SECTOR STUDY

WATER GLOBAL PRACTICE

Lesotho Water Security and Climate Change Assessment

WORLD BANK GROUP

GFDRR
Global Facility for Disaster Reduction and Recovery

ACP-EU Natural Disaster Risk Reduction Program
An initiative of the African, Caribbean and Pacific Group, funded by the European Union and managed by GFDRR

Water Global Practice

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Foreword by Hon. Ralechate ‘Mokose

Water is a source of wealth and prosperity for the people of the Mountain Kingdom of Lesotho. Although ownership of water is vested in the Basotho Nation, the Government of Lesotho has the duty to ensure sustainable development of the resource to maximize its socioeconomic benefits for the country. Reflecting this, the National Strategic Development Plan emphasizes that water is a key determinant of economic growth, which can drive sustainable development. Water in Lesotho has the potential to contribute to the development of significant investments, enabling growth in other sectors and stimulating job opportunities.

The relative abundance of water, coupled with the Government's sustained commitment, has contributed to Lesotho's having among the highest rates of access to safe water in Sub-Saharan Africa. Despite this, the country remains vulnerable to the shocks of regular and recurrent floods and droughts. The floods in 2011 were the largest on record since the 1930s, while the drought in 2015–16 is the driest in living record. These have substantial economic impacts.

In conjunction with the national development plan, the government has actively pursued development of water resources in the highlands of Lesotho. The Lesotho Highlands Water Project has facilitated investments of more than $3 billion under Phases 1A and 1B, providing sustained annual revenues that amount to M715,896,672 ($61m) in 2015 and M6.7 billion (nearly $800m) since 1996.

The prospects of an increasingly unpredictable and variable climate have profound implications for the structure of the economic prospects of Lesotho. This analysis gives direction to the national development goals and identifies important options to consider the risks from climate change. The country is at an early stage of addressing this agenda, and this is an important contribution.

Hon. Ralechate ‘Mokose
Minister of Water
Kingdom of Lesotho

Foreword by Jennifer J. Sara

The World Bank has been a long-standing partner in Lesotho's efforts to harness the sustainable development of the Kingdom's abundant water resources. Support to the sector dates back to the 1970s, with the construction of piped water systems and measures to strengthen the Water and Sewerage Branch. This culminated in establishment of the Lesotho Water and Sewerage Company as an independent entity, resulting in an increase in the overall customer base and level of service, and improved operational efficiency. More recently the Bank has supported the government's sectoral reforms and investments in the Metolong Dam and Water Supply Program as the first in a series of investments in improving bulk infrastructure in the lowland areas of Lesotho.

The World Bank has a proud and long-standing relationship with the Lesotho Highlands Water Project (LHWP)—one of the world's most ambitious water transfer projects. The World Bank's support to the government dates back to the 1980's, when the Bank was the executing agency on behalf of the government for United Nations Development Programme–financed design studies. Since then, the Bank has provided US$165 million in support of the LHWP, including through the Lesotho Highlands Water Engineering Project in 1986, which assisted in the design and preparation of the LHWP, and two loans for Phases 1A and 1B. The revenues and ancillary developments realized under the LHWP present unique opportunities for further development, with the potential transfer of water to Botswana under investigation. Sustained revenues from water transfer have helped mitigate economic uncertainties and have been central to poverty alleviation.

Climate change expresses itself through water. As this report shows, water remains one of the great opportunities for Lesotho and the measures identified here provide a clear roadmap for increasing resilience and improving development outcomes.

Jennifer J. Sara
Director, Water Global Practice
World Bank Group

Acknowledgments

This work represents one in a series of three reports documenting the findings of a program of support to the government of Lesotho aimed at enhancing the capacity for water resource modeling and management and enhancing capacity for the assessment of climate-related vulnerabilities. The World Bank team was led by Marcus Wishart (Senior Water Resources Management Specialist) and Ijeoma Emenanjo (Natural Resources Management Specialist), and included Rikard Liden (Senior Hydropower Specialist), Christine Heumesser (Agricultural Economist), Nathan Lee Engle (Climate Change Specialist), and Louise Croneborg (Water Resource Specialist). Model development and analysis was undertaken by the Stockholm Environment Institute, led by Annette Huber-Lee, and included Brian Joyce, David Yates, and Stephanie Galaitsi, along with David Groves, James Syme, and Zhimin Mao from Evolving Logic. The program was implemented under the guidance of Asad Alam (Country Director), Guang Zhe Chen (Country Director), and Jonathan Kamkwalala (Practice Manager) of the World Bank.

The program in Lesotho was coordinated by the Ministry of Energy, Meteorology and Water Affairs in collaboration with the Ministry of Agriculture and Food Security and the Lesotho Highlands Development Authority (LHDA). The reports represent the culmination of a series of virtual meetings, physical workshops, and reverse missions over the course of the program that included representatives from a wide range of national institutions, such as the office of the Commission of Water, the Department of Water Affairs, the Lesotho Meteorological Service (LMS), the Crops Department of the Ministry of Agriculture, and the LHDA.

Specifically, we are grateful for the participation of Commission of Water colleagues Lebohang Maseru, Matebele Setefane, and Khotso Mosoeu; Department of Water Affairs colleagues Nthati Toae, Phaello Leketa, Molefi Pule, Thabo ‘Mefi, Thabiso Mohobane, Motoho Maseatile, and Neo Makhalemele; Ministry of Agriculture colleagues Mahlomala Manoza, Lebone Molahlehi, Moeketsi Selebalo, Tsitso Marabe, Tiisetso Monyobi, and Tsoanelo Sekoiliata Ramainoane; LMS colleagues Kabelo Lebohang, Pheello Ralenkoane, Mathabo Mahahabisa, Tseole Charles, and Tsekoa Maqhanolle; Leshoboro Nena from the Lowland Water Supply Unit; and from the LHDA, Fred Tlhomola, Khojane Lepholisa, and Thelejane Thelejane.

The team acknowledges the peer reviewers who contributed to the study: Ademola Braimoh (Senior Natural Resources Management Specialist), Ana Bucher (Climate Change Specialist), Raffaello Cervigni (Lead Environmental Economist), Mukami Kariuki (Lead Water and Sanitation Specialist), and Regassa Namara (Senior Water Resources Economist).

Finally, the team wishes to acknowledge the generous support provided by the European Union–funded ACP-EU Natural Disaster Risk Reduction Program, an initiative of the Africa Caribbean Pacific Group of States, managed by the Global Facility for Disaster Reduction and Recovery.

Abbreviations

BCM	billion cubic meter
BCSD	bias-correction and spatial disaggregation
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM	Centre National de Recherches Météorologiques
CSAG	Climate Systems Analysis Group
ENSO	El Nino, Southern Oscillation Index
FAO	Food and Agricultural Organization (United Nations)
GCM	General Circulation Model
GDP	gross domestic product
IPCC	Intergovernmental Panel on Climate Change
LHDA	Lesotho Highlands Development Authority
LHWP	Lesotho Highlands Water Project
LLWSS	Lesotho Lowlands Water Supply Scheme
LMS	Lesotho Meteorological Services
MAFS	Ministry of Agriculture and Food Security
MCM	million cubic meter
MDWSP	Metolong Dam and Water Supply Program
NSDP	National Strategic Development Plan
RDM	robust decision making
USAID	United States Association for International Development
WEAP	Water Evaluation and Planning

All dollar amounts are U.S. dollars unless otherwise indicated.

Executive Summary

Abundant water, along with high altitude and geographic proximity to major demand centers in southern Africa, is one of Lesotho's most valuable renewable and sustainable natural assets. In a country characterized by high levels of poverty and income inequality, water contributes roughly 10 percent to overall gross domestic product (GDP). A large portion of this benefit comes from revenues associated with the Lesotho Highlands Water Project (LHWP), a multistage infrastructure project that enables the transfer of water from the water-rich highlands of Lesotho to the economic engine of the African continent in Gauteng and contributes to the development of hydropower resources in Lesotho. Balancing the opportunities afforded by the LHWP with the need to enhance national water resources infrastructure and increase water security against potential future vulnerabilities is central to the government's long-term vision for development and to sustainable economic growth.

This analysis conducts the first systematic examination of the vulnerabilities of Lesotho's water management system to climate change by exploring a set of adaptation strategies across a wide range of potential future conditions. Given the importance of water to long-term sustainable economic growth in Lesotho, extensive quantitative and qualitative analyses have been used to identify strategies that demonstrate successful system performance over a wide range of plausible future scenarios. The analysis looks specifically at the need to ensure continued development of water resources within Lesotho, to increase security around the nexus of water, food, and energy along with sustained economic development, while also ensuring that Lesotho is able to meet its obligations under the Treaty with South Africa governing the LHWP. The analysis does not prescribe a water management strategy for Lesotho based on a single prediction of the future, but quantifies the range of possible future conditions to empower stakeholders and demonstrate the benefits that can be realized over a broad range of possible future outcomes.

Developing a System Model for Lesotho. The analysis is based on a water resource decision support model developed specifically for Lesotho. The Water Evaluation and Planning (WEAP) model couples climate, hydrologic, and water management systems to facilitate an evaluation of the uncertainties and strategies of impacts on specified management metrics. The WEAP model has been developed over the past 20 years by the Stockholm Environment Institute working in partnership with a number of agencies (including the World Bank) and has been applied in numerous research and consultative projects around the world. The WEAP model is designed to evaluate the performance of water supply reliability for different water use sectors (such as domestic and industrial water users, rainfed and irrigated agriculture, hydropower, instream flow requirements, and water transfers to South Africa) across a range of future climate conditions. The model lays a foundation for a national system to monitor the development and use of water resources in Lesotho. The Lesotho WEAP model was developed through an iterative series of workshops with key stakeholders from various governmental departments. The first step in the development process focused on developing the rainfall and runoff routines and calibrating these to observed historical streamflow time series. The second step focused on adding representations of the existing and planned water management infrastructure to the model to facilitate scenario planning.

Assessing Climate Change Scenarios for Lesotho. The WEAP model was used to simulate the historic climate based on data from the national government archives and global datasets available in the public domain. These included 121 downscaled Global Climate Model (GCM) projections of future climate over two possible water demand scenarios, for a total of 244 scenarios up to the year 2050. This large collection of future climate projections is based on a bias-correction and spatial downscaling (BCSD) procedure that applies a four-step process to generate monthly climate on a 0.5° grid for the world's landmasses. The grid cells corresponding to the river basins of Lesotho are extracted, and an averaging procedure estimates average monthly precipitation and temperature for each catchment in the WEAP model.

Robust Decision Making. Although WEAP is a powerful modeling tool, models applied in isolation do not necessarily provide guidance to support decision making and policy setting. To play this role, models must be embedded within decision analytic frameworks that guide the development of experimental designs and the evaluation of the results that the models produce. In this study, a robust decision-making (RDM) framework was applied to frame the analysis and help interpret the results. The analysis examines which strategies demonstrate robust performance across the range of future scenarios to show positive performance over a broad range of circumstances. Because individual future scenarios cannot be assigned a probability of occurrence, the use of broadly applicable robust strategies reframes the management dilemma for climate adaptation. Demonstrations of robustness can empower decision makers to implement interventions even under highly uncertain conditions.

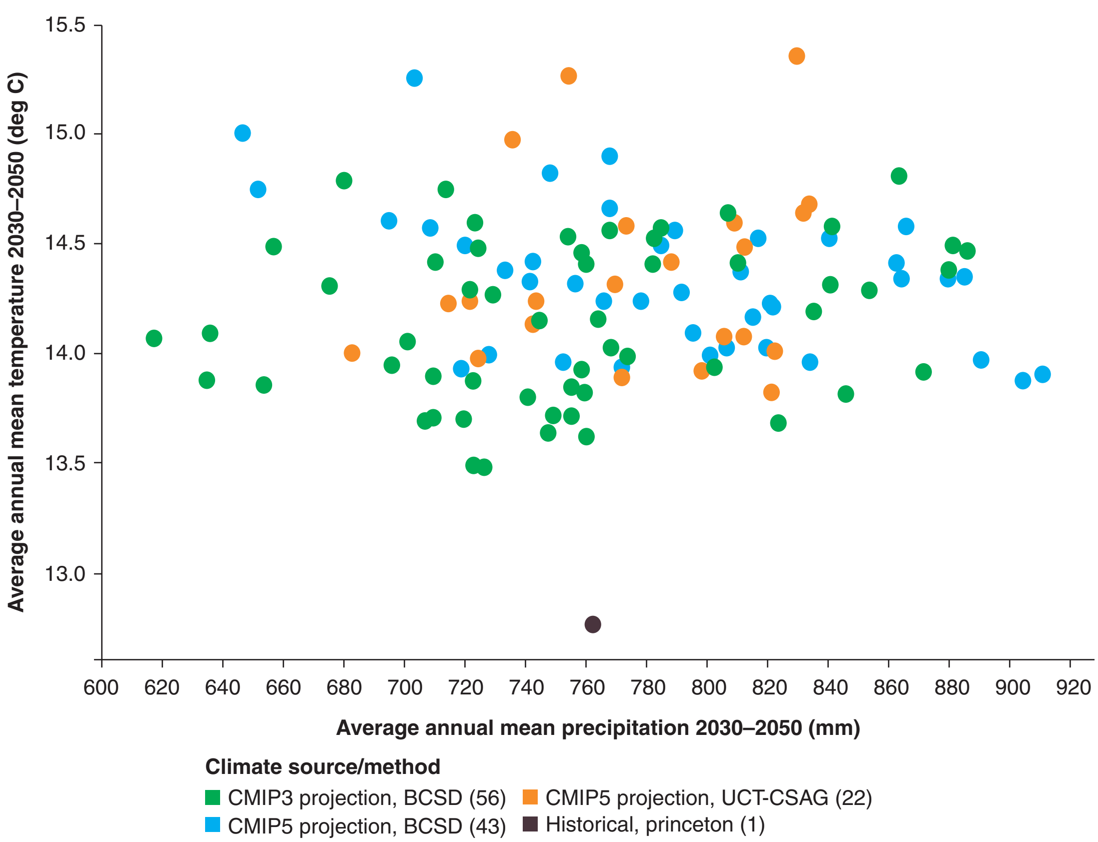
The project worked with national experts, stakeholders, and policy makers in an iterative process to identify key uncertainties that could compromise Lesotho's water management strategy. These include climate change, domestic and industrial water demand, agricultural production, and changes in water transfer opportunities. The stakeholder process was also used to identify a range of potential adaptation strategies. These included new infrastructure, such as the Lowlands Bulk Water Supply Scheme, which could provide additional water to communities across the lowlands of Lesotho, the allocation of water for further development of irrigated agriculture, and development of future phases of the LHWP. To evaluate the performance of these strategies, stakeholders specified the key management metrics of the water supply system, including the reliability of water for agriculture, domestic and industrial demands for Lesotho, as well as water transfers.

Capacity Building. Recognizing that adapting to future challenges, including climate change, is a long-term process, the approach to model development and application of the analytical tools focused on capacity enhancement for resource managers. The aim was to provide the necessary background and experience needed to use the models and analytical tools in support of forward-looking decision-making processes. A number of training sessions were held with managers and professionals to (1) improve the development and use of the WEAP-based water management model; (2) understand and apply the statistical programming language, R, for climate data analysis; and (3) apply the interactive visualization software, Tableau. Proficiency in WEAP will allow planners to continue to use, improve, and interrogate the WEAP model, while the R language is crucial for climate analyses and GCM processing for future climate investigations. The Tableau software facilitates the interpretation of large quantities of results that often characterize climate change investigations. Opportunities remain in Lesotho for further capacity building in these tools to examine and evaluate climate projects for use in the WEAP model. This experience in Lesotho suggests also that similar capacity building efforts could be extended to other countries and water management authorities within the Southern African Development Community as a means of supporting vulnerability assessment and adaptation planning.

Climate Change Projections. Key vulnerabilities within the current system have been identified with respect to water supply for domestic and industrial water demand, irrigation, and water transfers. A summary of projected future surface air temperatures from the ensemble of GCM datasets analyzed for this study suggests warmer conditions for the period from 2030 through 2050. The projected increase in air temperature derived from the GCMs ranges from a low of about 0.8°C to a high of 2.9°C above the historical average of 12.7°C. In contrast, there was no strong consensus among the climate models for projections of future precipitation for the same period. Some GCM-modeled future projections, on average, are wetter while others are drier. For the twenty-year period, more future projections are drier (64 GCM projections) on average than wetter (57 GCM projections). The range of projected future precipitation includes both an increase and decrease of about 20 percent or 160 mm annually. The historical annual average precipitation over Lesotho is about 760 mm. These climate projections for precipitation and temperature are shown in figure ES.1.

Climate change scenarios suggest diminishing capacity to meet the future growth in demand for domestic and industrial water in Lesotho. Over half of the future scenarios evaluated predict unmet domestic demand of more than 20 percent for the 2041–50 period. The analysis shows that development of the Lesotho Lowlands Water Supply Scheme (LLWSS) would reduce the vulnerability to unmet demand and improve overall water security for the continued economic development of the industrial sector, meet increasing domestic demand, and provide for further development of irrigation potential. The Metolong Dam and Water Supply Program, the first project to be implemented under LLWSS,

FIGURE ES.1 Summary of Temperature and Precipitation for 122 Climate Scenarios, 2031–50



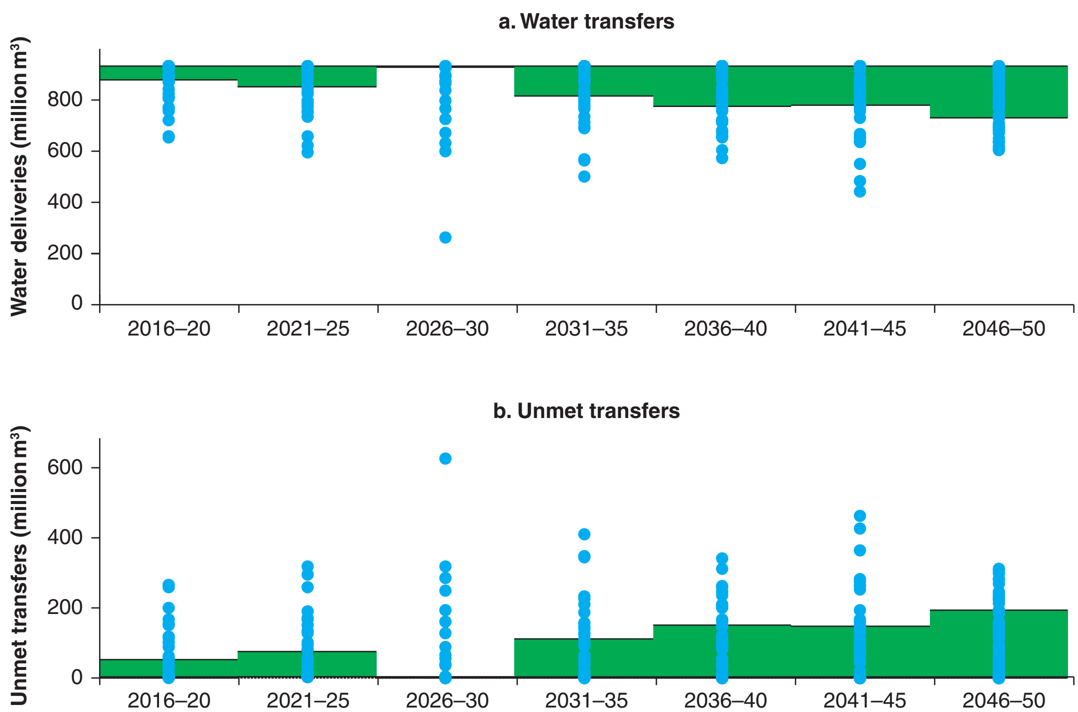
Note: UCT = University of Cape Town.

has increased security of supply to Maseru, Teyateyanang, Roma, Morija, and other surrounding towns. The study recommends the implementation of further phases of LLWSS as an adaptive measure to mitigate the potential effects of future climate change and current variability.

