised as potential solutions to the current WAHSH situation (herein referred to as “current innovations”) in the study area.

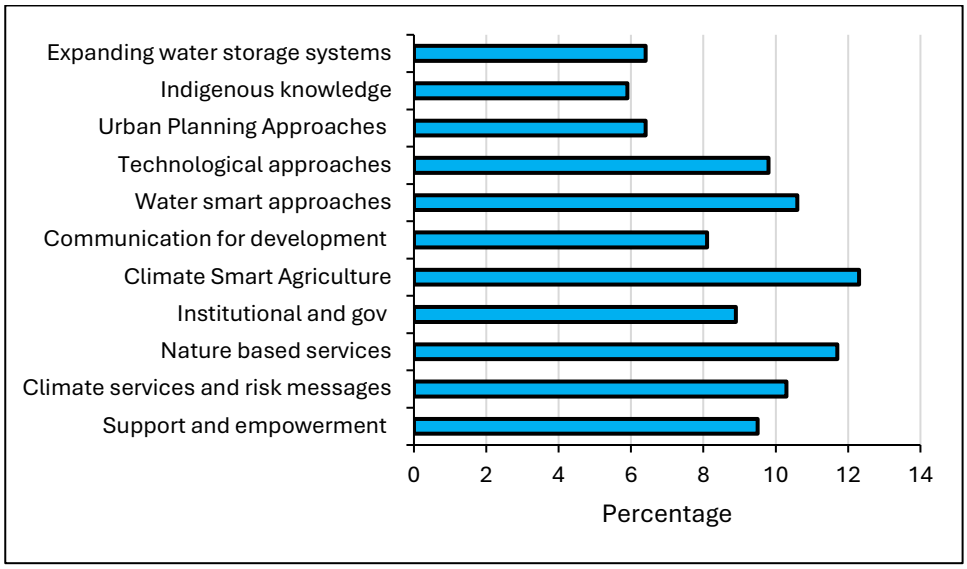


Figure 7.5: Current coping WAHSH strategies and innovation

Climate Smart Agriculture (CSA) and nature-based services (NBAs) were the most popular coping strategies, as indicated by 13 and 11% of the respondents, respectively, indicating that livelihood related coping strategies are the most popular. This suggests a livelihood lens to prioritising innovations. Water smart approaches, climate services/risk messages, and adaptation support and empowerment were selected by about 10% of the respondents. The results indicate that there is diversity in coping pathways for WAHSH innovation, most of which appear to be autonomous. This suggests a need for a deliberate, concerted planning effort that can leverage the synergies inherent in each strategy.

Flexibility is a critical metric in no regret adaptation and fundamentally involves imagining the policy across a series of decision points distributed across the future, rather than constraining the decision-making process and policy design to the present (Hallegatte, 2009). Figure 7.6 presents the suggested best-case exploration scenario, yet flexible pathways under changing climate risks and uncertainties. Nature based approaches (NBA) and collective action at 87% and 73%, respectively, emerged as the best scenarios suggested by communities and experts alike. Smart

agriculture and water productivity (suggested by 60%), water tenure reforms (suggested by 53%), and sanitation technologies (suggested by 33%) were the other pathways identified by the FGDs. IKS and urban planning and expanding water infrastructure were mentioned by 20%, while risk communication and transparency, as well as accountability were mentioned by 27%.

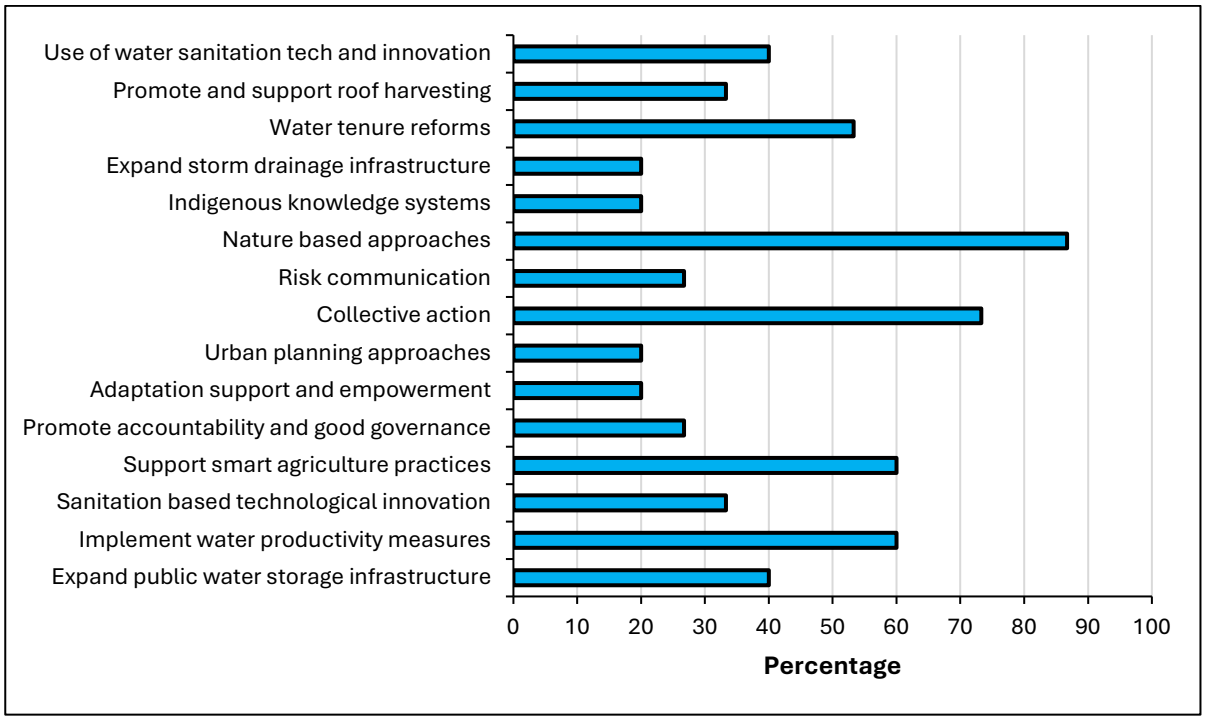


Figure 7.6: Best scenario innovation pathways on WAHSH

Most of the suggested pathways point towards the need for deep transformation. As climate risks arise from interactions between bio-physical (hazards) and socio-economic (vulnerability, exposure, and response); responses (innovations) are more likely to account for the outcomes of climate interventions on hazard and exposure (Ara Begum et al., 2022; Simpson et al., 2023). This suggests the need for an integrated approach to Day Zero water-risk transformations, in general and health risks, in particular. Systemic effort should be targeted across ecosystem services management, water infrastructure development, land use, and the actor agency. The identified pathways provide an opportunity to address current infrastructure (technological) focused lock-ins, as part of no regret adaptation planning for Day Zero water scenarios. The high governance

transformation aspirations of water tenure reforms, expanding public water storage, and support for water sensitive sanitation technologies, suggested that climate change adaptation goes beyond addressing specific climate scenario risks, but also focuses on systemic drawbacks.

Figure 7.7 summarises the governance pathways identified in the workshops. Small wins (grassroot local initiatives, experiments, and startups) were suggested by 21, 31, and 48% of the respondents at Dopeni, Tiyani, and Ribungwane, respectively. Big wins (in-depth and systematic public service reforms, technological projects, large scale infrastructural investments, and land use planning) were suggested by 17, 33, and 50% at Dopeni, Tiyani, and Ribungwane, respectively. This should be contextualised with past planning legacies in water tenure and land-use planning, and their impact pathways. Rules' change (enacting new regulations, economic incentives, behavioural change, and minor changes to existing schemes as well as behaviour change (risk communication)) were suggested by 16, 32, and 52% of the respondents at Dopeni, Tiyani, and Ribungwane, respectively.

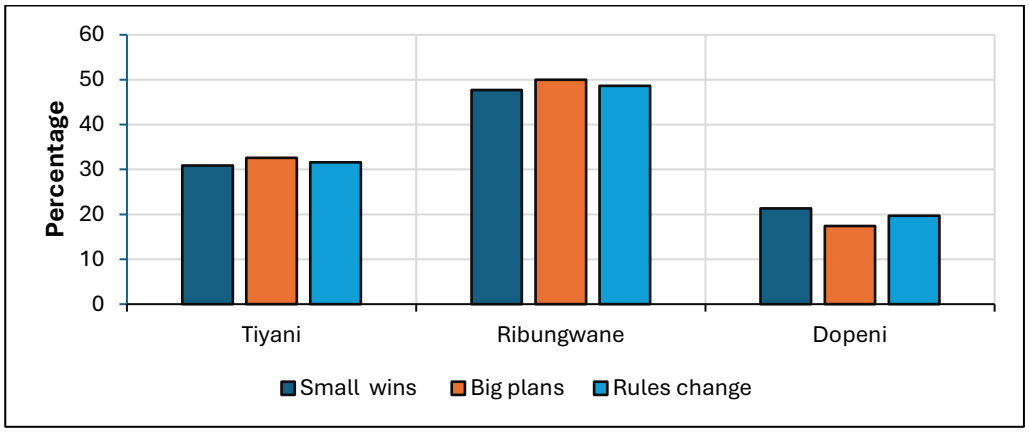


Figure 7.7: Lived experiences disaggregated governance innovation pathways

7.7.2 Emerging local context asymmetries on innovation pathways: Gender and age

Table 7.1 presents the governance trajectories of innovation across the studied municipalities. Big plans trajectories are the most favoured, with 38% in Collins Chabane and 41% in Thulamela. Rules change in existing schemes were favoured by 35% and 32% of those in Collins Chabane and Thulamela local municipalities, respectively. Small wins were preferred by 27% in both municipalities. The low preference for small wins could be attributed to poor/or nonexistent CBDRR and governance structures in the study area. This suggests the need for innovation platforms at the community level. The within transformation was most preferred for all pathways, with a range of 81-84% in Collins Chabane, while Thulamela had a low range of 16-18%. This suggested less contestation on the governance pathway as opposed to high contestation in Collins Chabane local municipality. It is important to note that the contexts identified in the study's findings are critical to transformative planning.

Table 7.1: Summary of governance pathways for innovation transition in WAHSH by municipality

Municipality		Small wins (%)	Big plans (%)	Rules Change (%)
Collins Chabane	Within municipality	27.20	38.30	34.50
	Within transformation	82.60	81.60	83.90
Thulamela	Within municipality	27.20	41.20	31.50
	Within transformation	17.40	18.40	16.10

Figure 7.8 provides the age disaggregated analysis on governance trajectories for innovations on WAHSH. Generally, big plans innovations were the most preferred (68%) by respondents of all age groups, followed by rules change (31%) and small wins (22%). All transformation categories were more popular among the 30-60-year age group, which also had the highest preference for rules change (63%). In general, there was no preference for specific innovation pathways among those under 30 and those over 60 years old. These demographic factors are critical socio-economic lenses for planning transformation.

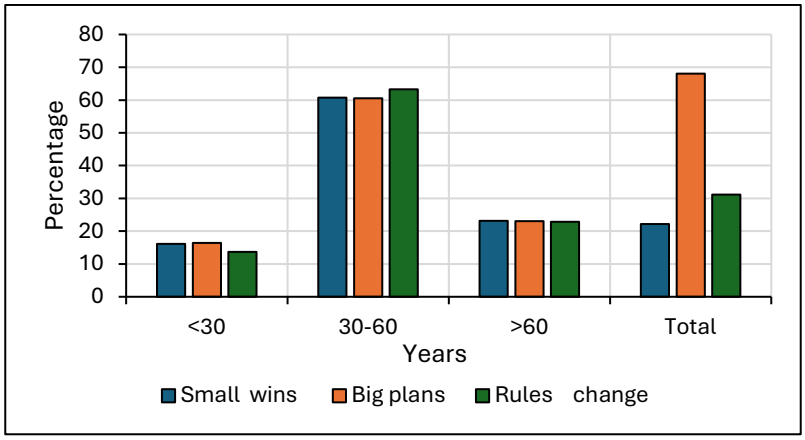


Figure 7.8: Age disaggregated governance innovation pathways

Big wins emerged as the most preferred by females (59%) compared to males (41%). This was followed by the rules change being preferred by 58% of the females and 42% of the males (Figure

7.9). Small wins were preferred by 57% of the females and 43% of the males. The results indicate that transformation and innovation have higher priority among females than males across all governance trajectories. Most water-related actions were centred on women, and they are on the front lines of climate-triggered water risks. A gender-sensitive innovation process and collaborative learning are therefore critically required.