Lesotho's agricultural sector is predominantly rainfed, thus susceptible to climatic variations and vulnerable to projected increases in climate variability. Rising temperatures will increase the amount of water required for crops, exacerbating water stress during dry periods. Without irrigation schemes, any shift toward drier precipitation patterns could reduce agricultural yields. Coupled with projected increases in population, Lesotho's dependence on food imports will likely increase. Developing additional irrigation capacity and expanding existing schemes could increase food security. The increased allocation of water required to expand from the 1,000 hectares currently under irrigation to the 12,000 hectares that have been identified as potentially irrigable could be met without reducing transfers of water to South Africa under all future scenarios.

Water transfers to South Africa will be increasingly vulnerable in the coming decades (see figure ES.2). Specifically, the analysis finds that in 10 percent of the climate scenarios (indicated as the points outside the shaded area in figure ES.2) the average amount of unmet water transfers increases from

FIGURE ES.2 Water Delivered to South Africa and Water Deficits under the Baseline Strategy for 122 Climate Scenarios, 2016–50

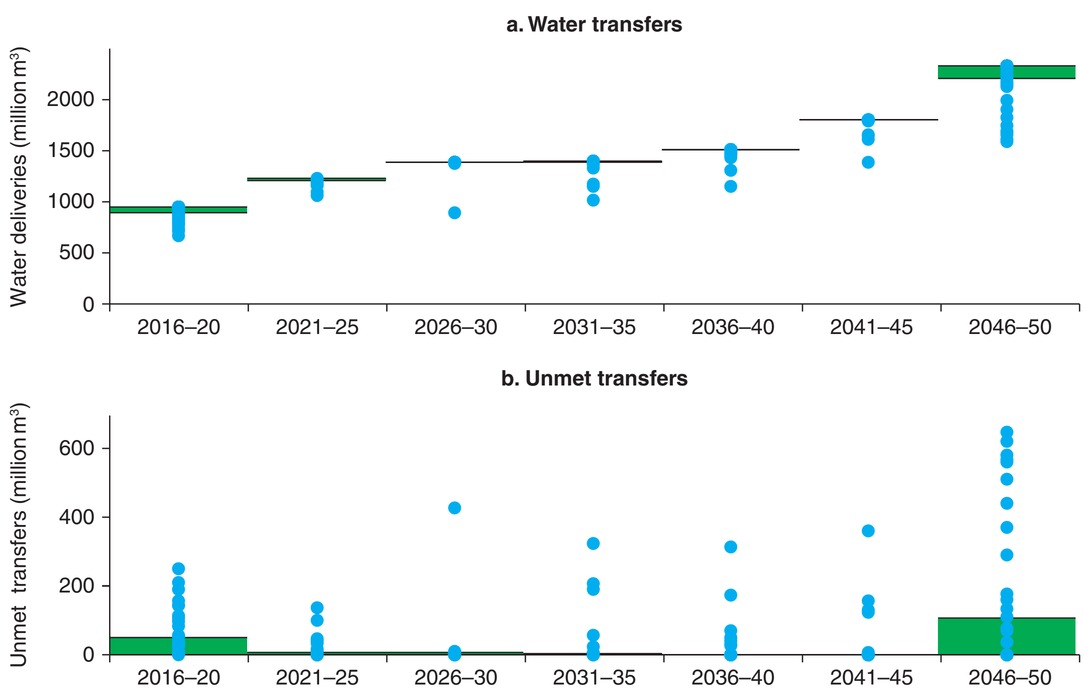


Note: Range of average water deliveries in five-year increments. Shading indicates 90 percent of the range of values.

about 500 million m³ in the 2016–20 period to almost 2 billion m³ in the 2046–50 period in the absence of implementation of the additional phases envisaged. Delays in implementing the LHWP could undermine water security in South Africa and limit the economic and development benefits that accrue to Lesotho. The analysis then finds that various adaptation strategies, including full construction of the proposed Polihali Dam and the full build-out of all five phases of the LHWP infrastructure, both increase the amount of transfers to South Africa and increase their reliability over a wider range of climatic conditions (see figure ES.3). For each of the strategies evaluated, the analysis identifies the key climate conditions for which the deliveries to South Africa (and other performance metrics) are unacceptable. For example, the analysis confirmed that the system with the Polihali dam is highly reliable under most climate futures and that deficits occur only in the very driest of futures (16 of the 122 cases, in which precipitation is less than 725 millimeters per year).

The development of the water transfer and hydropower components under Phase 2 of the LHWP are projected to bring additional benefits to Lesotho. In addition to increasing the potential delivery of water in response to growing demand in South Africa, the projects are expected to contribute about 11,000 jobs annually during the construction period. Approximately half of these jobs will be in construction, with the rest in such indirect activities as agriculture, transport, and services. The majority of these jobs will be

FIGURE ES.3 Water Delivered to South Africa and Water Deficits for Full Build-Out of the Highlands Strategy for 122 Climate Scenarios, 2016–50



Note: Shading indicates 90 percent of the range of values.

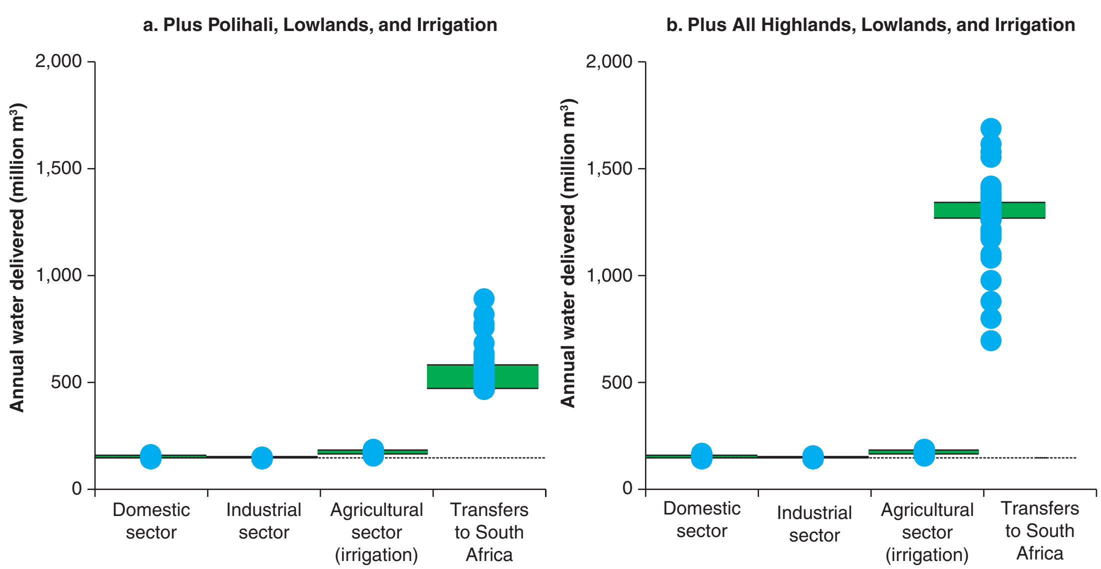
temporary and so the challenge will be to transfer skills and leverage income for sustainable employment after major civil works are completed. However, improved road access and reduced travel times and transport costs will have substantial longer-term benefits through better access to and from agricultural markets and will boost tourism and other local development opportunities.

Implementing the lowlands scheme and expanding irrigation through the diversion of a portion of water captured by the LHWP would not jeopardize the reliability of the water transfers to South Africa. The analysis identified both a *Plus Polihali, Lowlands, and Irrigation* strategy and a *Plus All Highlands, Lowlands, and Irrigation* strategy. These two strategies both dramatically increase the amount of water exported to South Africa and divert enough water to the lowlands to significantly reduce the projected shortages and increase food production in future decades (see figure ES.4).

The assessment indicates that transfers to both South Africa and Botswana could be reliably met under future scenarios in which the climate is about the same, or wetter, than as shown by historical trends. Under drier climates, there would be a tradeoff between meeting the transfer targets for Botswana and South Africa. The percentage impact on the transfers to South Africa would be much lower than that on the transfers to Botswana. When the transfers to Botswana are prioritized, they are very reliable, with shortfalls in only 4 of the 122 climates examined. With the development of the Polihali Dam, the South African transfer targets can be met under most, but not all, plausible future climates.

Conclusions and Recommended Next Steps. The analysis outlines a range of possible scenarios for Lesotho based on a comprehensive assessment of

FIGURE ES.4 Allocation of Additional Water Supplied, by Sector, Compared to the Baseline Strategy for 122 Climate Scenarios, 2050



Note: Shading indicates the middle 80 percent of the range of results.

the potential changes associated with climate change from 2030–50. The analysis does not prescribe a water management strategy for Lesotho based on a single prediction of the future, but quantifies the range of possible future conditions as characterized by the latest GCM results and stakeholder assessments of internal demand predictions and future water transfers. This quantification empowers stakeholders to act with more confidence by demonstrating that the implementation strategies can provide benefits to water resources management and provision over a broad range of scenarios. Implementing a series of the adaptive interventions identified can improve overall system performance across the range of future scenarios and enhance the overall water security for Lesotho. Specifically the analysis draws the following conclusions:

- Climate change will create important determinants for the future, long-term sustainable macroeconomic development of Lesotho. All future scenarios consistently demonstrate an increase in temperature, while changes in patterns of precipitation vary among the different scenarios. This will have implications for long-term domestic and industrial water security, patterns of agricultural production, and opportunities afforded through the further development of water transfer infrastructure.
- Domestic and industrial water security is highly vulnerable under historical and current climate conditions, as well as under the full range of climate future scenarios. These results are driven by the current configuration of the water management infrastructure system, which does not provide interconnections between the developed water sources used to support the LHWP with domestic and industrial demand in the lowlands.
- Agriculture production will remain vulnerable to interannual variability over the coming decades, particularly with continued reliance on rainfed agriculture. Irrigation schemes can be supported without significant reductions in transfer reliability to South Africa. Investing in monitoring and enhanced data acquisition would help improve future adaptive capacity and on-farm responses to changes in climate patterns and levels of variability.
- The LHWP will continue to reliably meet transfers to South Africa over the coming decades unless climate conditions are about 5 percent drier or more than the historical record. Construction of the Polihali Dam, and associated infrastructure, will increase transfers and reliability. Build-out of the full LHWP increases the transfer capacity and can also support the development of water supply schemes in the lowlands along with irrigation development.

Adapting to future challenges, including climate change, is a long-term process that affords time and opportunity for strategically positioned and driven enhancements. The analysis clearly points to a number of areas for further development.

Improve Data Monitoring and Management. Data limitations will undermine Lesotho's ability to monitor predictions and respond to changes in climate. Design and implementation of an optimized hydrometeorological network would enhance the capacity of Lesotho to prepare for and respond to potential future changes in climate. Detailed agricultural data and information about the economic uses and value of water were not readily available. These limitations led to a more cursory evaluation of the agricultural sector and the omission of a more formal economic analysis.

Continued Capacity Enhancement. The tools and analysis required to support the planning for robust climate adaptation necessitate sustained capacity development. The nature of the analysis here provided support to the first iteration of an interactive participatory process. The time required to develop the tools and capacity needed provides a foundation, but should be further developed and integrated into government planning processes.

Economic Evaluation. The climate modeling and RDM framework illustrates important decision pathways for future development in Lesotho. The cost and valuation data required to support a cost-benefit analysis across the wide range of climate conditions would also support an important economic evaluation of different adaptation options. These data could be incorporated into the current RDM analysis to evaluate the economic robustness of the different adaptations.

Extending Adaptation Analysis. Using the existing data and tools to undertake additional iterations of the vulnerability and adaptation analysis up to the end of the 21st century would increase the scientific rigor. The analysis would enhance the capacity to evaluate climate risks and weigh different tradeoffs. Further adaptation of the WEAP model to a shorter time step, such as one day, would enable the evaluation of operational strategies for water allocation among competing uses, such as water deliveries and timing for domestic and agricultural use, as well as hydropower generation. Extending the geographic scope of the model to demand areas in South Africa that rely on water imported from Lesotho would also produce a more complete understanding of vulnerabilities and tradeoffs.

Lowlands Water Supply Scheme. Continued development of the LLWSS is critical to improving the reliability and resilience of the domestic and industrial sectors. Exploring interconnections between the developed water resources through LHWP and linking these to address domestic and industrial demands in the lowlands could help improve the resilience of the existing system. Such integrated planning could also help to manage the associated political economy between perceived national benefits and the development of water transfer projects.

Agricultural Sector Assessment. The results highlight the need for a more thorough assessment of the risks and opportunities for Lesotho's agricultural sector of potential changes in climate. An evaluation of the implications of increasing atmospheric carbon dioxide (CO_2) concentrations, together with rising temperatures and water stress on agricultural productivity, should be further elaborated. A better understanding of these dynamics could help develop agricultural strategies suited for the unique climatic changes under way in Lesotho. This information could help direct a program to incorporate the traits of such plans into desirable crop production cultivars to improve yield.

Using a deliberate, inclusive process with Lesotho managers, this project incorporated Lesotho's most pressing needs to demonstrate the vulnerabilities, challenges, and opportunities in the Lesotho water management system. With a new quantification of options for improving system robustness, managers can move forward with plans that are most aptly positioned to support their objectives.

Chapter 1

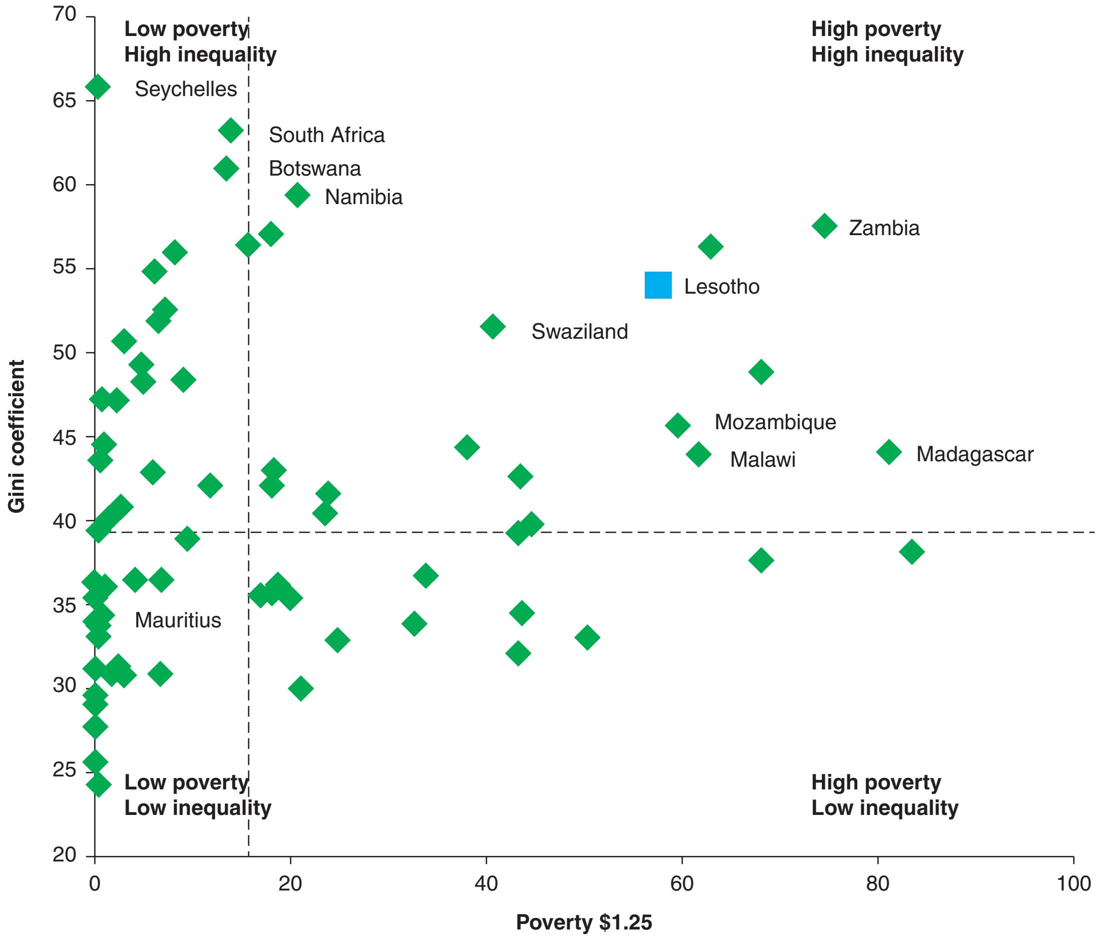
Motivation and Overview

1.1 Overview of Lesotho and the Water Sector

The abundance of water, coupled with Lesotho's high altitude and geographic proximity to major demand centers in southern Africa, makes water one of the country's most valuable renewable and sustainable natural assets. A large portion of the benefits derive from revenues associated with the LHWP. These contributions will increase with development of phase 2 of the LHWP, implementation of the LLWSS, and additional investments in agricultural development and improvements. A strong framework to guide the development and management of water resources in the face of increasing uncertainty is also central to long-term macroeconomic water security.

In a country characterized by high levels of poverty and income inequality (see figure 1.1), water contributes approximately 8-10 percent to the overall gross domestic product (GDP) and is central to long-term sustainable economic growth and development. The government's preliminary estimates show that the national poverty head count rate has remained unchanged over the past decade at around 57 percent of an estimated 2 million people,[1] with a Gini coefficient based on consumption of approximately 0.53.

FIGURE 1.1 **Distribution of Poverty and Income Inequality for African Countries**



However, the pattern of poverty has changed, decreasing in urban areas and becoming concentrated in rural areas. These rural areas are home to about three-quarters of the total population.