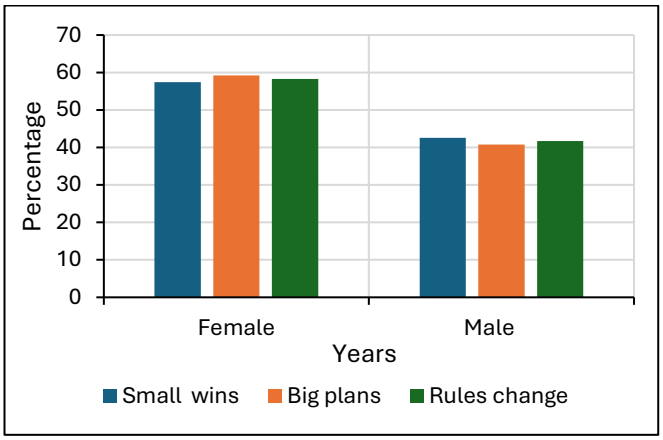


Figure 7.9: Gender disaggregated governance innovation pathways

7.3.3 Remarks on policy and practical implications from the emerging issues on WAHSH transformation and innovation

Future complexity and uncertainty due to climate change demand new ways to plan for water resources, among many other human and ecosystem needs. However, integration of lay and dominant knowledge cultures for transformation can be undermined by asymmetry in access to, control over, or influence on policy and decision-making structures, processes, and institutions (Hochrainer-Stigler et al., 2024; Gugerell et al., 2023; Turnhout et al., 2020). This is a critical consideration for policy design and innovation processes.

There is a need to enhance the ability and performance of the governance system to deal with climate change challenges (Termeer et al., 2017). The centrality of systems and complexity of SES in nexus framing are exemplified through several analytical system approaches, such as climate-resilient health, climate-resilient livelihood systems, climate resilient food systems, and climate resilient water systems, in multi-level integrative research and policy.

Social learning and agency are integral to socio-economic status assessments and the design of interventions. Social learning mediates the convergence of diverse stakeholders' perspectives on a particular problem and the generation of possible solutions (Gonzales-Iwanciw et al., 2025). Such learning not only mediates a change in individual understanding but also collectively impacts society and social networks (Ison et al., 2015; Reed et al., 2010). Social learning, thus, includes any outcomes that are attributed to any policy intervention, such as - enhanced sustainability of social ecological systems, enhanced trust, adaptive capacity, attitudinal and behavioral change, stakeholder empowerment, and strengthening of social networks.

Fostering agency, values, as well as capacities and empowerment requires the integration of diverse knowledge, plural pathways, and associated contestations at individual and collective levels (Scoones et al., 2020). Agency refers to the process that enables people to influence decisions, co-construct alternatives, based on their framings, and make a reasoned choice, within a particular decision-making process (one's ability to pursue goals that one values). The decision-making, agency-focused perspective represents the outlook of actors, when engaged in a particular decision-making process, with its various constraints of time, resources and institutional arrangements.

Agency goes hand-in-hand with social learning, herein, defined as concerted action in complex and uncertain situations, including individual learning that takes place in a social context, hence is influenced by social norms, for instance, by imitating role models (Bandura, 1977; 2006). Learning

is critical in an agency. According to Huitema et al. (2010), the broad objectives of learning, including acquisition of knowledge (cognitive), attitudinal change (normative), and trust building (relational), are better improved under the multi-level learning (MLL) structure. Trust, ownership, and learning are integral cognitive lenses in governance for transformation, specifically in the linkage of technical dimensions to actual decision-making and policy processes (Mathetsa et al., 2024). This mainly arises from the observation that prioritising of options, and the resulting policies, are derived from value systems embedded in institutions, the policy frames held by stakeholders, and the ways stakeholders are informed (Nilsson, 2016). Such triple-loop learning or transformative learning, challenges the values, norms, and higher-order thinking processes that underpin assumptions and actions (Fazey et al. 2020), and the ability to critically assess the knowledge and information received/ learned.

Integrating agency and social learning is the essence of self-organisation and critical to innovation and transformative adaptation planning, especially for wicked global change challenges – WAHSH, under Day-Zero water scenarios. As a process of social change, social learning facilitates peer learning that can benefit wider social-ecological systems, through individual and collective self-reflection on a given social challenge (Ison et al., 2015; Reed et al., 2010). The relational learning networks (Ziervogel et al., 2017; Di Gregorio et al., 2019) not only enhance adaptive capacity but also address risks associated with silo planning, for complex disaster risks (Gonzales-Iwanciw et al., 2023). At the national level, these networks, allow for hybridizations of lessons learned, testing, and scaling of innovations (Gonzales-Iwanciw et al., 2025). Such learning not only deepens learning and innovation (Pelling et al., 2008) but also enables continuous testing, refinement, and scaling of emerging innovations (Fünfgeld, 2015). Social learning processes may be context specific, however, they have the potential to enhance policy learning, hence system-wide transformation (Ison et al., 2015; Reed et al., 2010).

Formalised social and policy learning norms across governance levels, as well as multi-level governance networking (Ziervogel et al. 2017), offer a valuable perspective on the organisational factors that facilitate MLL. The MLL can also be assessed through cognitive, normative (ethical), or relational lenses (Baird et al. 2014). A focus on organisational factors provides a baseline for social network analysis on the influence of collaboration on learning outcomes. Learning networks are more likely to be inclusive of the most vulnerable groups (Naess et 2013; Jabeen et al., 2010), facilitate the acquisition of knowledge, facilitate attitudinal change, and build trust, ultimately transformational, by questioning existing subjectivities (Huitema et al., 2010). The MLL platforms may also inform policy learning (the diffusion and adoption of policies) (Benz, 2012), institutionalisation of new rules, while supporting institutional continuity (Getimis, 2003). From the aforementioned, it is apparent that integrating learning into adaptation is a dynamic, iterative process that requires continuous refinement, innovation, and flexibility (Adger, 2003). Learning is acknowledged for its role in deepening the understanding of climate change challenges, enabling the anticipation and adaptation of responses (Pelling et al., 2015); sharing and scaling up of possible responses, and integrating diverse perspectives, particularly those of vulnerable groups (Jabeen et al., 2010; Naess, 2013). As a critical pillar in governance, learning contributes to resilience and adaptive capacity building (Pahl-Wostl, 2009). The MLL may also increase coherence across different levels of governance (Di Gregorio et al., 2019), as well as:

- create commitments and relationships for new action, trust for the intent; be a voice that can be heard; provide understanding, advocate and influence social mobilisation; generate confidence to influence policies/ advocacy, social relations, and collaborations and motivate communities to act.
- a form of social innovation hubs, which can provide transformative spaces if they have these three core characteristics - they must be social (cooperative), experimental (iterative), and systemic (addressing root causes) (Hassan, 2014).
- Act as “transformative spaces” that mediate inclusionary and systemic responses to wicked problems (Moore et al., 2014).

7.7.4 Emerging gaps and opportunities

The UN's "Local Communities and Indigenous Peoples Platform" (UNFCCC, 2014) aims to empower indigenous peoples, and local communities so they can actively participate in climate action. However, existing adaptation learning platforms are characterised by limited involvement of local actors (Fünfgeld, 2015; Naess, 2013). The study suggests learning pathways to address the CWH impact scenarios in drylands of South Africa, by testing the underlying assumptions that underpin existing (planned) adaptation against community values and expectations. The aim is to improve adaptive planning-process outcomes and inform innovations for no regret adaptation options. Analysis of results in Chapter 4 highlights the following critical issues in designing innovation systems for WAHSH under the Day Zero scenario:

- dissonance at expert and lay levels on critical issues, notably the justice lens for transforming WAHSH;
- WAHSH priorities and innovations differ across contexts (villages, municipalities, gender, and age); and
- inherent influence of power (control over decision-making) in framing innovation and transformative pathways.

A summary of the CWH nexus in South Africa and lessons for no regret adaptation, as well as possible lessons for mainstreaming into Day Zero scenario planning, is presented in Table 7.2. The analysis suggests the following issues:

- Direct and indirect effects of drought, floods and other forms of climate change, on health, thereby, suggesting the need to consider shifting vulnerabilities.
- Linkage of disease episodes to unreliable supplies that force rural communities to use untreated water sources (rivers and streams) in which microbial contaminants are inherent, and that Health Chain impacts are transmitted across other sustainable

development goals (SDG), such as food in(security) with smart agriculture technologies being particularly critical to climate adaptation, mitigation, and safe water access.

- Strong need for a holistic lens in framing, specifically, land use planning (agriculture, settlements, and others) in no regret adaptation planning for anticipated Day-Zero drought risk, as well as an integrated (landscape) approach in development planning. Apparently, an Integrated CBDRR in planning Day Zero responses and no regret adaptation is inevitable.
- The need for DRR, specifically integrated CBDRR in planning Day Zero responses and no regret adaptation. Smart agriculture technologies are recognised as critical to climate mitigation and safe water access.

Table 7.2: Evidence on the CWH nexus in South Africa and lessons for no regret adaptation governance

Description of the nexus	References	Key lessons for CWH nexus planning
Climate change- food production-health (pathogenic diseases') nexus	Links Salmonella pathways to adaptation to climate change through irrigated agriculture using waste / contaminated water (Gumbo et al., 2010)	This reflects cognitive failure, governance gaps, and failure of autonomous adaptation, hence the need for integrated CWH nexus planning that accounts for shifting vulnerabilities.
Health impacts of climate change-health nexus	Extreme weather events, such as floods and heat waves, also cause health issues, including food-borne and water-borne diseases and heat stroke (Mabhaudhi et al., 2019; Haine et al., 2006; Ziervogel et al., 2014; Musengimana et al., 2016). Effects of climate change by exacerbating land degradation, especially in agricultural lands, linked to water pollution, sanitation, and health challenges (Wlokas, 2008).	Indirect effects of drought (floods) of climate change, on health.
Climate change- food security-health nexus	Increasing aridity has a direct knock-on effect on food security (Schreiner and Beleta, 2015; Mabhaudhi et al., 2016), leading to hunger and a decline in the supply of nutritious food (Wlokas, 2008).	Suggests a holistic lens in framing, hence the need for structures, institutions, and processes for anticipated Day Zero drought risks (no regret adaptation planning)

Climate change–land resource degradation-water nexus	Climate change increases demand and exacerbates the already existing pressure on land and water (Mutanga et al., 2024) Land degradation (degradation of agricultural lands linked to water pollution, sanitation, and health (Wlokas, 2008).	Suggests a holistic lens in framing and specifically, land use planning (agriculture, settlements, etc.) in no regret adaptation planning for anticipated Day Zero drought risks. Highlights the role and need for an integrated (landscape) approach in development planning
Health-development-nexus	Crises like the COVID-19 pandemic divert limited resources to immediate needs like health and hunger alleviation (Wlokas, 2008; Mabhaudhi et al., 2019). This can exacerbate other critical issues like energy insecurity and poverty, further hindering progress on pursuit of other livelihood and sustainable development goals such as water, energy, education, etc. (Mutanga et al., 2024)	Health Chain impacts are transmitted across other SDGs.
Disaster Risk Reduction lenses in CWH nexus	Detection systems and cutting-edge health facilities are necessities for an integrated response (Mabhaudhi et al., 2019); as well as use of livelihood lens, agency and integrated community-based DRR approaches in planning for health-related outcomes (Volenzo and Odiyo, 2019)	Suggests the need for DRR, specifically Integrated community CBDRR in planning Day Zero responses and no regret adaptation. Smart agriculture technologies are recognised as critical to climate mitigation and safe water access.
Water quality - health nexus	Bessong et al. (2009); Edokpayi (2018a); Edokpayi et al. (2018b)	Link disease episodes to unreliable water supplies that force rural communities to use untreated water sources (rivers and streams) where microbial contaminants are inherent.

The emerging issues suggest the need to co-design and scale promising innovations across the three broad governance pathways. The “how” question, and particularly the appropriate institutional framework and structures for transformative learning and innovation, implicitly emerged from the aforementioned**.** In a previous report on policy and governance, it was concluded that the use of anticipatory adaptation planning frameworks guarantees wider actor engagement in exploring innovative Climate Resilient Development (CRD) pathways. Such co-produced actions by multiple actors are likely to capture divergent worldviews, knowledge, and values on CWH and construct context-specific, no regret adaptation pathways. In so doing, a focus on how governance decisions have shaped development pathways and power dynamics, could

lead to innovations to address inequitable and maladaptive outcomes that may arise in anticipatory Day Zero no regret planning. The following section, thus highlights pathways towards innovation and collaborative learning, based on the above identified gaps and opportunities.

7.8 Innovations for collaborative learning and co-production

Systems research often focuses on the implementation, uptake, and scaling-up of policies (Hanson et al., 2003). Taking a systems approach is, thus, more akin to a frame of mind that weighs the importance of understanding interdependence in evidence-informed policymaking. We have suggested community learning labs, through CBDRR-IP approaches, as an innovation for collaborative learning, co-designing, and amplification of WAHSH innovations. The novelty and potential contributions to policy and practice from the study and their potential application are as outlined hereunder:

i. Responsive multi-level learning and policy platform in transformative adaptation planning.
   - Actionable perspective in the design and steering of fit-for-purpose (scope, depth and speed(timeous)) and grassroots' transformation;
   - Mixed methods that test assumptions, hence convergence and resolution of knowledge conflicts/ integrate expert and lay knowledge, through deliberative learning; and
   - A multitude of approaches that address social innovation through self-organisation and CBDRR.