The combined efforts to develop further phases of the LHWP, increase the national coverage for water supply, and enhance agricultural development are central to the government's efforts to eradicate extreme poverty and promote shared prosperity. The government's development goals are reflected in its National Vision 2020 and the National Strategic Development Plan (NSDP). Issued in 2002, the National Vision 2020 articulates the long-term strategic priorities that will enable Lesotho, by 2020, to be "a stable democracy, a united and prosperous nation at peace with itself and its neighbors [and to] have a healthy and well developed human resource base, a strong economy, a well-managed environment, and an established technological base." The NSDP, which is the basis for the implementation strategy of National Vision 2020, reaffirms the government's commitment to the objectives of fiscal consolidation, economic diversification, infrastructure, and human development. The NSDP sets the following strategic goals: pursue high, shared, and employment-generating economic growth;

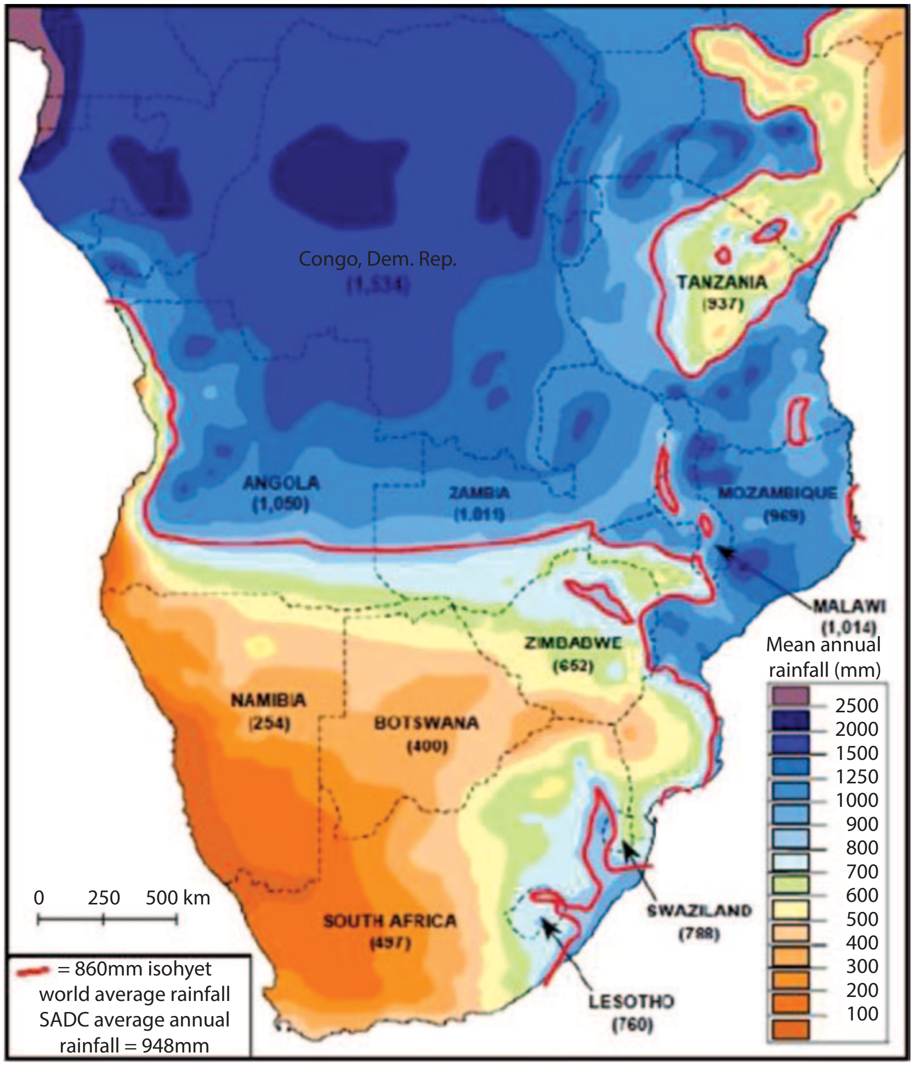
develop key infrastructure; enhance the skills base, technology adoption, and foundation for innovation; improve health, combat HIV and AIDS and reduce vulnerability; reverse environmental degradation and adapt to climate change; and promote peace, democratic governance, and build effective institutions.

Within the national development framework, water remains a sustainable, renewable asset, demand for which is largely immune to the volatility of global markets and international policy positions. Over the past decade, the key drivers of growth in Lesotho have shifted from dependence on net exports to an economy driven primarily by government spending. Despite these changes in the drivers of growth, the main exports continue to be textiles, water, and diamonds, with water exports from the LHWP remaining consistently at about 3 percent of GDP. In contrast, agriculture products contribute about 0.6 percent of GDP. Volatility is shown in the decline of the relative contribution of the manufacturing sector from 20.1 percent in 2004 to 10.8 percent in 2013. The textile sector has stagnated, and exports have dropped from a peak of 49.6 percent of GDP in fiscal 2002/03 to less than 16 percent in fiscal 2013/14. Employment in the textile and clothing industry also fell to below 38,000 workers from highs of 45,000 to 50,000 in the late 2000s, although this industry still accounts for 86.5 percent of total employment in the manufacturing sector. Diamond exports also continue to vary from 3.3 percent of GDP in fiscal year 2004/05 to 14 percent of GDP in fiscal year 2013/2014 depending on global demand.

The value of Lesotho's water resources is derived from its strategic position in the Orange-Senqu River basin (map 1.1). The basin accounts for over 10 percent of GDP in Sub-Saharan Africa and is the third most economically important basin per unit area on the African continent after the Nile and the Limpopo river basins. With its headwaters in the highlands of Lesotho, the Orange-Senqu River basin encompasses Botswana, Lesotho, Namibia, and South Africa, with a catchment area of over one million square kilometers. The river flows approximately 2,300 kilometers to the west before discharging into the Atlantic Ocean. Its main tributaries are the Senqu, Vaal, Fish, and Molopo-Nossob river systems. The mountain Kingdom of Lesotho is fully situated within the basin but accounts for only 5 percent of the basin surface area, while contributing 40 percent of the annual runoff. Mean annual precipitation is nearly 1,800 millimeters in the headwaters in Lesotho, but only 50 millimeters at the river's mouth between South Africa and Namibia. In contrast, Botswana accounts for 12 percent of the basin and contributes little to the basin runoff; South Africa occupies 64 percent of the basin, accounting for 56 percent of the total mean annual runoff and 98 percent of the consumption among the riparian basin states.

The LHWP is central to realizing the government's development objectives and securing sustainable revenues in support of economic growth. The LHWP is a binational project between South Africa and Lesotho, governed by a treaty signed in October 1986 that provides for the transfer of water from the water-rich highlands of Lesotho to the dry Gauteng region of

MAP 1.1 Southern African Rainfall Patterns



Note: SADC = Southern Africa Development Community.

South Africa. Water is transferred within the Orange-Senqu River basin through a series of dams, transfer tunnels, and associated infrastructure, and provides opportunities to supply electricity to Lesotho through associated hydropower developments. The LHWP is the largest of a number of schemes within the Orange-Senqu River basin and capitalizes on the high-quality water and high altitude areas of Lesotho to provide the least-cost solution for securing water for more than 12 million people in the Gauteng Province, which generates more than 40 percent of South Africa's gross national product. Four phases of the program were envisaged, ultimately enabling the transfer of a maximum of 70 m^3/s downstream. To date, the first phase of the project has been completed, comprising two dams, two transfer tunnels, and a power station. The current capacity of the scheme is approximately 900 Mm^3 per year.

Phase 1A of the LHWP, which included construction of the Katse Dam and water transfer tunnel and the Muela Dam and hydropower project, was implemented between 1991 and 1999 at a total cost of US$2.4 billion. Phase 1B, which included the construction of the Mohale Dam and associated transfer tunnel, was implemented between 1998 and 2006 at a cost of roughly US$885 million. The agreement for Phase 2 of the LHWP was signed on August 11, 2011, and committed South Africa and Lesotho to the construction of the Polihali Dam and water transfer infrastructure along with associated hydropower developments, identified at the time as the Kobong Pump Storage Scheme. The government of South Africa is responsible for the costs of water transfer. The government of Lesotho is responsible for the costs of the hydropower and ancillary development activities.

The cost of development of the first phase of the LHWP amounted to approximately three times Lesotho's 2002 GDP of M4.175 billion. The sharing of benefits under the LHWP is based on the lower cost of the project alternatives in South Africa. The benefits are split between Lesotho (56 percent) and South Africa (44 percent), with South Africa saving on the lower costs and Lesotho benefitting from royalties, ancillary developments, and hydropower. Royalties are based on a fixed portion paid over 50 years, reflecting the lower capital cost for full delivery of 70 m^3 compared to the alternative Orange-Vaal Transfer Scheme, and a variable portion, due to the lower operation and maintenance, and electricity costs based on the volume of water delivered. Under phases 1A and 1B water transfers are currently 18 m^3 per second and 12 m^3 per second of water. Revenue in the form of royalties from water sales was M630 million (approximately $74 million) in fiscal year 2012/13. Electricity sales totaled M50 million ($5.9 million) to Lesotho Electricity Company and M2.7 million ($318,000) to Eskom (Commission of Water 2014). Currently the revenues from Phase 1 amount to between $65 million and $75 million annually (approximately 3 percent of GDP). With limited options for augmenting existing water supplies, Botswana has also approached the government of Lesotho to explore potential development options for the further transfer of water from the highlands of Lesotho. This would consolidate Lesotho's position as the water tower of southern Africa and allow for the potential development of additional, sustainable revenue streams for Lesotho based on renewable water resources.

Balancing the development of water resources for export against the national priority to improve domestic levels of access is one of the key challenges for the government. According to the Continuous Multipurpose Survey conducted by the Bureau of Statistics in April 2012, 72.1 percent of the population in urban areas and 63.3 percent of the population in rural areas have access to improved water services. The government has articulated an ambitious vision to provide 100 percent of the population with improved water sources by the year 2020 (Lesotho 2012b; Ministry of Natural Resources, 2007). Meeting these targets and realizing the vision requires major investments in urban water and sanitation services, particularly in the lowland areas that account for 75 percent of the population (Lesotho 2012b).

Historically, the supply of water to urban areas in the lowlands has come from river extraction and pumping from underground sources. Increases in the urban population and commercial activity in the lowlands have led to growing demand on these resources and water supply facilities. The increase in population is due mainly to rural migration driven by the industrialization of the capital city of Maseru and urban towns through the establishment of garment industries. A number of towns in neighboring South Africa also draw water from the same sources along the Mohokare/Caledon River. This has created an additional strain on scarce resources and has been a major constraint to continued economic growth.

The LLWSS has identified a series of investments to address the challenges of water security and improve supplies for domestic, institutional, and industrial purposes in the lowland areas of Lesotho with populations in excess of 2,500 people. The LLWSS includes (1) development of new water sources; (2) treatment of water as necessary; (3) transfer of water to demand centers; and (4) bulk storage of treated water at suitable locations serving those centers. These recommendations included the preliminary design of five treated bulk-water supply schemes serving eight designated water demand zones, falling into three regions: northern, central, and southern. The first major investment was the multidonor-funded Metolong Dam and Water Supply Program (MDWSP). Inaugurated in 2015, the MDWSP represented the first and largest of the investments envisaged under the LLWSS, increasing the capacity of safe drinking water to a large portion of the population in the lowlands by as much as 70 megaliters per day.

The MDWSP is expected to alleviate supply constraints to Maseru and the towns of Teyateyaneng, Morija, and Roma. Intermittent water supplies and the lower elevation areas of Lesotho have suffered severe water shortages in a number of years. Efforts have been made to improve the system: Of 24 African countries sampled between 1995 and 2005, Lesotho was ranked third behind Uganda and Ethiopia on the success rate of improving the levels of service of water supply to its population, from informal untreated sources to formal water supply systems. Appreciating the important role that water plays in the development of the Lesotho economy, the government has made supplying plentiful and reliable water to industrial zones a priority.

Agriculture provides a lifeline for the majority of Lesotho's population, despite accounting for only 10 percent of GDP. An estimated 75 percent of the population live in rural areas, the majority of whom rely on rural livelihoods and depend on agriculture—both crops and livestock—to survive. Only 13 percent of the total land area is deemed suitable for crop production, with the principal crops of maize, sorghum, and wheat planted on nearly 85 percent of the cultivated area. Livestock contribute 30 percent of the total agricultural output and are susceptible to drought and rangeland degradation.

The agricultural sector in Lesotho is characterized by low and declining production, accentuated by the effects of climate variability. As a result, the agricultural and food sectors are at high risk not only from historical annual rainfall, but increasingly, from climate change (FAO 2005; Hachigonta et al. 2013). The reliance on rainfed agriculture only serves to increase this vulnerability. The area under rainfed and irrigated cultivation is reported to have been as high as 450,000 hectares in the 1960s (Hachigonta et al. 2013). However, current cultivation is less than 125,000 hectares, including only 1,000 hectares under some form of irrigation. This represents less than 10 percent of the long-term irrigation potential, which is estimated at about 12,000 hectares.

As much as 80 percent of the variability of agricultural production in Lesotho results from weather conditions, especially for rainfed production systems (Hachigonta et al. 2013). For example, between 1990 and 1996 the total area under cultivation fluctuated between 150,000 and 300,000 hectares, down from 450,000 hectares in 1960 (Hachigonta et al. 2013). In 2009, only 120,000 hectares had been planted with crops, representing a decrease of about 18,000 hectares (15 percent) from the previous season (Hachigonta et al. 2013). Rainfall variability affects not only the land area planted but harvests as well.

The lack of irrigation imposes a serious constraint on production and undermines national food security. Domestic agricultural production provides only about 30 percent of the national food requirement (Hachigonta et al. 2013). The balance depends on imports. Future climate scenarios suggest that there may be potential food deficits caused by the stresses of decreased rainfall and increased temperature. In the absence of effective adaptation, yields may continue to decline across the country. Predicted increases in temperature may open up new areas for agriculture, which will permit cultivation in areas that were previously unproductive, but continual challenges with shallow soils on steep slopes may increase the risk of soil erosion.

Although the geographic context and location of Lesotho provide it with several opportunities, the underlying structure of the economy is highly exposed to potential changes in climate variability. Ensuring a robust regime for sustainable management and further development of water resources will be critical to securing long-term benefits through economic development of its industrial, commercial, service, and agricultural sectors.

1.2 Institutional Framework for Water

Ownership of water is vested in the Basotho Nation, with the government of Lesotho having the duty to ensure sustainable development of the resource in order to maximize the socioeconomic benefits to Basotho. To meet these demands, the government has committed to a series of sectoral reforms with an evolving legal framework and institutional arrangements to address fragmentation of the sector and improve capacity. The apex of these reforms was the development and endorsement of the Lesotho Water and Sanitation Policy in 2007 and the enactment of Water Act in 2008. The Water Act is supported by a Water and Sanitation Strategy that sets out the strategies, objectives, plans, guidelines, procedures, and institutional arrangements for the protection, conservation, development, management, and control of water resources.

The development and management of water resources requires a range of multisectoral inputs, which coupled with climate change create a complex array of different stakeholders with various roles and responsibilities at various levels. Lesotho has endeavored to ensure broad service through a range of different institutions and to support communication and coordination among them. Although these provide a cohesive framework for institutions within the water sector, cross-sectoral coordination with water dependent sectors, such as agriculture, and emerging areas, such as climate change and disaster management, continues to present challenges to integrated planning and development.

The Water Act provides for the management, protection, conservation, development, and sustainable use of water resources. The Office of the Commissioner of Water has the following mandates:

- Provide policy direction to the water sector
- Implement and monitor water and sanitation policy
- Develop water and sanitation strategies and plans
- Act as custodian of the national water resources database
- Coordinate water management activities, including transboundary waters
- Advise the Minister on use and management of water resources
- Produce the annual State of Water Resources Report

BOX 1.1 Key Institutions within the Water Sector

- **Ministry of Water Affairs**: sector ministry providing policy guidance and oversight of sector institutions
- **Office of the Commissioner of Water**
- **Department of Water Affairs**: responsible for monitoring, assessment, and allocation of water resources
- **Department of Rural Water Supply**: responsible for support to local governments and communities for water and sanitation in areas not covered by Water and Sewerage Company
- **Lesotho Meteorological Services** (LMS): responsible for meteorological data collection and weather forecasts; secretariat for climate change adaptation activities
- **Water and Sewerage Company**: government-owned company responsible for water and sewerage services in major urban areas and operation of bulk water services
- **Lesotho Electricity and Water Authority**: responsible for regulation of electricity and water services
- **Metolong Authority**: responsible for implementing the Metolong Dam and Water Supply Programme (MDWSP) for bulk water supply to Maseru and surrounding towns and major villages and the associated environmental and social management plan
- **Lesotho Lowlands Water Supply Unit**: originally responsible for feasibility study and design of the bulk water schemes for the lowlands; presently providing technical services to the Commission of Water.

The Lesotho Highlands Development Authority (LHDA) was established in 1986 under article 7 of the treaty with South Africa governing the Lesotho Highlands Water Project. Under these provisions, the LHDA is responsible for the implementation, operation, and maintenance of the LHWP in Lesotho. Supplementary Arrangements Regarding the System of Governance for the LHWP were approved through protocol VI to the treaty, which was signed and came into effect on June 4, 1999. The Supplementary Arrangements provided for a restructuring of the functions, powers, and obligations of the LHDA. The provisions of the treaty require the LHDA to apportion all costs incurred by the LHDA to one or more of the following activities: (1) the delivery of water to South Africa; (2) the generation of hydroelectric power in Lesotho; and (3) ancillary developments in Lesotho. The government of Lesotho is responsible for the costs of the Hydropower and Ancillary Development activities and the government of South Africa is responsible for the costs of the water transfer activities. The LHDA is managed and controlled by a board of directors appointed by the Lesotho Highlands Water Commission. Nonexecutive members are nominated by Lesotho and executive board members from nominations submitted by the chairperson.

The Ministry of Energy, Meteorology and Water Affairs is responsible for coordinating all activities relating to climate change. Within the ministry, LMS conducts research through the National Climate Change Study Team, which carries out greenhouse gas inventories and develops climate change scenarios. It also engages with other institutions to conduct vulnerability assessments and to identify adaptation measures and mitigation options. Although the LMS is responsible for climate change actions, it relies on various institutions to inform a coordinated national response.

Institutions within the water sector cooperate with a number of related ministries such as the Ministry of Agriculture and Food Security (MAFS, the Ministry of Tourism and Environment, the Ministry of Forestry and Land Reclamation, the Ministry of Health, the Ministry of Education, and the Ministry of Local Government, as well as with the Ministry of Finance and the Ministry of Development Planning, which are responsible for overall coordination and planning. At the local level, there is active cooperation with local councils, communities, and traditional leaders as well as with the private sector and NGOs.

Within MAFS, the Crops Department includes an Irrigation Section, which researches new irrigation technologies, and an Engineering Division that provides planning, design, and implementation support for irrigation. The Soil and Water Conservation Division of the Department of Conservation, Forestry and Land Use Planning of MAFS is involved in irrigation development for dam planning, design, and construction. The Extension Division of the Department of Field Services of MAFS is involved in irrigation through its District Agricultural Offices in the 10 districts.

The Department of Forestry contributes climate change research to establish and predict links between climate change and the response of vegetation. The Department of Agricultural Research conducts climate change research through agricultural research projects or programs that include impact assessments and adaptation and mitigation options. Also involved in conducting research are the Department of Environment, the Department of Water Affairs, the Disaster Management Authority, which coordinates the Vulnerability Assessment Committee activities, the Department of Forestry, the Lesotho Agricultural College and the National University of Lesotho.

1.3 Outline and Objectives

This is one of three reports in a series exploring the role of water and the vulnerability of macroeconomic development in Lesotho to the risks of climate change. The aim was to strengthen the capacity of the government of Lesotho to account for risks associated with climate change and effects on water resources, increasing its resilience against the associated physical and economic risks.

The three reports are based on analyses that have focused on building knowledge and capacity relating to climate change and risk analysis by bringing global expertise and best practices to Lesotho, while mainstreaming the assessments into the government's economic decision making and development planning process. This has been achieved through a highly participatory, iterative process of model development, application, and interrogation.

The first report provides a description of the methods and tools used to establish the effects of climate change and the process for facilitating robust decision making. These tools are used to assess the effects of, and vulnerabilities of water resources to, climate change on the urban and industrial sectors, agricultural water use, and hydropower and water transfers to South Africa under the LHWP. Adaptation strategies are identified and detailed to help inform policy decisions and suggest specific actions that can address the most critical vulnerabilities, while examining the effects on other sectors and on the transfer to water to South Africa. This includes an economic evaluation of robust strategies along with key recommendations and next steps.

The second report documents the development of the models and the definition of the future climate scenarios to facilitate RDM. This includes the development of a comprehensive Water Evaluation and Planning (WEAP) model for Lesotho. The WEAP model provides an integrated, open-source analytical platform that includes supply and demand functions and allows water resources planners to link hydrological processes, system operations, and end-use. The WEAP model supports collaborative water resources planning by providing a common analytical and data management framework to engage stakeholders and decision makers in an open planning process. Within this setting, WEAP can be used to develop and assess a variety of scenarios that explore physical changes to the system, such as new reservoirs or pipelines, as well as social changes, such as policies affecting population growth or the patterns of water use.

The third report looks specifically at the macroeconomic implications of the LHWP by providing a contemporary, user-friendly representation of the Royalties Model. The report provides a thorough description of the Royalties

Model and the methods and tools used to recreate it, including the WEAP impact assessment tool, Visual Basic scripts and Excel spreadsheets. The updated representation of the Royalties Model is compared to the existing tables in the Royalties User Manual to assess the level of accuracy in the replication. Based on the use of the Royalties Model, the report identifies a number of exciting opportunities to explore routines that can inform long-term development strategies to optimize opportunities under the LHWP through a series of recommendations and next steps.