ii. Cross-sector partnership for the transformation of WAHSH with the following applications:
The innovation provides a baseline on theoretical and implementation gaps and opportunities for producing, assessing, and sharing context-relevant knowledge and innovation for no regret adaptation and climate-risk management, as well as participatory co-designing, fundraising, monitoring, and evaluation of innovations that are tailored to specific needs and vulnerabilities. This has potential for facilitating:

- Problem identification and definition of transformation for Day-Zero planning, hence the transformative policy cycle;
- Integration and reconfiguration of transformative planning under deep uncertainty in general, and Day-Zero water scenarios' transformative needs;
- Holistic socio-political innovation lens that has the potential to address the scope, speed, and depth of transformative-action needs in the planning horizon, hence resolution to the drawbacks of silo-planning cycles. Such win-win strategies have the potential to address multiple stressors/compound disasters and support CRD;
- Interagency collaboration and coordination on wicked global change challenges;
- Strengthening and adopting incentive-based policies and regulations on CRD water development, in general and WAHSH in particular;
- Facilitating access to multiple funding sources;
- Creating reflective planning, implementation, and monitoring structures, mechanisms, and systems, as well as integration of funding into design and implementation of WAHSH interventions, with, and by communities; and
- Citizen science-informed adaptation initiatives and continuity in data collection through the lens of local experts that confront BAU and change power dynamics.

iii. Framework for resilience planning with potential for supporting policy learning, coherent MLL and MLG systems for transformative adaptation

The study identified a multitude of approaches that address social innovation, through self-organisation and CBDRR_IP. The mixed-method approach for deliberative learning and transformation (protocol) are critical for community-engaged planning, especially in co-designing transformative adaptation action, navigating climate-related water crisis, from a multilevel governance and systems approach, and can be applied in:

- Integration and reconfiguration of transformative planning, under deep uncertainty in general and, in particular, Day Zero water (sanitation, hygiene and potable water) transformative needs;

- Integrating contextualised innovation visions, based on lived experiences, needs, priorities and cultural aspirations; and
- Informing the transformation of production, consumption and investment in WAHSH within earth system boundaries.

The study identified innovations and mechanisms for collaborative learning and co-production for no regret adaptation, using CWH nexus lenses. Self organisation through CBDRR-IPs was concluded to be critical for co-designing and regime amplification of transformative innovations on hygiene, sanitation and potable water amidst the climate change crisis. The study, therefore suggests CBDRR-IPs as local level approach to WAHSH adaptation planning and innovation planning. The possible functions of CBDRR-IPs, among many others, include:

- Cognitive mapping: sensing, interpreting Day Zero scenarios;
- Creating and maintaining institutional memory on WAHSH and Day Zero scenarios;
- Institutionalisation, commitment, internalisation of community actions;
- Monitoring, evaluating, reporting and learning (ME & RL) as information processing and learning to inform policy formulation/experimentation at scale;
- Networking and facilitating community spillovers (peer learning); and
- Resource mobilisation/fundraising for adaptation initiatives and innovations.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusion

This study explored innovative scenario building for no regret adaptation along the CWH nexus and informed policy and institutional transformation at local and national levels. It presented the intersecting social, institutional, policy, and governance dimensions of the CWH nexus and their interactions, which must be considered simultaneously in the transition to address Day Zero future drought risks for communities in the drylands of South Africa. This also covered visioning scenarios across the studied community and climate change adaptation planning initiatives. Further, the study highlighted multiple innovations in water system governance for Comprehensive Risk Management (CRM) that will not only reduce risks but also address deep-seated vulnerability to future climate change. The study, therefore, informed innovative multi-sectoral collaborative learning and planning, rather than as a specific innovation product on sanitation, hygiene, and potable water, under climate change risks.

Policy, governance, and institutional assessments were conducted to evaluate the current policy, governance, and institutional systems for transformation in CRD and identify existing gaps. The review indicated that although South Africa follows a multi-governance approach to respond to climate change impacts, it has yet to be formally and effectively institutionalised. The multilevel governance system on the CWH nexus is characterised by multifaceted interdependence and complex relationships, hence the need for a systems approach to identifying policy problems and for no regret adaptation planning. The existing policies are relevant, coherent, and effective in responding to climate change impacts. However, it is currently difficult to determine whether their implementation will, in practice, deliver their objectives and generate significant positive impacts, as the unavailability of funds limits the implementation of some of them. In addition, there is limited meaningful participation by relevant policy actors, and overlapping ministerial mandates result in a lack of ownership over implementation agendas. The findings of the multi-stakeholder

consultative process indicated unanimous agreement that conveyance losses, inadequate water access, poor governance, and unsafe drinking water were issues at the household level. All the FGDs unanimously agreed that increased vulnerability to water-borne diseases and water insecurity can be expected if the current water situation is not addressed under changing climate risks and uncertainty. Smart agriculture approaches from 13%, of respondents and nature-based services at 11 % of respondents are the most popular coping strategies. Water-sensitive technologies, climate services/risk messages, and adaptation support, at about 10% of respondents, come second. Water and sanitation innovations, as well as smart water technologies, were identified as the most preferred future adaptation pathways. Increased vulnerability to food and nutrition risks emerged as a major uncertainty to consider when planning for Day Zero, according to 63.4% of respondents. In the current study, it is posited that decision-makers are likely to encounter deep uncertainty when assessing a community's vulnerability to changing climate patterns that may be experienced decades from now, due to water development and land use planning, as well as urbanisation patterns.

A lagged correlation analysis was conducted to explore temporal associations between climatic conditions and the incidence of infectious diseases (malaria, diarrhoea, and bilharzia). A multivariate negative binomial regression was trained and tested to predict monthly case counts of infectious diseases for the VDM. The tested model was used to predict monthly case counts for the periods 2021–2040, 2041–2060, and 2081–2100. Malaria models exhibited the highest error levels, while the bilharzia model demonstrated the lowest error metrics. The poor predictive performance observed for malaria may be partly influenced by the limited data (2020-2025) used in the modelling. The results indicate that climate change may amplify variability rather than produce linear increases. Climatic disease relationships are evident but disease specific. Rainfall and temperature showed short-term associations with malaria, particularly at 0–1-month lags, while relative humidity plays a weaker role. Diarrhoea and bilharzia also demonstrated climate sensitivity, although with differing response patterns. Malaria responded most strongly with a

short delay (1 month for Tmax), consistent with vector biology. The Poisson XGBoost model captures temporal trends and seasonality reasonably well, particularly for diarrhoea. However, negative R^2 values indicate limited predictive skill and the need for model refinement. The future projections indicated persistence of pronounced peaks under SSP5-8.5, highlighting the potential for episodic surges for all diseases. For diarrhoea, substantial overlap was observed between SSP2-4.5 and SSP5-8.5 projections, suggesting that future diarrhoeal risk may be governed more by threshold exceedance and infrastructure vulnerability, than by emissions pathway alone. Under SSP2-4.5 and SSP5-8.5 scenarios, all three diseases show continued variability and recurring outbreak spikes, through 2100.

Big wins (in-depth and systematic- public service reforms, technological projects, large-scale infrastructural investments and land use planning) emerged the highest among females at about 59% against 41 % for males. This is followed by rules change at 58 % for females against 42% for males. Small wins for females are at 57%, against 43% for males. Transformation and innovation, therefore, have a higher priority among females than among males across all governance trajectories. Most water-related actions are centred on women, implying that they are on the front line of climate-triggered water risks. Through a gendered lens, big wins were highest among females at about 59%, compared with 41% for males. This is followed by rules change at 58% for females against 42% for males. Small wins for females emerged at 57% compared with 43% for males. In conclusion, transformation and innovation have a higher priority among females than males across all governance trajectories. Most water-related actions are centred on females; hence, they are on the front line of any climate-triggered water risks. A gender sensitive innovation process and collaborative learning are inherently critical. Participants at the validation workshop endorsed the key findings from the participatory workshops, confirming their accuracy and relevance. There was also a strong agreement that adaptation strategies should be tailored to specific planning horizons (short-, medium-, and long-term) to ensure their effectiveness and sustainability.

8.2 Recommendations and gaps for future research

Upscaling hygiene and sanitation water sensitive innovations from experiments and niches to regime levels and how to accumulate and broaden them into system-wide changes, while connecting them to socially relevant challenges, such as poverty, remains one of the major gaps in climate adaptation planning. The testing of some of the identified innovation pathways, for instance, water sensitive hygiene and sanitation practices under CBDDR-IP, is recommended at the community level (especially where this study was undertaken) and subsequent amplification of the same in several contexts, as part of water CRD adaptation initiatives and institutionalisation of learned lessons.

Contextual metrics such as gender and age play critical roles in framing various innovations and governance pathways. Incomplete knowledge among experts and at the community level, as well as dissonance on lenses for prioritising pathways, undermine transformative intent. This necessitates the use of boundary organisations as facilitators of the innovation processes at the community level. Innovative CRD strategies, underpinned by participatory planning and citizen science, can be critical, yet they are poorly understood and/or poorly integrated into policy and practice. Citizen science and bottom-up planning approaches provide an overall framework for conceptualising solutions. A gender-sensitive innovation process and collaborative learning are, therefore, recommended for testing some of the identified innovation pathways.

The study established that there is diversity of coping pathways for WAHSH innovation, most of which seem to be autonomous, with little coordination effort in the adaptation policy space. Systemic transformations of the underlying drivers of water security dynamics and vulnerability to climate change are therefore needed to reduce water-related harm (water-borne diseases, hence the primary focus on sanitation and hygiene) and enable the majority of people in communities to live within the safe corridor under climate change-related uncertainties.

The utility of existing adaptation pathway approaches is largely unstandardised and vulnerable to biased understanding and interpretation of adaptation problems, on account of the researchers' experience, at the expense of the decision context. The study has suggested an integrated approach that can inform conceptual advancement and integration in general, and the operationalisation of transformative objectives in particular. The nexus methodological approach can be used to overcome silo-planning dilemmas and to bridge the gap between academic research and practical CRD policy design, beyond WAHSH, complexity, and context. Contexts are, therefore, critical in transformative planning.

The identified gaps in designing and scaling a CBDRR_IP orchestration model include:

- Reflective learning and adaptation of some of the findings and recommendations into regulatory, bureaucratic, financial, and technological institutions through self-amplifying feedback mechanisms;
- Collaborative testing of identified innovation pathways at the implementation level and institutional mainstreaming of the same; and
- Critical evaluation/ testing of the identified solutions/ innovations and their feasibility, based on factors like cost benefit analysis of identified innovations, testing and validation in different socio-economic and demographic contexts under the districts' focus for development approach.

Other future research studies that are recommended include:

- Collaborative testing of identified pathways at the implementation level for collaborative learning, institutional mainstreaming, and policy innovation; and
- Use of social economic evaluation tools, such as cost effectiveness and net present value, in the assessment of the identified exploratory pathways.

Only 2 workshops were conducted due to financial and time constraints associated with the multi-stakeholder planning process. It is therefore recommended that further workshops be conducted to cover wetter parts of the District (Vhembe East towards Mozambique) where the risk of flooding is high. This will assist in generating community-based adaptation strategies for those areas.

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APPENDICES

Appendix 1: Stakeholder identification and assessment in climate- water- health nexus, VDM

Sector	Actor e.g., Municipality, Local leadership structures	Category e.g., public-sector, civil society, Academia, policy, NGO; Norms, Rules	Programmes/ policies/projects on water /Health adaptation e.g. masterplans, policies, regulations, laws; Climate Smart Agriculture (Specify each e.g., Climate Change Act 2015)	Scale of operation E.g., Nationwide, International, District, municipality	Collaboration and Networking (What are the collaboration mechanisms e.g. Stakeholder forum, advocacy, and information campaigns etc)	Timeframe of projects/ programmes e.g., 1,3, 5, over 5, over 10; over 20 Yrs. etc	Funding source (Exchequer; External; donations	Planning documents e.g., adaptation plans, Strategic Environmental Assessments;	Challenges e.g., Funding; Technical knowledge; Inadequate governance and policy framework etc
Water and sanitation									
Urban planning									
Energy									
Local Municipality									

Cooperative Governance and Local leadership									
NGOs and civil society									
Agriculture and rural development									
Roads and Infrastructure									
Department of Health									
Climate Services									

Appendix 2: Theory of Change Interview guide

- What are the key drivers of change (Economic, cultural, technological, institutional and governance, climate, biophysical at community level?
- What are the climatic changes in the community (i.e., temperature, rainfall)?
- How are the climatic changes impacting water and health and associated scenarios (BAU and optimistic)?
- What have been the responses (and challenges, if any)?
- What is the extent of effectiveness for the adaptive (SWOT/ PESTEL model)?
- What are the short-, medium- and long-term measures for no regret adaptation suggested by interested actors and related assumptions?
- Are there better ways to current responses (adaptations) with reference to government, behavioural and informational, governance and institutional frameworks?
- What are the likely best future practices and the underlying assumptions (based on good practice criteria such as efficiency, coherence and sustainability dimensions)?
- What are the visions for no-regret adaptation strategies?