The overall objective of this report is to assist planners in Lesotho with selecting water resources management strategies that demonstrate robust performance under a range of potential climate change scenarios. Through Climate Change and Water Impact Scenario Analysis, the specific objectives are the following:

- Assist in the development of a national planning tool for the evaluation of water resources in Lesotho
- Develop an understanding of climate trends and identify appropriate climate scenarios
- Analyze the potential effects of various climate scenarios, together with other uncertainties, on the water resources of Lesotho
- Assess the long-term opportunities of the LHWP for Lesotho
- Develop recommendations for adaptation strategies to reduce the effects of climate change across water-related sectors, including agriculture
- Build capacity within agencies in the water sector to maintain a continuous, adaptive process of planning to ensure water security for Lesotho.

Note

1. Based on the 2010–11 Household Budget Survey.

Chapter 2

Climate Change Analyses

2.1 Analysis Overview and Key Study Questions

Water resource planners are increasingly using methods for decision making under uncertainty to address climate change and other uncertainties in their long-term plans (Groves et al. 2008; Brown 2010; Cervigni et al. 2015). Central to these approaches is the recognition that despite the development of GCMs, it is not possible to assign sufficient probability to any of the proposed future scenarios to help identify optimal water management strategies. The most appropriate set of water management investments may differ significantly depending on what the future holds. Therefore, developing an optimal strategy and then exploring performance sensitivities does not provide the necessary information to determine a prudent course of action. Instead, the goal must be to identify robust strategies—those that will perform satisfactorily across a wide range of possible scenarios (Groves et al. 2014; Kalra et al. 2014).

Rather than weighting futures probabilistically to define an optimal strategy, methods for decision making under uncertainty identify the vulnerabilities of an agency's or utility's system and then evaluate the key tradeoffs among different adaptive strategies. Through iteration, ideally with extensive and direct participation of decision makers and stakeholders, a robust, adaptive strategy is identified. The strategy defines a set of near-term investments, signposts (conditions that would trigger new actions or adjustments), and deferred actions for possible future implementation. These decisions are then pursued and subsequently revisited in an iterative manner to adjust actions based on updated analyses and new data and information.

This study uses a similar approach to identify the vulnerabilities of Lesotho's current and proposed water management system and then to structure an evaluation of adaptations. Specifically, the analysis addresses the following questions:

- How might future climate change affect Lesotho?
- How would the current Lesotho water system perform across a wide range of plausible future climate and demand conditions?
- What are the key drivers of vulnerability?
- How would system performance change with the construction of the Polihali Dam, a lowlands water supply project, and increased irrigation?
- Can baseline vulnerabilities be reduced?
- How would the full build-out of the LHWP (with and without the lowlands water supply project and increased irrigation) affect Lesotho's climate resilience?
- How do assumptions of water transfers and other values and costs affect the net benefits of water management strategies for Lesotho?

2.2 Analysis of Observational Data and Climate Trends

Observational data from the LMS were used to explore trends in observed climate over the period for which records were available. Data were generally available for the period from 1980 through 2012. The analysis evaluated daily precipitation (mm) and minimum and maximum air temperature (°C) for several stations across Lesotho. The data varied in length and quality of the measurements such as frequency of the observations, data not recorded or unavailable, outliers, and their homogeneity.

The LMS observed climate data that included several large, unformatted ASCII files of daily precipitation, maximum temperature, and minimum temperature. Sample data lines from this dataset are shown in table 2.1. For each meteorological variable, there were more than 300,000

TABLE 2.1 Sample Minimum Temperature Archive for Lesotho

Station ID	LAT	Long	ELEV	YYYY	MM	DD	Obsvalue
LESBER08	−29.2159	27.61744	1500	1994	9	17	12.1
LESBER08	−29.2159	27.61744	1500	1994	9	20	12.1
LESBER08	−29.2159	27.61744	1500	1994	9	21	5.2
LESBER08	−29.2159	27.61744	1500	1994	9	22	11.8

records in each data file. These included daily measurements at multiple locations throughout Lesotho. Because the data were unfiltered and had not gone through a quality control procedure, an R script was developed to extract the data from the archive, select stations with common periods, and perform homogeneity testing.

Through the filtering process, nearly 30 stations were retained with the daily precipitation (Precip), daily maximum temperature (Tmax), and daily minimum temperature (Tmin) fields. These stations cover a large part of Lesotho and are fairly evenly distributed across the country. Map 2.1 shows the Upper Orange-Senqu River basin with the border of Lesotho indicated by the dark line. Because the analysis was intended to evaluate regional climate trends, stations that are situated in South Africa and in close proximity to the border of Lesotho were also included. The daily data were supplied in two groups corresponding to the reporting and storage methodologies of the LMS. There is no significance to the definition of the two groups other than ease of visual interpretation. Once these large climate data archive files were read and filtered, they were explored to determine if there were observable trends in the climate extremes[1] in Lesotho.

It is interesting to note that these data suggest a slight increasing trend in total annual precipitation over the 32-year period for both sets of precipitation data (see figure 2.1). We estimated the annual coefficient of variation, which is the standard deviation divided by the average annual precipitation and which indicates the spread in the precipitation that can occur relative to the annual average. The standard deviation gives an estimate of the range of values on either side of the average that occurs around 67 percent of the cases. From the meteorological stations, the average annual precipitation for Lesotho is about 720 millimeters, with a standard deviation of rainfall of about 130 millimeters, resulting in a coefficient of variation of about 20 percent.

MAP 2.1 Correlation of the Warm ENSO Phases for the Southern Summer (December-January-February)

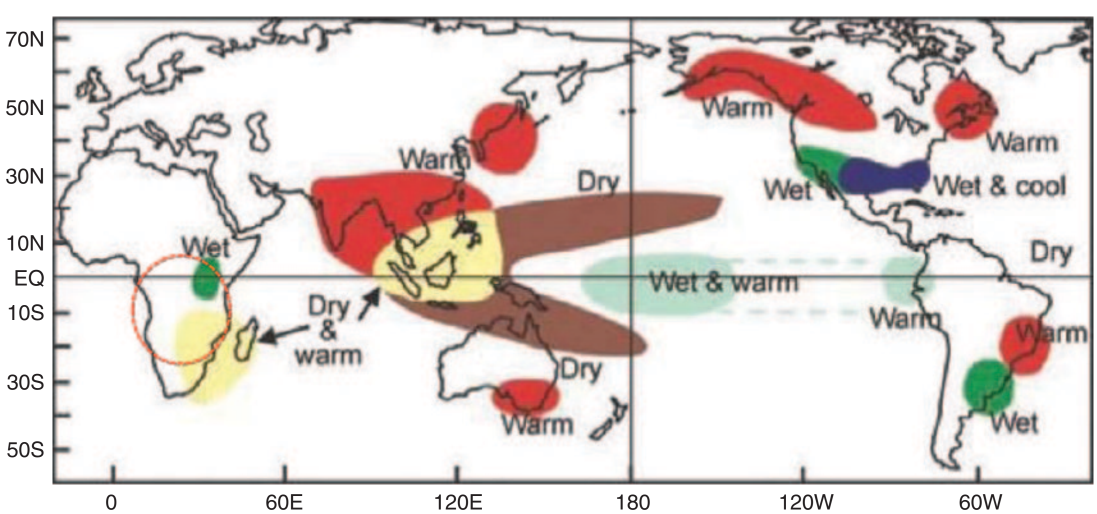


FIGURE 2.1 Daily Average Precipitation and Linear Trend

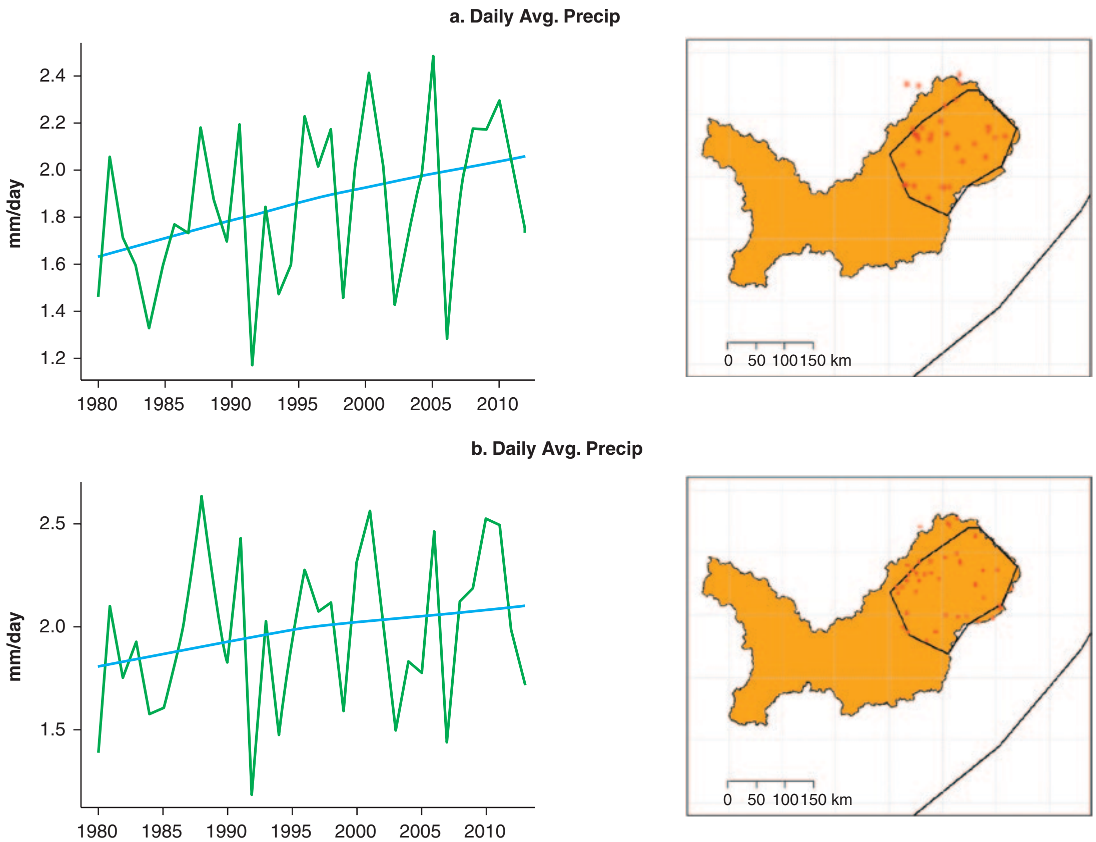
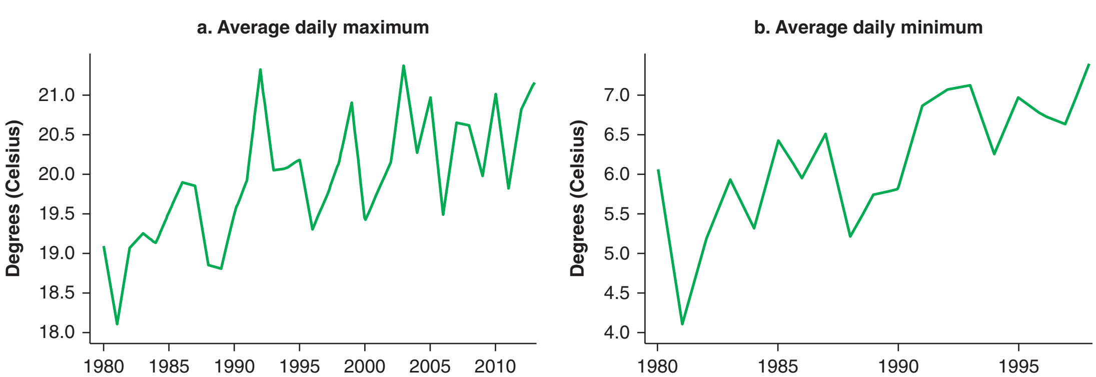


FIGURE 2.2 Average Daily Temperatures for All Stations



This means that 67 percent of the time, rainfall will vary plus or minus 20 percent from the long-term average.

The estimate of the annual average minimum and maximum temperatures from all stations in Lesotho are shown in figure 2.2. These data seem to suggest a warming of approximately 2°C over the period 1980–2003 for both fields.

However, considerable bias was observed in the annual average minimum temperature data after 2003. Interrogation of the data with the LMS suggests that this bias was likely caused by practices introduced when temperature data were entered into the national database after 2003. Inhomogeneity in the minimum temperature data precluded its use in the analysis after 2003; however, assuming that the data for the maximum temperature past 2003 are valid, figure 2.3 suggests that while there has been warming, the rate has slowed over the past decade. Although data after 2003 also exhibited trends in warming, the team had to truncate the data at 2003, these data were truncated given the considerable bias.

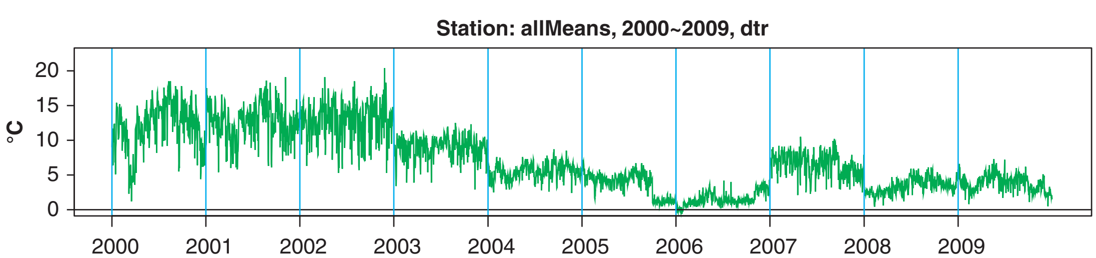
Climate extremes have been identified as good measures of climate change emergence. For example, shifts or trends in indicators such as the amount of annual maximum daily precipitation, the daily temperature range, and the number of frost days can be used as proxies or indicators of current change and can be used to evaluate the nature of the future projected climate based on GCM outputs (See, for example, Alexander et al. 2006.)

The RClimDex[2] tool was used to explore the various climate extreme indices. Although the analysis was able to draw on a large archive of daily precipitation and minimum and maximum temperatures, some stations were missing considerable amounts of data, resulting in their having shorter record lengths than others. To overcome these issues, a regional daily average temperature was generated from stations with daily data available for the period from 1980–2013, with missing values excluded from the averaging process. A total of 28 stations were used to generate this daily *grand-average* time series for Precip, Tmin, and Tmax. This time series was used to generate ClimDex climate indices.

The analysis revealed an apparent inhomogeneity in daily minimum temperatures after 2003, with the daily difference between the minimum and maximum temperatures showing an abrupt shift in 2003 (see figure 2.3).

The most important determinants of the impact of climate change are the degree of exposure to climate stressors and the basic sensitivity of local systems to these stressors (Dejene et al. 2011). Exposure includes climate variability, which includes the frequency, magnitude, and duration of extreme climate events such as floods, frost, hail, droughts, and heat waves; and long-term climate changes, such as increasing temperature and changing rainfall patterns. The indices for the annual count of frost days, diurnal temperature

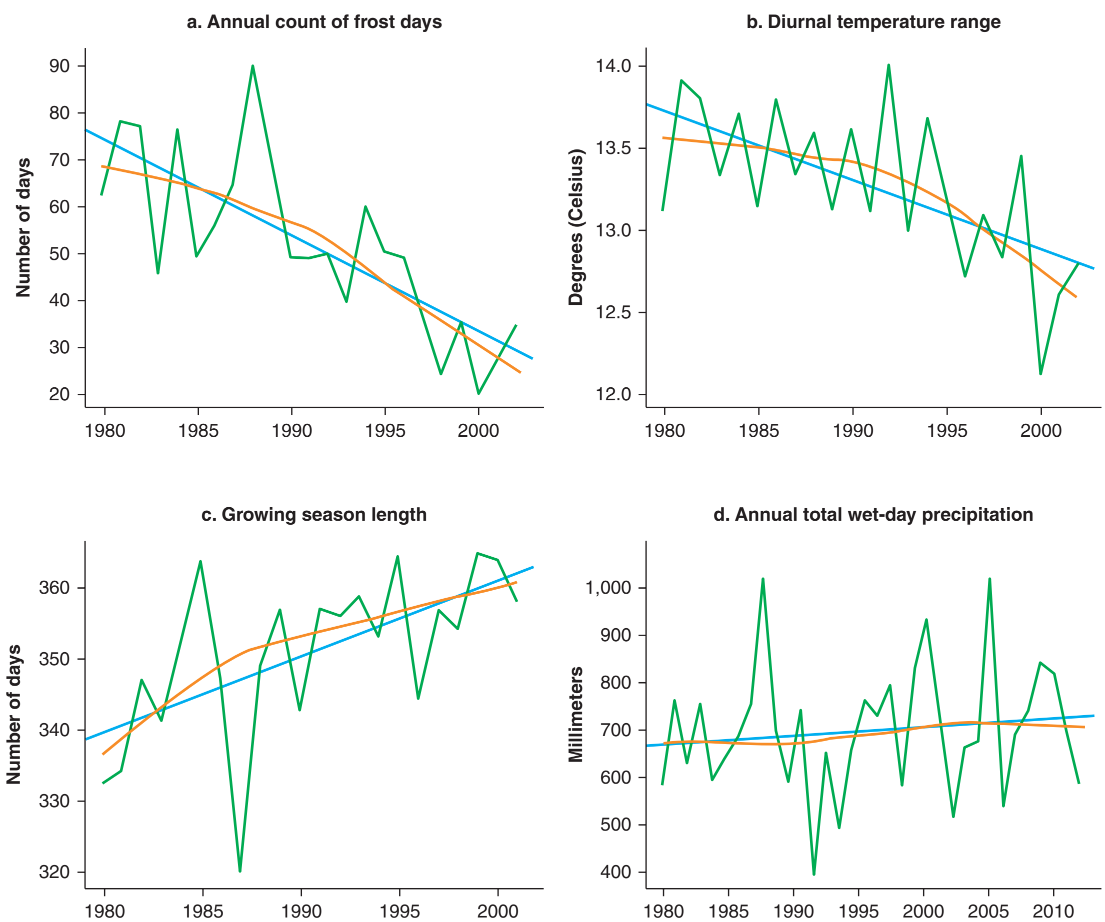
FIGURE 2.3 Difference between Minimum and Maximum Daily Temperatures, 2000–09



range, growing season length, and annual total wet-day precipitation suggest warming over the period 1981–2003 (see figure 2.4).

The number of frost days in Lesotho under future climate scenarios is expected to fall from 70 to 40 days, and the growing season is likely to lengthen from 340 to 360 days, as shown in figure 2.4. These trends could create opportunities for new crops in Lesotho, especially in the highlands. The expected gradual warming would have positive effects on the productivity of most crops and livestock during the winter. Some crops grown in Lesotho (such as legumes and tubers) could benefit from the increase in heat indices; heat stimulates plant growth and development, particularly in spring when the greatest increase in temperatures is expected (Dejene et al. 2011). Another benefit of this warming would be increased nutritional diversity, which is currently very low in Lesotho (Dejene et al. 2011). However, the expected gradual warming may negatively affect summer crops, such as maize, especially in the lowlands. In contrast, the predicted effects for other crops, such as sorghum, which depends on the availability of sufficient soil moisture during the period of early growth,

FIGURE 2.4 Select Daily Climate Extreme Indices from the Grand Station Daily Average, 1981–2003



range widely, from negative to positive, due to significant uncertainties for future precipitation. (Dejene et al. 2011).