Appendix 3: Participatory planning workshops

- What are the drivers of vulnerabilities on the basis of identified focal health concerns?
- What is the desired socio-cultural, climatic, governance/ institutional, economic (production systems) for addressing CWH challenges?
- What could be potential future changes in water (moisture) availability and its effect on health under BAU, pessimistic and optimistic scenarios?
- Can the current CWH nexus practices be improved?
- What are the priority no-regret adaptation strategies and actions on CWH?
- Do current and planned development programs meet community expectations on CWH nexus challenges?
- Is there potential for improvement of the current and planned CWH development programs?

Appendix 4: Scenario planning

- What is the current situation (vulnerabilities, capacities, planning cultures, governance arrangements, stakeholder preferences, assumptions, and values as well as expectations)?
- "What should be" or community vision for no-regret adaptation on CWH?
- "What could be" or the possible scenarios on moisture (water flow) changes and health risk propellers?
- "What can be" or better ways to address gaps (potential) for improvement of existing and planned CWH adaptation plans?
- What are the other factors that increase vulnerability?
- How do you cope?
- How can this be reversed?

Appendix 5: Household questionnaire

Whose future are you concerned about with respect to water, climate related diseases, environment, and food.
(Use the matrix below)?

	Water quantity	Water quality	Health/ Disease	Environment	Food
Self only (current)					
Children (+30 years)					
Grand children (+ 60)					
Great grandchildren) + 90 years					

Have you observed any changes (negative (-) or positive (+) in the above in your lifetime?

Water quantity	Water quality	Health/ Disease	Environment	Food

If negative what are the causes / factors leading to such negative trend

……
……
……
……
……

If positive what are the causes / factors leading to such positive trends

……
……
……
……

Could any of the above be made better for the current and future generation?

Factor	Specific measures Currently	Specific measures in the Future	Remarks
Communication			
Technology			
Information			
Governance			
Policy			
Collective action			
Behavioural			

Are there any positive or negative climate impacts on water, health, food, and environment that you can identify and suggestions on how such can be addressed?

	Positive (+)	Negative (-ve)	Suggestion on improvement (what and how)
Water quantity • Stream flows • Flooding events • Water access			
Water quality			
Climate diseases • Vector borne such as malaria. • Water borne such as typhoid/ cholera etc			

• Hygiene such as diarrhoea, listeria • Sanitation • Cold waves • Heat waves **Food**			
• Cost of food			
• Availability of food			
• Quality of food			
• Affordability of food			
Environment • Aesthetics • Habitat • Pollution • Forest cover • Shading • Wetland size and integrity • Catchment • Agricultural land			

Comment on how the current planning, policies, implementation, collective and individual actions contribute to undesirable status of water, disease, and food situation?

……
……
……
……
……
……

"Given that we cannot accurately predict the climate, what actions can we take today to best prepare for the future"?
(Can water, disease and food situation be reversed or enhanced?) If yes how

	Reversed / Enhanced	How	Remarks
Food situation			
Environment situation			
Climate diseases			
Water quality			
Water quantity – Flooding			
Water quantity – Droughts			
Water quantity – Streamflows			

What is the (should be) ideal future and how can it be achieved?

	Ideal future	How it can be achieved	Remarks
Food situation			
Environment situation			
Climate diseases			
Water quality			
Water quantity- Flooding			
Water quantity -Droughts			
Water quantity- stream flows			

Appendix 6: Workshop evaluation and learning

The criteria for participant assessment and learnings gained to be assessed on the following as well any other recommendations by the participants

- Politics in CWH
- Empowerment of individuals and institutions
- Knowledge on adaptation planning and particularly the utility of TSP
- Networks - likelihood of emergent behaviour on networking, collaboration in addressing CWH adaptation needs.

Appendix 7: Pathways assumptions

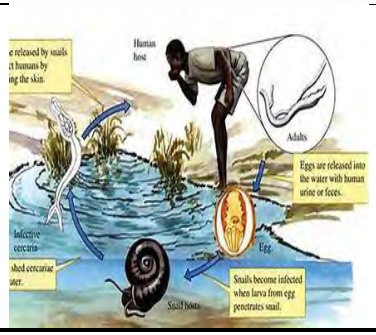
Pathways	Assumptions (scorecard)							
	Cost (affordability)	Co-benefit (win-win)	Justice (equal access), prevent significant harm for current and future generations, assures minimum access	Benefits (Number of people)	Equity (respect rights, gender etc); support flourishing for all	Does not destroy environment	Does not increase global warming	Transformative (addresses root causes of the problem)
Nature based (tree planting, roof water harvesting, infiltration) etc								
Water productivity (efficiency measures)								
Climate services and Early warning systems								
Risk communication (informational and behavioural change)								
Adaptation support and empowerment								
Rules, norms and regulatory change (water tenure)								
Smart Agriculture								
Collective action								
Governance (transparency and accountability)								
Technological (water and sanitation such as automatic taps)								
Alternative water sources such as boreholes								
Storm water infrastructure expansion								
Public water storage infrastructure								
Alternative energy sources								
Urban planning								
IKS								

Appendix 8 : Animations illustration CWH scenarios and pathways

Unsafe drinking water









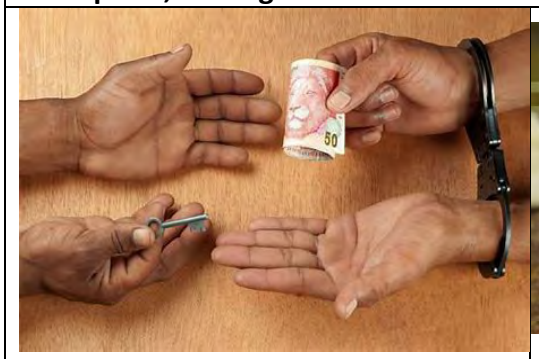
Water quantity levels



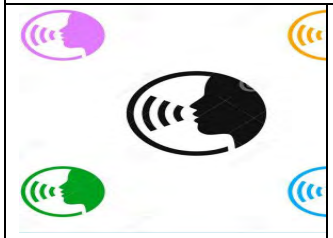
Inadequate water

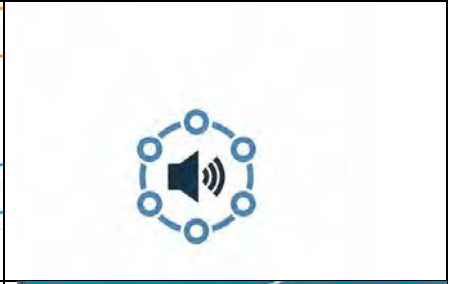


Adequate water

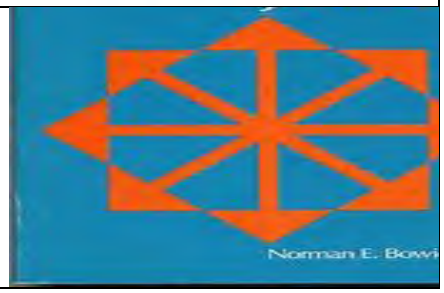
Transparency and accountability		Corruption, wastage	
			