The annual total wet-day precipitation (indicating precipitation of more than one millimeter) demonstrates a slight upward trend from about 650 millimeters to a little more than 700 millimeters for the period under investigation. Increasing temperatures may also reduce available soil moisture during periods of inadequate rainfall. The biophysical features of the country, especially the high proportion of high altitude rangeland and the acutely erodible soils in the lowlands, where soils are deeper in lowlands than highlands, make the country particularly vulnerable to climatic events (Dejene et al. 2011). Longer dry spells interspersed by heavy rainfall events could intensify the potential for soil erosion.

2.3 Analysis of Global Data for Climate Trends

A publicly available global climate dataset created at Princeton University, which included time series of near-surface meteorological variables, was used in the hydrologic simulation and water resource evaluation.[3] This dataset blends observations with reanalysis data[4] and disaggregates those data in time and space. The gridded dataset is available at various spatial and temporal resolutions, offering data at 0.25°, 0.5°, and 1.0° spatial resolution on a monthly time step over the landmasses of the globe for the period from 1948 through 2008. Figure 2.5 illustrates precipitation, based on the Princeton historical data, with a five-year moving average imposed on the annual series (black dotted line) for the period 1950–2008.

The global dataset was used for the baseline climatology as it was considered to provide the best representation of historical conditions for use in characterizing the attributes of the climate models and their projection of future climate. The analysis of the observational record from the LMS also provides a useful and informative baseline; however, because of the

FIGURE 2.5 Monthly Average and Total Annual Precipitation

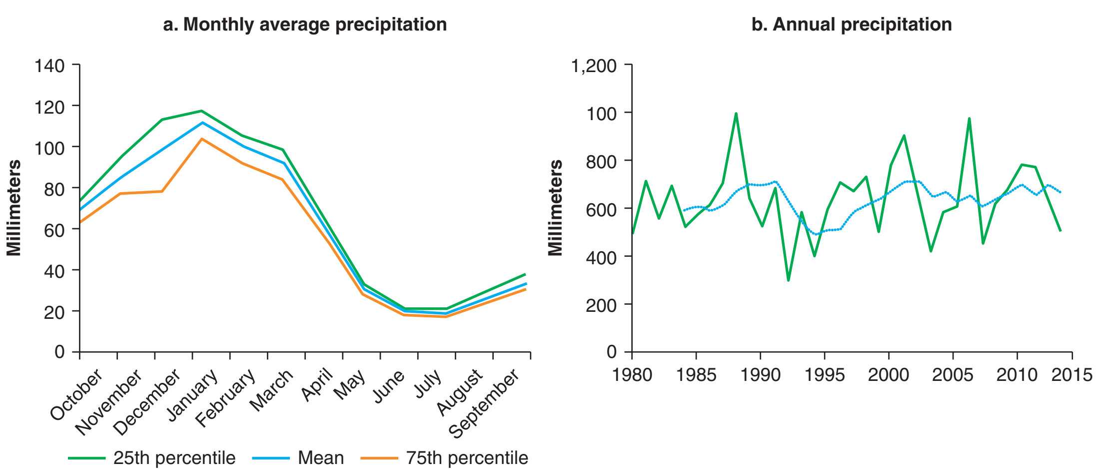
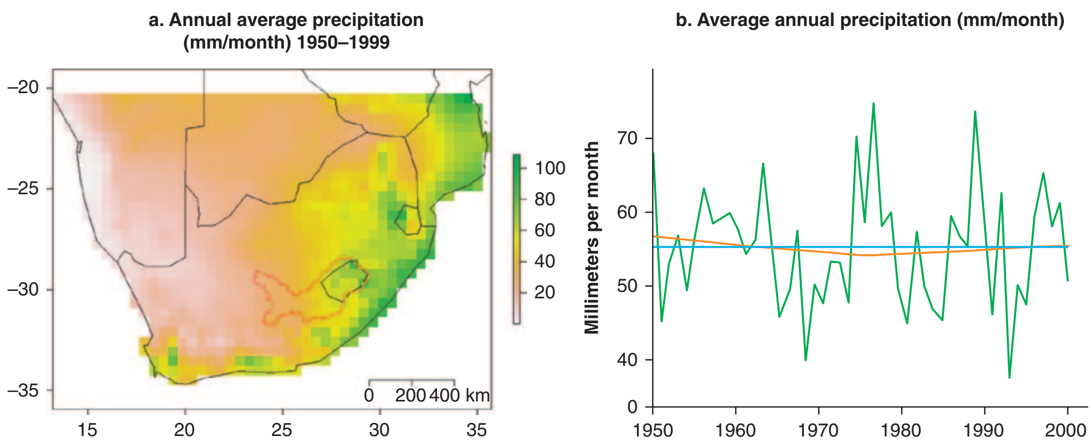


FIGURE 2.6 **Average Annual Precipitation in Southern Africa Based on Averaging the Grid Cells over Lesotho, 1950–1999**



incomplete spatial and temporal representation for Lesotho, coupled with the anomalies observed after 2003, these data were not used directly in calibrating the model for the historic period or in the construction of the WEAP model.[5]

Instead, the monthly average temperature and monthly total precipitation were extracted from the global dataset and mapped for the catchments of the Senqu and Caledon rivers over Lesotho (figure 2.6).

The global Princeton dataset for Lesotho estimates annual average rainfall at about 750 millimeters, with average monthly values ranging from a low of 12 mm in June to a high of about 120 millimeters in January (see figure 2.5). The monthly series shows the mean and the 25th and 75th percentile precipitation for all basins covered by the WEAP model and a relatively small range of precipitation. The range of interannual variability of rainfall for Lesotho as represented in the Princeton dataset is also relatively modest.

The water systems model, described in a separate document, makes use of the Princeton dataset to drive the WEAP rainfall-runoff hydrologic model for river basins in the highlands of Lesotho using monthly time series of total precipitation and average temperature.

2.4 Analysis of Future Climate Projections

A large collection of future climate projections generated and used under the African Climate Resilience Study carried out by the World Bank was used in this study (Cervigni et al. 2015). Three sets of climate data, encompassing 121 future projections, were used to represent plausible future climate conditions up to the year 2050 for the Senqu and Caledon River basins. These data serve as the starting point for the climate change scenarios used in this project. The first set includes 56 projections from the World

Climate Research Program Coupled Model Intercomparison Project–Phase 3 (CMIP3) (Meehl et al. 2007), and the second set includes 43 GCM projections from the World Climate Research Program Coupled Model Intercomparison Project–Phase 5 (CMIP5) archive, both downscaled using the bias-correction and spatial disaggregation (BCSD) method to 50 kilometers. The third set includes 22 CMIP5 simulations downscaled to 50 kilometers using the University of Cape Town Climate Systems Analysis Group (CSAG) methodology (Hewitson and Crane 2006), Projected CMIP5. The 121 future climate scenarios are shown in table 2.2.

This future climate dataset is based on a BCSD procedure that generates monthly climate on a 0.5° grid for the world's landmasses. The corresponding grid cells for the river basins of Lesotho were extracted from the archive and then an averaging procedure carried out to estimate the average monthly precipitation and temperature for each catchment in the WEAP model. The BCSD approach involves a four-step process: (1) identifying an observational, baseline dataset (here, the Princeton dataset) and selecting a set of GCM-emissions combinations from available Intergovernmental Panel on Climate Change (IPCC) archives, that includes both the historic period and the future period (1950–2100); (2) resolving the GCMs and the observational baseline to a common spatial resolution (~2°); (3) for each GCM, bias correcting the monthly values of the GCM against the observational baseline using a quantile mapping procedure and applying the bias correction to the monthly time series of the future projection; and (4) spatially downscaling those outputs from 2 x 2 degrees to the resolution of the Princeton baseline dataset, or 0.5 x 0.5 degrees. This procedure applies to the 2 x 2 temperature and precipitation grid maps for each month, year, and GCM combination.

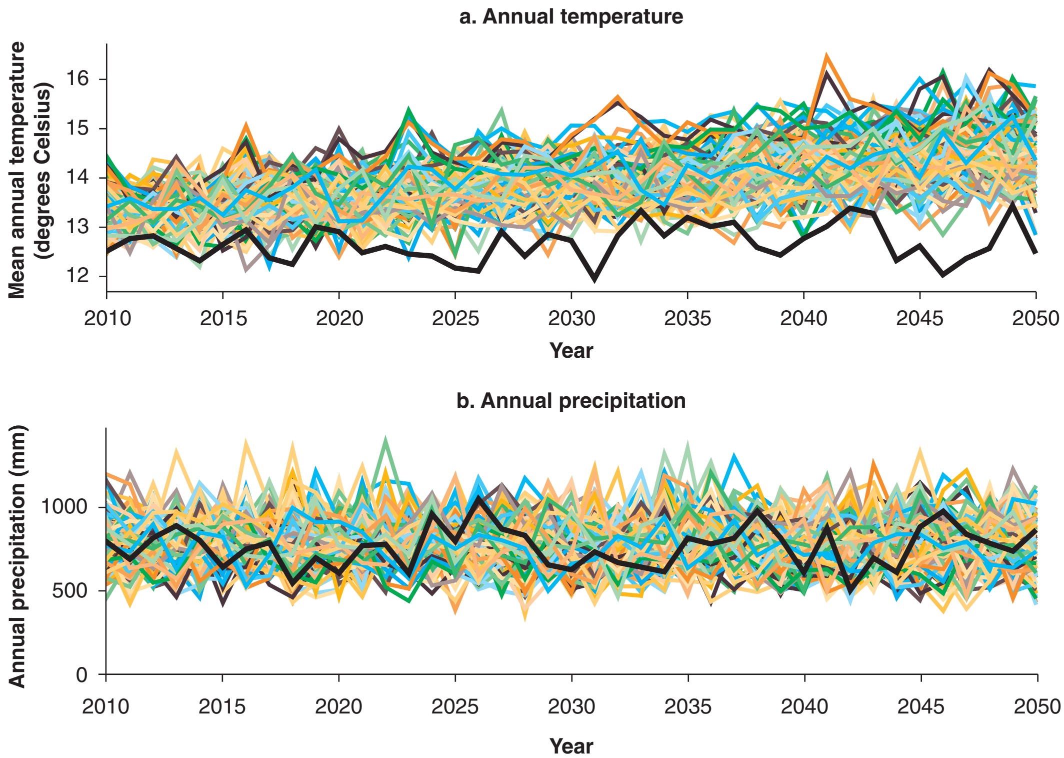
These climate projections suggest a wide range of plausible trends in future temperature and precipitation throughout Lesotho. Although there is consensus regarding a systematic overall rise in temperature of between 0.8°C and 2.9°C, precipitation predictions vary between wetter and drier futures compared to the historical record. This study addressed how users can manage such a large range of future projected climate change.

These scenarios are useful in describing the range of possible future changes. However, users of this information are left with little guidance as to which results might be most representative of the actual future. The vast uncertainty of climate projections at the regional scale means that one should obtain climate projections on as many simulations, representing as

TABLE 2.2 Summary of Climate Datasets Used in this Study

Projection	Downscaling	Number
Historical Princeton Data	n.a.	1
CMIP3	BCSD	56
CMIP5	BCSD	43
CMIP5	CSAG	22

FIGURE 2.7 Projections of Annual Temperature and Precipitation from All GCMs, 2010–50



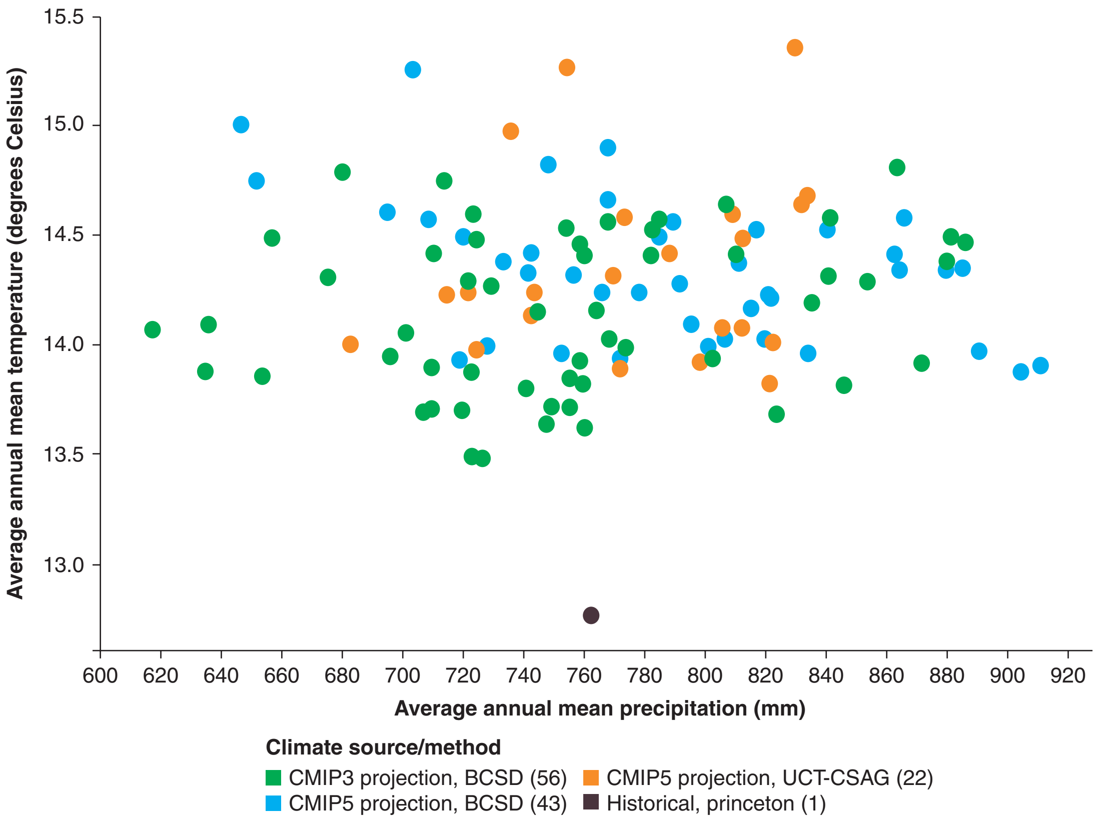
Note: The black line indicates the historical record.

many models and emissions scenarios, as possible. One might ask whether there is *actionable information* within the literally hundreds of climate model projections and wonder whether it is possible to develop robust management strategies based on an uncertain future climate (Rogers and Gulledge 2010).

All the available climate projections were used to understand how the Lesotho water management system would perform across a wide diversity of potential future conditions. Rather than estimating the relative value or reliability of individual climate projections, the results of the full evaluation of the projections are used to define performance thresholds. The performance thresholds define the range of climatic conditions that stress the different adaptation strategies evaluated. The orange dots are projections from the IPCC Assessment Report 3s, Coupled Model Intercomparison (CMIP3); the green marks are from the IPCC's AR5 Report (CMIP5) and the red dots are from the downscaling dataset from the Climate Research Group at the University of Cape Town, which also uses CMIP5 projections.

Annual average temperature shows a strong, consistent increase above the historical mean, with consensus among all 121 climate projections of the projected future climate for the twenty-year period from 2030–50

FIGURE 2.8 **Summary of Temperature and Precipitation Projections for 122 Climate Scenarios, 2031–50**



Note: UCT = University of Cape Town.

(see figure 2.8). The historical average temperature derived from all catchments delineated in the WEAP model for Lesotho based on the historical Princeton data is estimated at 12.7°C. This is reflected by the black dot against which the comparisons of the future climate projections (the colored dots) should be made. In all instances there is a demonstrable increase in temperature predicted, with the range of increase from about 0.8°C (using the CMIP3 archive) to about 2.9°C (using the CMIP5 archive from the University of Cape Town).

Projections in the change of annual total precipitation among the 121 climate projections for the twenty-year period from 2030–50 show a considerable degree of variability (see figure 2.8). The historical average total annual precipitation derived from all catchments delineated in the Lesotho WEAP model based on the historical Princeton data is estimated at 760 millimeters. The change in projected future precipitation ranges from an increase of between 150 millimeters and more than 900 millimeters annually (CMIP5 BCSD) to a decrease of between 150 millimeters and about 600 millimeters (CMIP3). Generally, a greater number of climate projections are dry (64) for this twenty-year period than are wet (57).

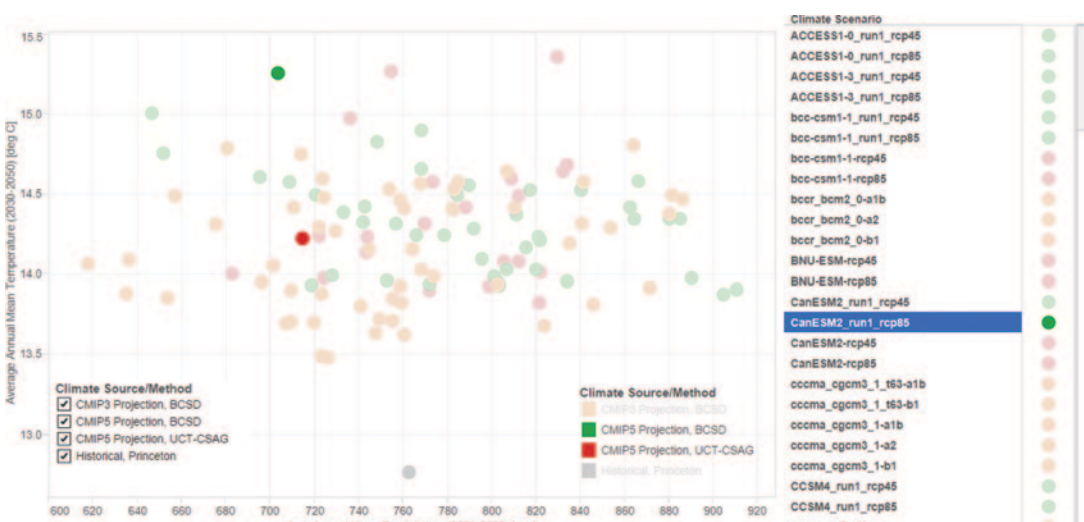
However, it should be noted that the range of interannual variability is relatively large over Lesotho, although within the range of natural variability (depicted in figure 2.6). It should also be noted that the averaging period of 2030–50 is relatively short; a different averaging interval could show very different results.

Although the analysis makes use of the full range of available climate projections, each is based on results from a single, unique GCM, each with its own attributes and characterization of both the global and regional climate. Estimating the efficacy of any single GCM is, in itself, an imprecise and uncertain task. Rather than restricting the analysis a priori to a particular set of projections, the sensitivity of the water system and the performance of adaptation responses were assessed using a wide range of projections, including those that seem less reliable. This was intended to better understand how the water system in Lesotho could respond and help position decision makers to understand the tradeoffs between cost and effort, and hedging against these possible, but uncertain, future risks.

Recognizing the variability that exists among the GCM models, results from two particularly dry projections were examined in more detail (see figure 2.9).

Note that the range of *bias-corrected*, projected precipitation from 2030–50 for these two models is about 710 millimeters, with the Canadian Earth Systems (CanESM2) model showing greater warming. However, although the projections of "change" in future precipitation are similar over this twenty-year period, the magnitude of the bias correction applied to each model to achieve nonbiased precipitation estimates is quite different. The French National Center for Meteorological Research model (CNRM-CM5)

FIGURE 2.9 Summary of Temperature and Precipitation, 2031–50



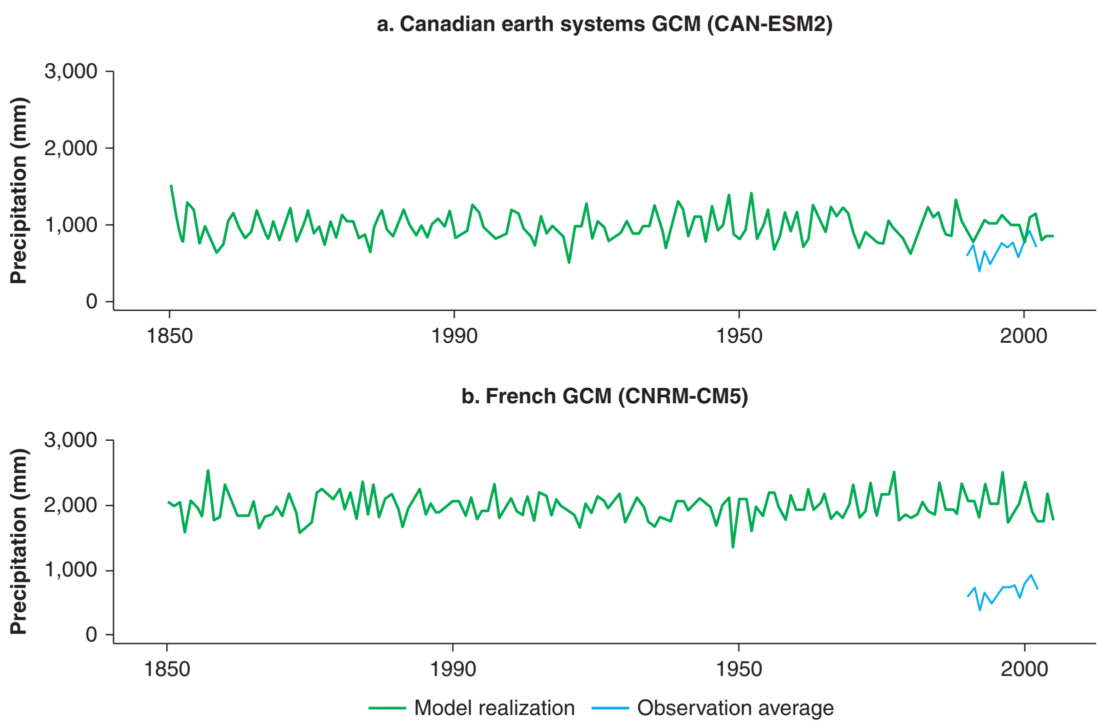
Note: The Canadian Earth Systems Model (CanESM2) is shown by the green dot, and the French GCM model (CNRM-CM5) is shown by the red dot. UCT = University of Cape Town.

has considerably more error in its simulation of precipitation for the historic period (see figure 2.10) with nearly three times the annual precipitation of the historic observations. Although the Canadian model exhibits a wet bias over the historic period, this precipitation bias is not nearly as large as the French precipitation bias.

The monthly average precipitation derived from the observations—the non-bias-corrected, historic precipitation and the non-bias-corrected, future precipitation for the CNRM-CM5 and the CanESM2 GCM models—reflects the southern hemisphere seasonality with a summer maximum (see figure 2.11).

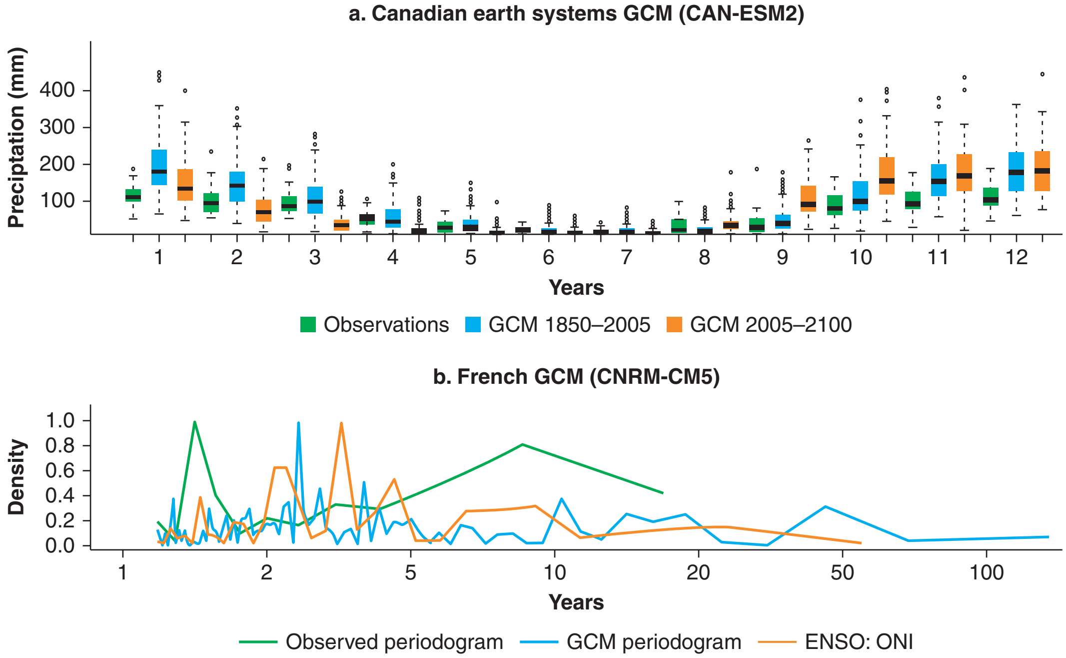
Note that both models capture the seasonality of precipitation. However, the CNRM-CM5 simulated precipitation is much greater than the precipitation observed, and the interannual frequency modes are much larger at the shorter time scales (modes of less than five years). In contrast, the CanESM2 model shows less bias in both the monthly average and total annual precipitation. The frequency mode of annual precipitation has a maximum value at about four years and appears to be somewhat aligned with frequencies of the El Nino, Southern Oscillation Index (ENSO). The correlation between ENSO warm episodes tends to result in a dry southeastern Africa (see map 2.1) and is an important attribute for evaluating the performance of GCMs.

FIGURE 2.10 Historical Simulations of Annual Precipitation, 1850–2100



Note: The green lines represent the historical simulations for each model. The blue lines represent the annual average precipitation for Lesotho calculated as the average of all available rain gauges.

FIGURE 2.11 Monthly Average Precipitation



Note: Shows the observations (light-blue); the historic period simulation (green); the future simulation (orange); and the periodogram of the annual precipitation for the observed precipitation (blue), the El Nino, Southern Oscillation Index Oceanic Niño Index (ENSO-ONI) and the historic period simulation.

Notes

1. "Extreme events are realizations of the tail of the probability distribution of weather and climate variability. They are higher-order statistics and thus generally more difficult to realistically represent in climate models. Shorter time scale extreme events are often associated with smaller scale spatial structure, which may be better represented as model resolution increases" (Flato et al. 2013).
2. RClimDex is an interface designed to compute indices of climate extremes. It computes all 27 core indices recommended by the Commission for Climatology (CCl) of the World Meteorological Organization's (WMO) World Climate Data and Monitoring Programme (WCDMP), the Climate Variability and Predictability (CLIVAR) Programme of the World Climate Research Programme (WCRP) Team for Climate Change Detection Monitoring and Indices as well as some other temperature and precipitation indices with user defined thresholds. The data are available at http://etccdi.pacificclimate.org/data.shtml.
3. The dataset was produced by the Terrestrial Hydrology Research Group, Princeton University. http://hydrology.princeton.edu/data.pgf.php.
4. Reanalysis data are developed using a systematic approach to produce climate data, created using an unchanging ("frozen") data assimilation scheme and model(s), which incorporates all available observations (from satellites, stations, and soundings). This unchanging framework provides a dynamically consistent estimate of the climate state at each time step.
5. In climate impact and adaptation practice, regional climate modeling is one approach to resolving important topographic gradients and meteorological attributes, especially over complex terrain such as Lesotho. Developing a regional climate modeling experiment that focuses on Lesotho would have been ideal, but was not feasible in the context of this project.

Chapter 3

Robust Decision-Making Methodology

Considering the importance of water for the long-term macroeconomic framework for Lesotho, robust strategies are required to secure and maximize sustainable development gains. The uncertainty surrounding future climate conditions and the trajectory of change necessitate the use of sound mechanisms to empower decision makers to act and implement interventions under highly uncertain conditions. The future scenarios envisioned suggest agreement on an increase in temperature for Lesotho but high variability in predictions of precipitation, with increases and decreases predicted across the range of scenarios. Extrapolating this variability to make predictions relating to future runoff conditions and yields associated with water resources infrastructure is even more uncertain. Because individual future scenarios cannot be assigned a probability of occurrence, the use of broadly applicable robust strategies reframes the management dilemma for climate adaptation.

RDM is a generalized decision-making framework that structures a quantitative analysis of vulnerabilities and adaptations to facilitate decision making under deep uncertainty (Groves and Lempert 2007; Lempert, Popper, and Bankes 2003). Deep uncertainty arises when decision makers cannot agree on

BOX 3.1 Application of Robust Decision Making in Water Resources Planning

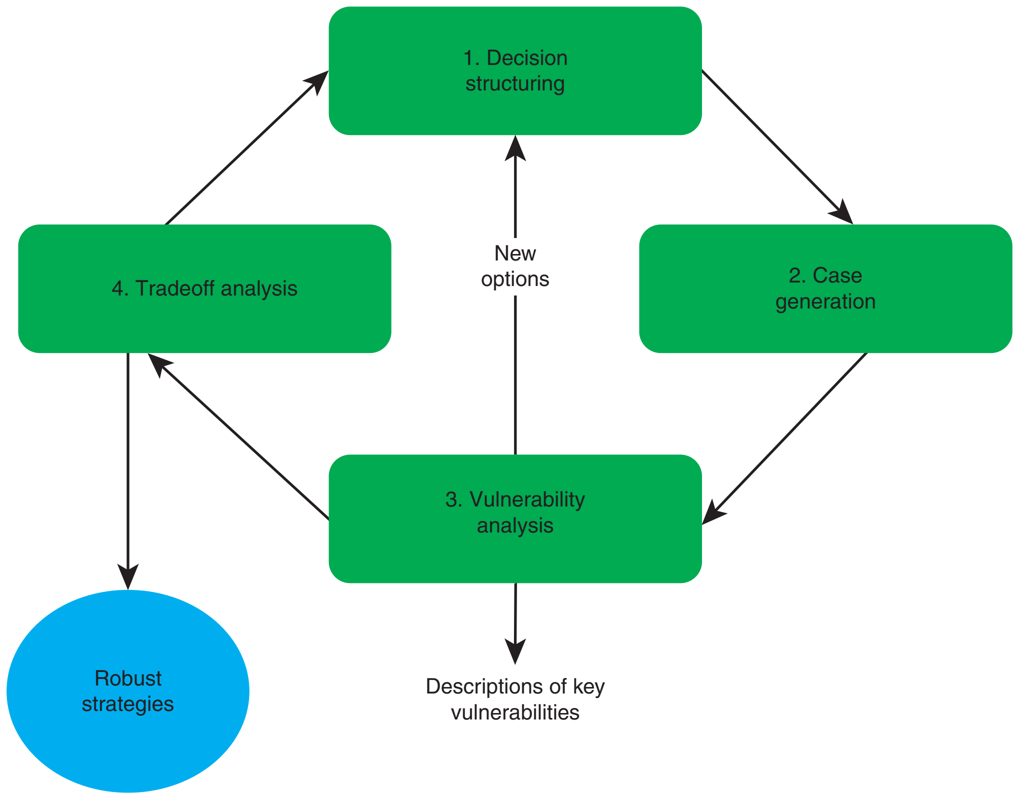
Early applications of RDM to water planning include case studies in Southern California (Groves et al. 2008, 2015; Lempert and Groves, 2010) and the United Kingdom (Dessai and Hulme 2007). These applications illustrated techniques for generating and evaluating a large set of future scenarios, identifying the key vulnerabilities of current management to these future scenarios through a process called "scenario discovery" (Bryant and Lempert 2010), and then highlighting key tradeoffs among the most robust strategies. The Southern California application also introduced rudimentary adaptivity into the robust strategies by implementing additional management actions if the supply buffer—the gap between available supply and water demand—grew too small. Other recent applications include two pilot studies for the Water Resources Foundation (Groves et al. 2015), an evaluation of the Integrated Resources Plan of the Metropolitan Water District of Southern California (Groves et al. 2014), an application to flood risk mitigation in Vietnam (Lempert et al. 2013a), and work for the U.S. Bureau of Reclamation's Colorado River Basin Study (Bureau of Reclamation 2012; Groves et al. 2013).

the likelihood of future events or on a conceptual model that relates actions to consequences. A robust decision-making framework was thus applied to examine which strategies demonstrate robust performance across the range of future scenarios and show positive performance over a broad range of circumstances.

RDM helps resource managers develop adaptive strategies by iteratively evaluating the performance of proposed options against a wide array of plausible future scenarios (see figure 3.1). The decision-making process systematically identifies the key vulnerabilities of those strategies and uses this information to suggest responses to the vulnerabilities identified (Lempert and Collins 2007; Lempert Popper, and Bankes 2003; Means et al. 2010). RDM runs through a set of statistical and software tools embedded in a process of participatory stakeholder engagement. Successive iterations develop and refine strategies that are increasingly robust. Final decisions among strategies are made by considering a few robust choices and weighing their remaining vulnerabilities. RDM follows an iterative and interactive series of steps consistent with the "deliberation with analysis" decision-support process described by the U.S. National Research Council (2009).

The robustness of the decision-making process results from its highly participatory and iterative nature (see figure 3.1). The decision structuring process (step 1), which generates the specific cases for analysis (step 2), is based on a participatory process with stakeholders, facilitated by analysts to define and frame a statement of the problem. Once the specific cases have been generated, the vulnerability analysis (step 3) and the tradeoff analysis (step 4) each require the combined effort of analysts, stakeholders, and decision makers. The iterative nature of RDM is embedded in the options to return to decision structuring after steps 3 and 4 to further expand and ultimately refine the analysis.

FIGURE 3.1 **Iterative Steps to Robust Decision Making**



An iterative process with a broad range of stakeholders from Lesotho was undertaken to identify key uncertainties that could compromise Lesotho's water management strategy. This process explored climate change, domestic and industrial water demand, expansion of irrigation, and implications for the development and operation of the LHWP. Specifically, the analysts, stakeholders, and decision makers worked closely to:

- Obtain and evaluate climate information (section 2);
- Analyze climate vulnerabilities and response options;
- Develop a new water management model (see the separate document on WEAP); and
- Evaluate the performance of the Lesotho water system with and without climate adaptations (sections 4 and 4.5)

This iterative and participatory stakeholder process was then used to identify a range of potential adaptation strategies. These included new infrastructure, such as the Lowlands Bulk Water Supply Scheme, which could provide additional water to communities across the lowlands of Lesotho, and the allocation of water for irrigated agriculture. To evaluate the performance of these strategies, stakeholders specified the key management metrics of the water supply system: reliability of water for the agricultural, domestic, and industrial demands of Lesotho, and the transfers of water to South Africa.

Three loops were performed through steps 1–3 in a series of meetings with various stakeholders and decision makers in Lesotho, ending with the initial evaluation of robust strategies.

The following subsections describe the decision structuring step, which is essential to ensure local buy-in as well as to develop a tool appropriate for the problem at hand. This is followed by further examination of the data and tools used to support the analysis.

3.1 Decision Structuring

This analysis estimates how different management strategies would perform over the wide range of climate and demand scenarios to gain an understanding of how to ensure that Lesotho's water management would meet diverse management objectives. The study used a decision scoping approach, called XLRM, developed to support RDM studies, to organize the key elements of a decision analysis:

- **Uncertainties (X)**: These are factors that affect the systems of interest that are outside the control of decision makers. Combinations of different assumptions about these uncertainties define future scenarios.
- **Management options or adaptations (L)**: These represent the specific decisions or "levers" that could be taken by decision makers to improve outcomes. Combinations of these levers define strategies.
- **Performance Metrics (M)**: These are the means by which the success or failure of Lesotho's water management system and strategies is evaluated.
- **Relationships (R)**: Systems and other types of models (such as financial models) are used to estimate the performance of the system (M) under different strategies (L) and future scenarios (X).

Using the XLRM matrix, the key factors for each of the variables were defined to help structure the decision-making process used in the final analysis (see table 3.1). The following subsections elaborate on each category.

TABLE 3.1 Decision Structuring Using the XLRM Matrix

Uncertainties (X)	Management Adaptations (L)
• Future climate and demand (Lesotho) 121 projections Temperature and Pressure Domestic demand Industrial demand	• Lesotho Highlands Water Project (*in two phases*) Polihali (2020) Mashai (2030) Tsoelike (2035) Ntoahae (2040) • LLWSS project to deliver highlands water to urban and agricultural sectors in lowlands • Irrigation development
Relationships (R)	**Performance Metrics (M)**
• WEAP Lesotho Validated to historical conditions	• Reliability Domestic and industrial supply Agricultural production Hydropower production Transfers to South Africa

3.2 Uncertainties and Future Scenarios (X)

A set of future scenarios was developed from the XLRM matrix to represent the climate and demand uncertainties. The analysis considered climate projections derived from the historical record and from 121 different projections of temperature and precipitation from downscaled GCM simulations (as described in section 2.4). The analysis also developed projections for nominal demand and high demand. The nominal projection was based on Lesotho's official estimate of future growth (Mouchel Parkman UK 2004). The high demand projection reflects an increase in domestic demand of an additional 20 percent by 2040 in the main development areas of Lesotho and an increase in industrial demand of an additional 10 percent. The 121 climate projections were combined with the two demand projections to provide to a total of 244 scenarios. The study used these 244 future scenarios to represent a wide range of plausible future conditions with the goal of defining the strategies that perform well across a wide range of future scenarios and that could be implemented.

3.3 Management Adaptations and Strategies (L)

This study focused on infrastructure-based adaptation strategies, which should be viewed as starting points for the region's long-term adaptation approach. Other institutional, management, and behavioral adaptations should be considered and may both improve the performance of the infrastructure-based strategies and allow Lesotho to achieve its objectives with lower levels of infrastructure investment.

The study considered the current management system that includes the completion of the Metolong Dam and Water Supply Program, the development of additional elements of phases II and III of the LHWP, and a national lowlands projectdesigned to enable some highlands water to be diverted to the Lesotho lowlands for domestic, industrial, and agricultural uses. This could enable an irrigation development project to support expansion to 12,000 hectares of irrigated agricultural production. These specific management approaches were developed through iterative discussions between the study team and Lesotho's water managers, informed by the technical analysis as described below.

3.3.1 LHWP

Two possible future configurations of the LHWP were explored. In the first case, it was assumed that there would be no further development of the LHWP after the construction of Polihali Dam.[1] Therefore the demand curve for South Africa would be capped at 40 m^3s^{-1} (1,261 MCM per year).

In the second case, the analysis assumed that the project will be fully implemented to include each of the facilities described in and shown in table 3.2 and map 3.1.