			

Social mobilisation, advocacy and behavioural change

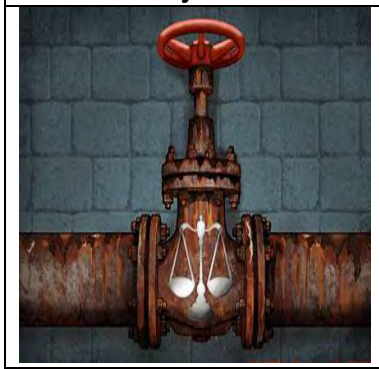








Distributive justice for water





Alternative energy in water provision





Sanitation and water challenges









Impacts of extreme events







Collective action on environnemental conservation









Clean and safe water for all





Water productivity and wetland conservation







Water conservation







Nature based approaches











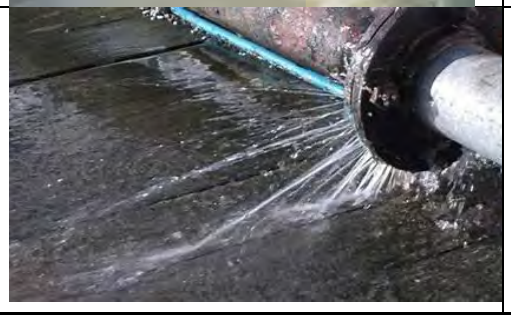


Water related conflicts

Some solutions to water related challenges		
		
Transparency and accountability	Expansion of drainage system	Wastewater disposal









Community awareness, mobilisation, capacity building / social mobilisation

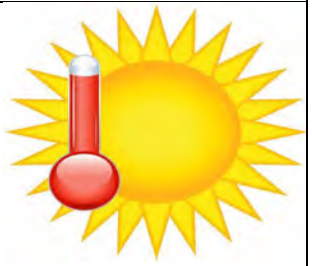






Projected heat and rainfall extremes









Environmental degradation and climate change challenges





Poor solid waste management



Hospitalisation, morbidity and mortality



Unplanned settlement

Water scarcity scenarios	
	

Appendix 9: Observed changes in components of CWH at household level

CWH component	N	%
Negative changes in water quantity/rationing over lifetime	19	28,4
Negative changes in water access over lifetime	27	40,3
Observed negative changes in water access over lifetime	18	26,9
Observed positive change in cost of water life	7	10,4
Observed positive changes in water access over lifetime	6	9,0%
Observed positive changes in water access over lifetime	14	20,9
Observed negative changes in colour of water over lifetime	13	19,4
Observed negative changes in taste of water over lifetime	14	20,9
Observed negative changes in turbidity of water over lifetime	16	23,9
Observed positive changes in colour of water over lifetime	29	43,3
Observed positive changes in taste of water over lifetime	23	34,3
Observed positive changes in turbidity of water over lifetime	20	29,9
Observed increase in food borne diseases	23	34,3
Observed increase in respiratory diseases	18	26,9
Observed increase in Skin Diseases	17	25,4
Observed increase in Eye infection	17	25,4
Observed increase in dental decolourisation	26	38,8
Observed increase in borne deformation	22	32,8
Observed decresed increase in food borne diseases	15	22,4
Observed decrease in respiratory diseases	17	25,4
Observed decrease in Skin Diseases	13	19,4
Observed decrease in Eye infection	15	22,4
Observed decrease in dental decolourisation	12	17,9
Observed decrease in borne dissformation	8	11,9
Decreased access to food	13	19,4
Increased cost of food	15	22,4
Decreased food availability	32	47,8
Increase in undesirable smell in the environment	17	25,4
Increases in air dust	13	19,4
Increase in incidences of cold waves	13	19,4
Increase in incidences of heat waves	4	6,0
Increased avian influenza outbreaks	15	22,4
Increased crop pest diseases	25	37,3
Increased small and large animal diseases	24	35,8
Increased access to food	23	34,3
Decreased cost of food	7	10,4
Increased food availability	12	17,9
Decreased avian influenza outbreaks	21	31,3
Decreased crop pest diseases	6	9,0
Decreased small and large animal diseases	18	26,9

Appendix 10: Effect of TSP tool on various dimensions of CWH

Dimension	Median	Mode
Level of trust for actors in adaptation planning	4,00	5
Degree to which one feels can have influence on adaptation planning	4,00	4
Degree to which they feel actors have shared interests	4,00	4
Degree to which they feel TSP is transparent	4,00	4
Degree to which they believe their voice can be heard in future	4,00	4
Degree to which actors complement each other	5,00	5
Degree to which one feels can influence planning to meet their needs	5,00	5
Degree to which empowered to understand individual and communal responsibilities	4,00	4
Degree to which they appreciate need for linkages	4,00	5
Empowerment for collective action	5,00	5
Degree to which current and taught knowledge can be integrated	4,00	5
Degree to which they have been empowered to perceive current and future	4,00	4
Shared thoughts and aspirations in adaptation planning	4,00	5
Degree to which new knowledge on climate impacts has changed	5,00	5
Degree to which knowledge on climate impact on hygiene has changed	4,00	5
Degree to which knowledge on climate impact on sanitation has changed	4,00	4
Degree to which knowledge on climate impact on water quantity has changed	5,00	5
Degree to which knowledge on climate impact on hygiene-sanitation nexus has changed	4,00	5
Degree to which knowledge on climate impact on water quality has changed	4,00	4
Gained better knowledge on impact of climate change on diseases	4,00	4
Gained better knowledge on impacts of climate change on agriculture and food	5,00	5
Gained better knowledge on impacts of climate change on better health	5,00	5
Perception on relationship between climate, water and health	4,00	5
Appreciate TSP tool as a better tool in adaptation planning for our community	4,00	5
Likelihood of seeking collaboration on CWH	4,00	4
Extend to which new contacts have been made	4,00	4
Likelihood of better collaboration	4,00	4
Degree to which exchanged information will influence CWH adaptation	4,00	4
Exchanged information has positively influenced water use practices	4,00	4
Degree to which you feel new information is likely to positively influence hygiene practices	4,00	4
Degree to which they feel new information is likely to positively influence sanitation practices	4,00	4
Degree to which they feel free expression of opinions prevailed	5,00	5
Degree to which they feel the interaction was mutual	5,00	5
Degree to which they feel the research team respected their opinions	5,00	5