TABLE 3.2 Dams Included in WEAP Model as Part of the Lesotho Highlands Water Project

Dam	Start Year	Storage Capacity (MCM)	Inactive Storage (MCM)	Instream Flow Requirement (MCM per year)
Katse	2001	1,950	433	65.86
Mohale	2003	938	87.5	30.44
Polihali	2020	2,322	418	22
Mashai	2030	3,305	0	47
Tsoelike	2035	2,224	924	53
Ntoahae	2040	1,432	720	63

MAP 3.1 The Lesotho Highlands Water Project

MAP 3.2 Lowland Zones of Lesotho

3.3.2 Lowlands Bulk Water Supply Scheme

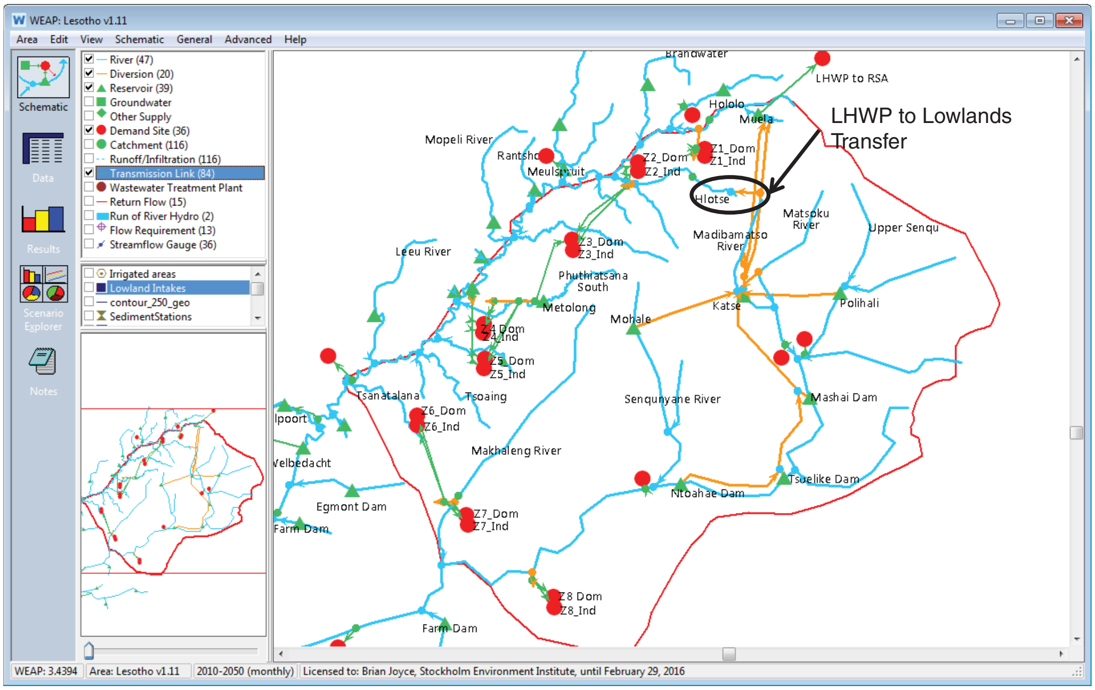
Although it is not currently operational, an existing access tunnel (or adit) could divert some water from the LHWP tunnel to the Hlotse River in the lowlands. The analysis considered a strategy in which this adit was actively used to provide a supplemental water supply for domestic and industrial uses in lowland zones 2, 3, 4, and 5 (see map 3.2).

For these analytical runs, the WEAP model was configured to provide that these demand zones had additional connections to surface water supplies and that any water diverted through the Hlotse River adit must equal the flow through these new connections. Furthermore, WEAP's water supply preference structure was constructed to provide deliveries through these new connections only when existing supply sources were insufficient to meet demand (see figure 3.2).

3.3.3 Irrigation Development

As in many developing countries, there have been efforts in Lesotho to promote irrigation as a means of increasing agricultural production and

FIGURE 3.2 WEAP Schematic Showing Adit Connecting LHWP Phase I Tunnel to Hlotse River



improving livelihoods. In the early 1970s, just over 12,000 hectares of land were identified as potentially irrigable. Unfortunately, very few of the attempts made to convert these lands to irrigation succeeded due to the top-down and supply-driven approach taken by the government and external donors (FAO 1995).

The most successful efforts at irrigation in Lesotho have been small-scale projects that were individually or communally owned, and where farmers control the on-field crop production (FAO 1995). Despite these developments, the number of food insecure more than doubled between 2013 and 2014 (GIEWS 2015).

Data provided by the Ministry of Agriculture and Food Security for five irrigation schemes were used (see table 3.3 and map 3.3).

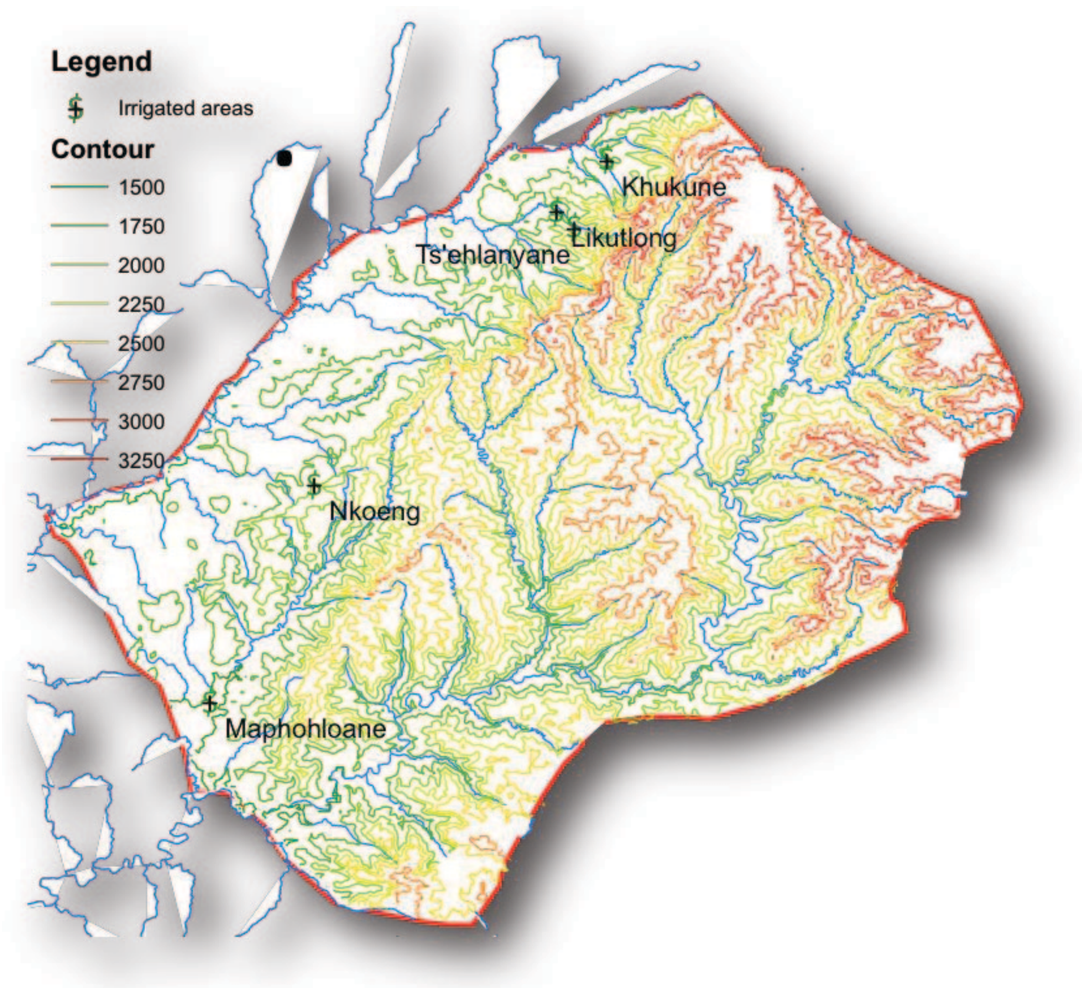
The expansion of irrigation will likely occur throughout the country. However, to gain some understanding of its implications for overall agricultural productivity, the project team considered a response strategy under which the existing irrigated footprint was expanded to the full potential of 12,000 hectares. For these model runs, we considered that each of the schemes would expand proportionally to their existing area to a total irrigated area equal to the 12,000 hectares of potential irrigable land identified.

Furthermore, it is generally understood that agricultural yields (as measured in metric tons per hectare) increase substantially as crop water requirements are more reliably met with irrigation. Estimates of maximum potential yield and yield factors for irrigated crops were obtained from the United Nations Food and Agricultural Organization's (FAO)

TABLE 3.3 Existing Irrigation Schemes in Lesotho

Site Name	Area (hectares)	Water Source
Khukune	140	Hololo River
Ts'ehlanyane	72	Hlotse River
Likutlong	184	Hlotse River
Nkoeng	82	Linkyok River
Maphohloane	225	Makhaleng River

MAP 3.3 Location of Existing Irrigation Schemes in Lesotho



crop water information database (FAO n.d.). Detailed data about crop types and characteristics are included in earlier sections on rainfed and irrigated agriculture.

These adaptations were grouped into six strategies to be evaluated by the water management model (see table 3.4). These are also described in detail in the separate document on WEAP.

TABLE 3.4 Adaptation Strategies

Strategy Name	Strategy Description
Baseline	The existing system
Plus Polihali	The existing system plus the construction of the Polihali Dam
Plus Polihali, Lowlands, and Irrigation	The existing system plus Polihali Dam, the lowlands bulk water supply scheme, and irrigation development
Plus All Highlands	The existing system plus all elements of the LHWP
Plus All Highlands and Lowlands	The existing system plus all elements of the LHWP and the lowlands bulk water supply scheme
Plus All Highlands, Lowlands, and Irrigation	The existing system plus all elements of the LHWP, the lowlands bulk water supply scheme, and irrigation development

3.4 Performance Metrics (M)

The Lesotho water management system is designed to serve five key areas:

- Domestic water use
- Industrial water use
- Irrigation
- Hydropower production
- Water transfers from the Lesotho highlands to South Africa

The performance metrics developed for this study consider how the system supports each of these sectors over time through the last decade of the analysis, 2041–50. They can be understood to be proxy representations of water, food, energy, and economic security. For example, water security is typically understood as meeting a basic human need, which is captured by domestic water use. More than 90 percent of the energy used in Lesotho comes from hydropower. Expansion of the irrigated area, which is extremely limited, would increase food security.

Although the model of the water management system includes instream flow requirements to meet baseline environmental objectives, specific environmental performance metrics were not considered because of data and modeling limitations.

3.5 Relationships (R)

A water management planning model was developed to estimate how the Lesotho water management system would perform under a wide range of future scenarios. This model is described in more detail in the separate document on WEAP.

Note

1. Phase 2 of the LHWP is also now configured to include a pump storage scheme, Kobong, which is not included in this analysis because its net hydropower generation is expected to be zero or even negative.

Chapter 4

Water Security and Vulnerability Assessment

In order to evaluate the effects of climate change and alternative management strategies, a detailed representation of the water management system in Lesotho was developed using the WEAP platform. This detailed watershed modeling software enables the simulation of supply and demand over time to reveal system vulnerabilities. The scenario modeling capabilities within the WEAP platform allow decision makers to explore environmental or policy changes and their effects on water availability in the management system. The development and application of the WEAP model in Lesotho is detailed in the accompanying Lesotho WEAP Manual (2015).

The WEAP model developed for Lesotho is a modified version of the tool developed for the World Bank project *Enhancing the Climate Resilience of Africa's Infrastructure* (Cervigni et al. 2015), which used a similar approach for assessing climate vulnerability and adaptation strategies across Africa. In that project, the Upper Orange-Senqu Rive basin represented one of seven WEAP models developed for major river basins across Africa that were each embedded within the RDM framework for assessing vulnerability and adaptation strategies.

The WEAP model was used to establish the plausible range of performance over time, up to 2050, for the water management system in Lesotho, both with and without the Polihali Dam and the water transfer augmentation under phase II of the LHWP. Specifically, the WEAP model was used to estimate met and unmet domestic and industrial demand, agricultural production, hydropower production, and monthly water deliveries to South Africa through the LHWP. These were estimated across all of the 244 future scenarios, representing the two demand scenarios for each of the 122 climate scenarios.

The results of these simulations are explored in depth to define vulnerabilities or key conditions that would lead to unacceptable performance of the water management system. The following metrics are used to reflect or define the vulnerabilities in the security of water, food, energy, and economic development opportunities:

- Water: domestic and industrial demand
- Food: rainfed agriculture
- Energy: hydropower production
- Economic: water transfers to South Africa

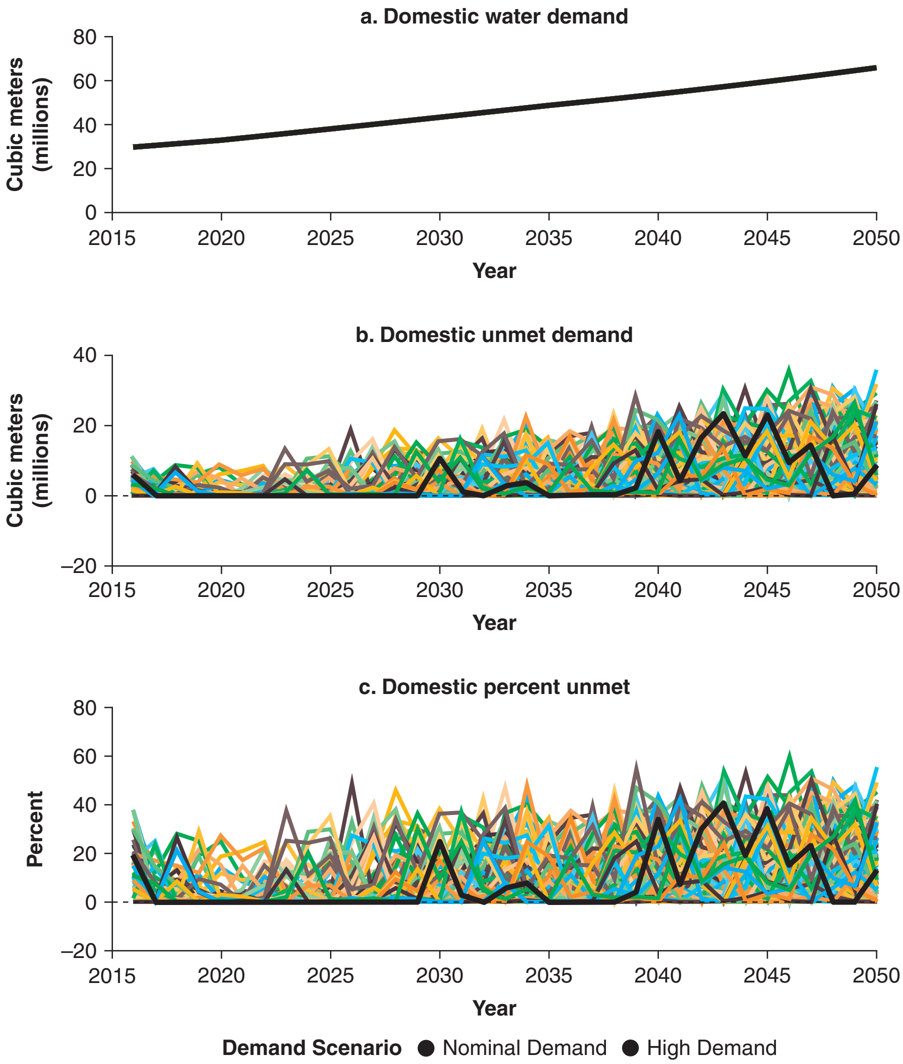
4.1 Domestic and Industrial Water Demands

Demand in the urban domestic and industrial sectors in Lesotho is not reliably met under a repeat of the historical climate or under the full range of climate futures, and, in the absence of augmentation measures, unmet demand levels will reach 40 percent by 2050. The simulated demand supplied and unmet demand over time for the baseline strategy and nominal demand projection across all 122 climate scenarios, with the result for historical conditions shown in black (see figure 4.1), show that over time, it will become more difficult to meet Lesotho's increasing demand. These results are driven in large part by the current configuration of the water management infrastructure system in the lowlands, which does not provide interconnections between the developed water sources used to support the LHWP and the domestic and industrial demands in the lowlands.

Although there are shortages for a small number of future scenarios in all years, unmet demand grows significantly starting in 2025. The unmet domestic demand is summarized by year using box and whisker plots (see figure 4.2). By 2050, more than half the future projections show shortages of approximately 10 MCM, or 15 percent of demand.

Unmet domestic demand is anticipated for the baseline strategy across all the future scenarios considered and exceeds 245 MCM or 37 percent across many of these from 2041–50 (see figure 4.3). Unmet demand is greater for the high demand scenario across all climate projections (see figure 4.4), and unmet demand for both scenarios is larger for drier climates. Even with average precipitation similar to the historical past, unmet demand could range between 32 and 110 MCM for the nominal demand projection and between 78 and 161 MCM for the high demand projection.

FIGURE 4.1 Nominal Demand Projection and Unmet Domestic Demand for the Baseline Strategy for 122 Climate Scenarios, 2015–50



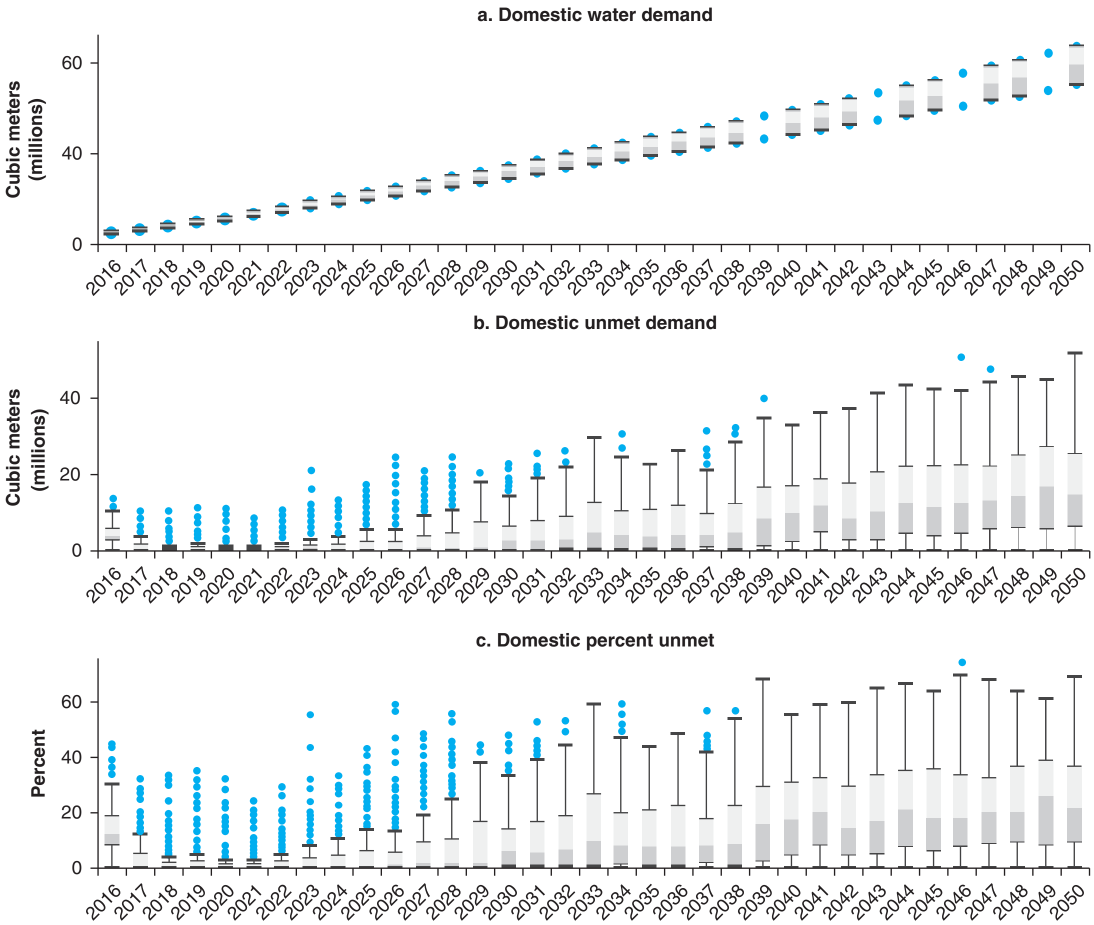
Unmet demand for the industrial sector shows similar results, ranging from 0 percent to almost 60 percent for the last decade of the analysis (see figures 4.5, 4.6 and 4.7).

The amount of water available to meet domestic or industrial sector demand in Lesotho does not change significantly with the implementation of the Polihali Dam because virtually all of this water is directed to South Africa.

4.2 Rainfed Agriculture

Rainfed agricultural yield, grouped into maize, beans, peas, sorghum, and wheat, ranges significantly year to year across the scenarios, and no long-term future trend is projected in WEAP. These five crops represent more than 90 percent of total production. The production ranges for the five crop types

FIGURE 4.2 Annual Summaries of Domestic Demand and Unmet Domestic Demand for the Baseline Strategy for 244 Climate Scenarios, 2016–50



Note: Box plots summarize results by the range between the 25th and 75th quartile results (shaded boxes), the median (dividing line between the shaded boxes), and the extent of outliers (whiskers that extends 1.5 times the interquartile range and single results beyond this range).

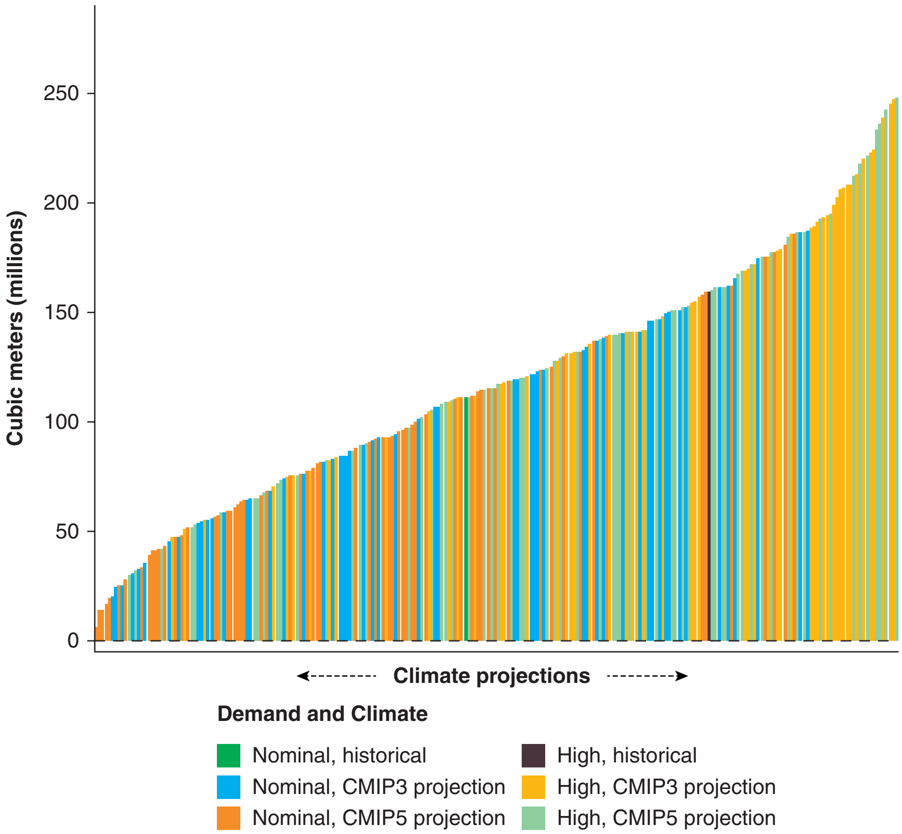
over the 2015–50 simulation period, based on FAO CROPWAT calculations, are as follows:

- Maize: 130,000–175,000 metric tons
- Beans: 14,000–23,000 metric tons
- Peas: 1,100–2,300 metric tons
- Sorghum: 25,000–37,000 metric tons
- Wheat: 17,000–34,000 metric tons.

Although no long-term trends are evident from the WEAP model simulations for maize cultivation for the climate projections across the baseline strategy (see figure 4.8), the amount of precipitation strongly affects production—wetter decades lead to higher production and drier decades lead to lower production.

There is a strong positive relationship between total rainfed agricultural production for all crops and precipitation from 2041–50 across the

FIGURE 4.3 Total Unmet Domestic Demand for the Baseline Strategy for 122 Climate Scenarios, 2041–50



121 climate projections (see figure 4.9). The rainfed agriculture under climatic conditions is distinct from the agriculture that would be affected by diverting more water from irrigation.

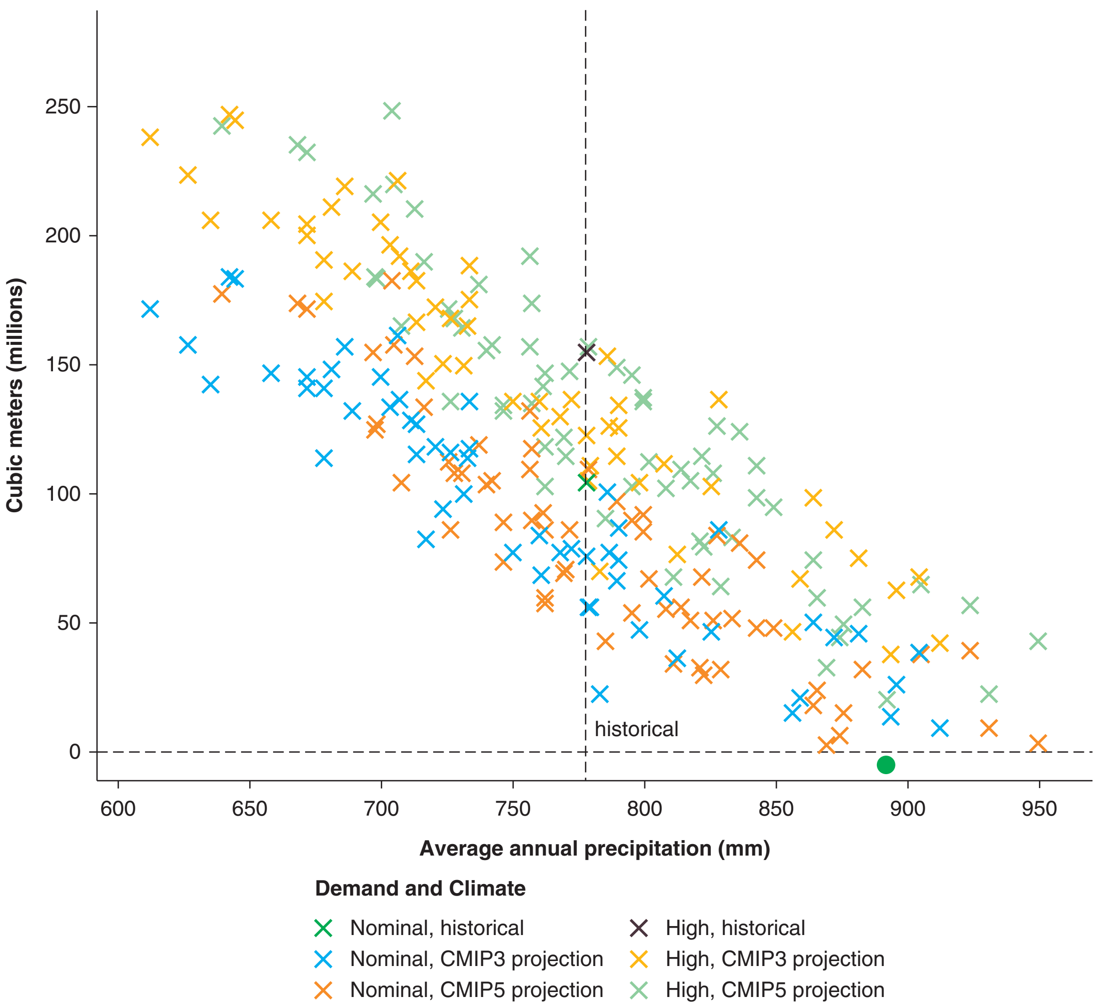
Stagnant and interannually variable agricultural production could be viewed as highly problematic for a developing country like Lesotho.

Increasing population under Lesotho's official forecast[1] leads to significantly declining per capita agricultural production if population growth is not accompanied by increased production (see figure 4.10). In 2015, Lesotho produced 0.2 metric tons per person per year, which falls to about 0.1 metric tons per person per year by 2050, a 50 percent decline.

4.3 Hydropower

Hydropower production under the historical climate and the baseline strategy is constant, producing the maximum amount of 674 GW hours for all but one year (figure 4.11). Production is also at or near the maximum for most years for the other climate scenarios. Only in the late 2040s does production fall below the maximum for more than 25 percent of the future scenarios.

FIGURE 4.4 Unmet Domestic Demand versus Precipitation for the Baseline Strategy for 244 Climate and Demand Future, 2041–50



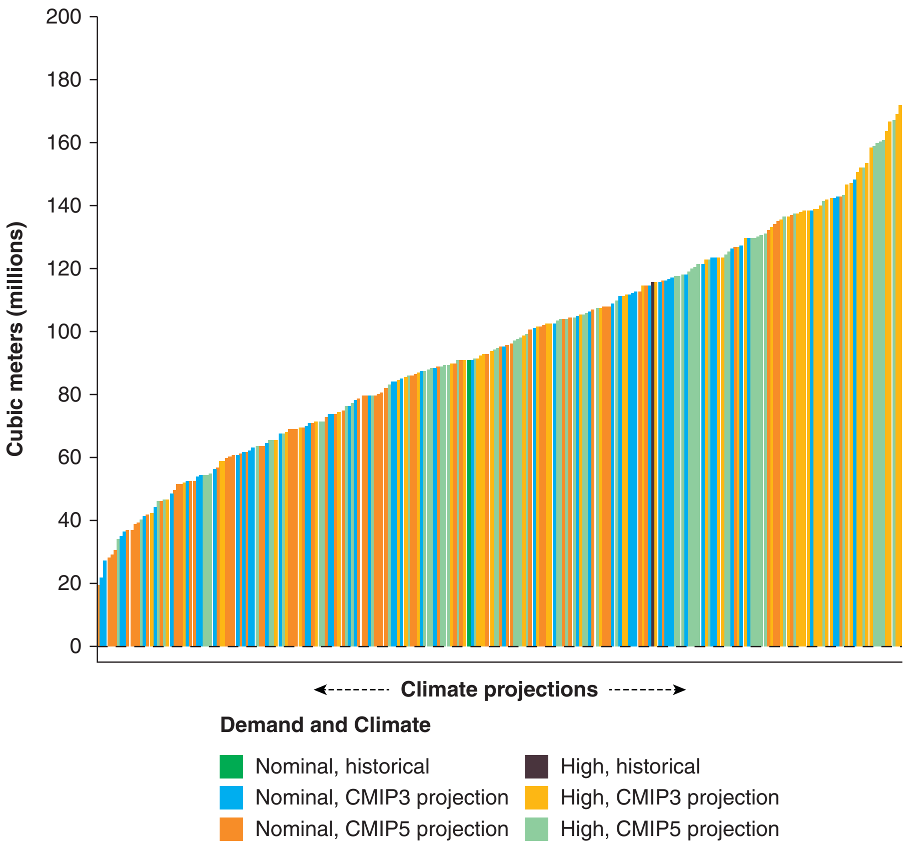
Note: Blue symbols correspond to the nominal demand scenario. Green symbols correspond to the high demand scenario. "x" symbols are results in which unmet demand is larger than a specified unmet demand threshold of 10 MCM.

Implementing the *Plus Polihali* strategy leads to increased hydropower production after 2020, up to a maximum of 874 GW hours. Production is also very reliable, with only a few climate projections predicting less than maximum production for some years (see figure 4.12). The reliability of this sector is consistent with the transfers of water to South Africa, which produces the hydropower.

4.4 The Lesotho Highlands Water Project

Under the current management system, phase I of the LHWP seeks to deliver 867 MCM per year to South Africa. Under repetitions of historical climate conditions up to 2050 (shown by the black line in figure 4.13), the WEAP simulations show that this delivery target would be met—LHWP would be

FIGURE 4.5 **Total Unmet Industrial Demand for the Baseline Strategy across the 122 Climate Futures, 2041–50**



able to deliver the 867 MCM of water to South Africa required by the Treaty—in all but one year.

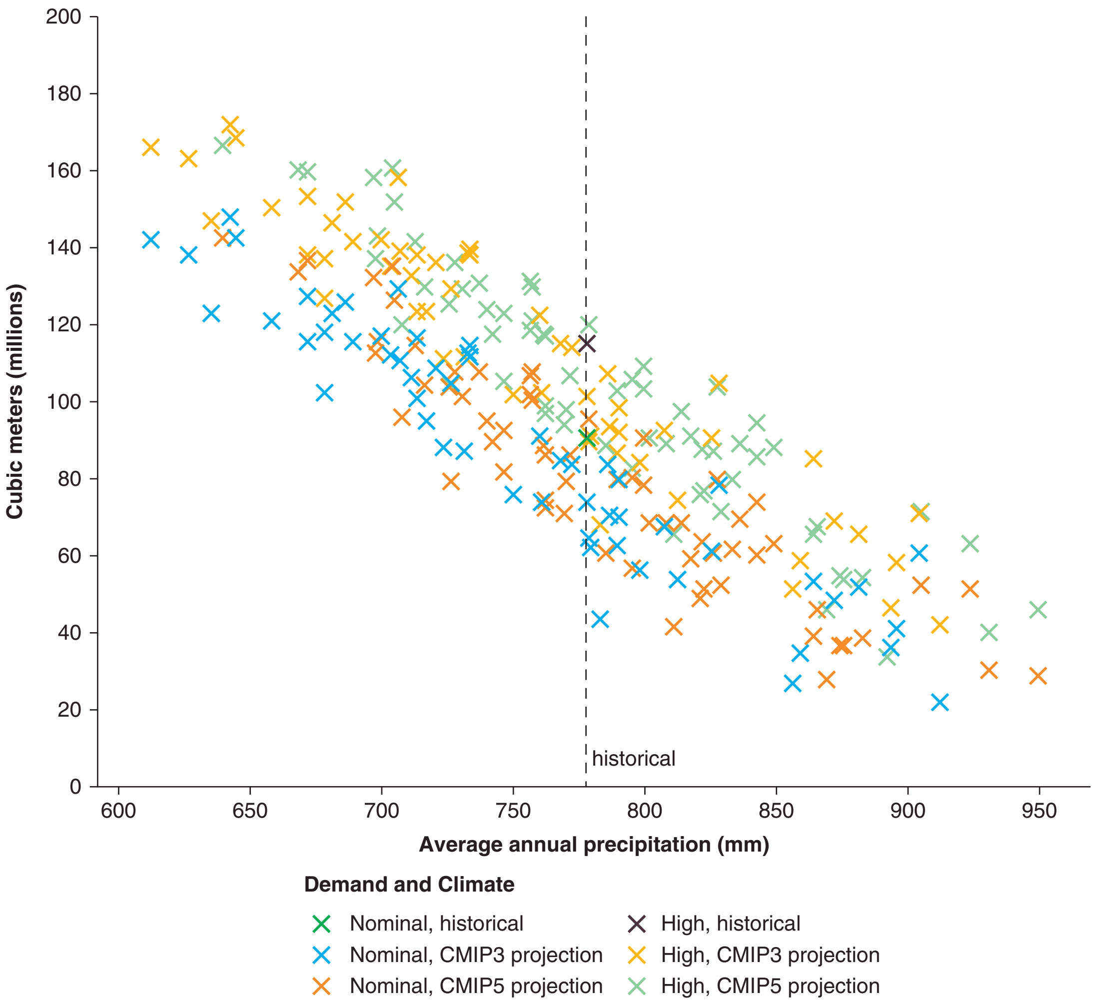
Across the full range of 121 future climate projections, however, the delivery target is not always met. This is shown in the growing density of scenarios with high values of unmet demand in figure 4.14.

The delivery target deficiencies for transfers become more pronounced in the last decade of the simulation. Figure 4.15 summarizes the total transfer deficits in MCM from 2041–50 for each of the 122 climate scenarios. The figure shows that transfer deficits occur in 49 percent of the future scenarios and range from 0 MCM (0 percent) to 3.4 BCM (36 percent).

Water transfers to South Africa are at risk only when the climate is drier than the historical record of less than 778 mm per year (see figure 4.16). The plot shows transfer deficits against precipitation in the last decade for the 122 climate scenarios. In this figure, the amount of unmet transfers that would occur under historical conditions—154 MCM—is used as a performance threshold. The Xs indicate the 48 cases in which unmet transfers would exceed this threshold.

Construction of the Polihali Dam, scheduled for 2020, increases the delivery target from 2020 to 2025 for the baseline conditions. This additional transfer capacity is reflected under the *Plus Polihali* strategy (see figure 4.18).

FIGURE 4.6 Unmet Industrial Demand versus Precipitation for the Baseline Strategy for 244 Climate and Demand Futures, 2041–50



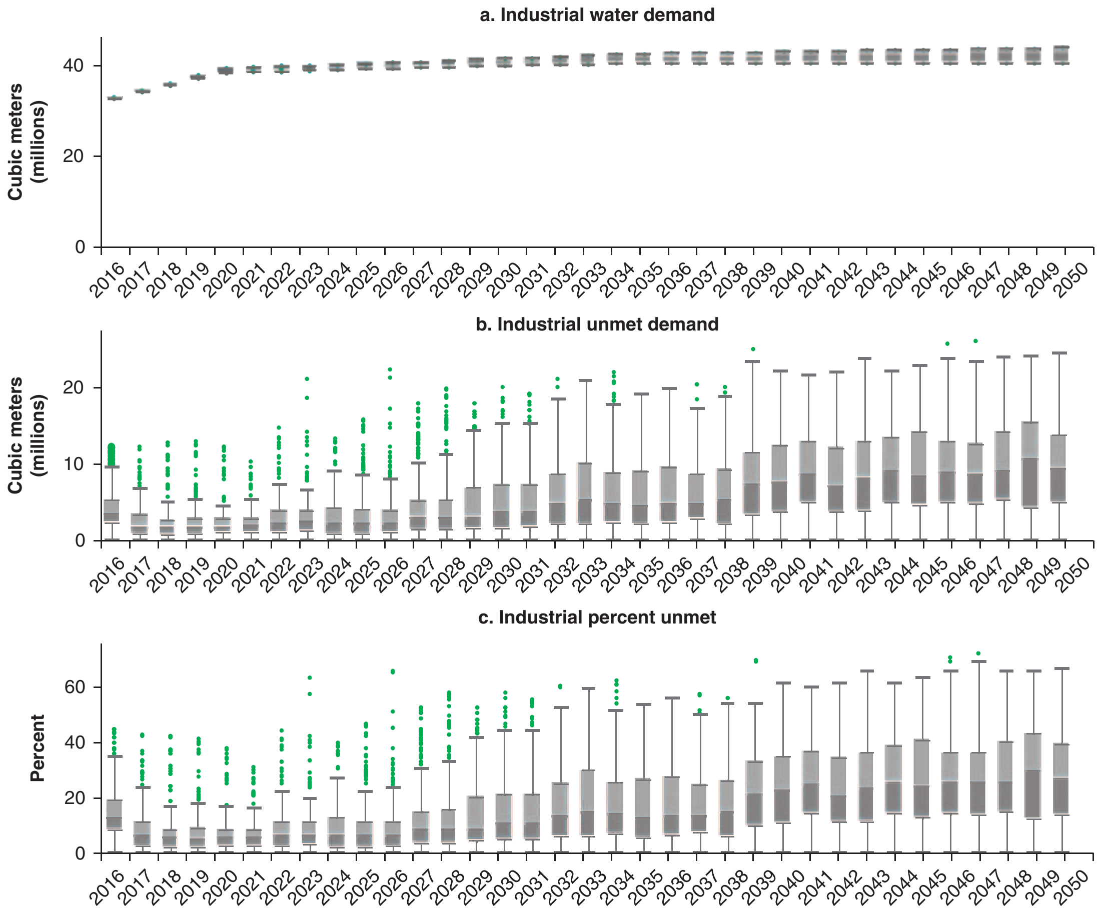
Even with the higher target, deliveries can be met under most future scenarios (106 of the 122 cases). This suggests a higher reliability of deliveries than under the baseline strategy.

The transfer deficits in the last decade of this period show the vulnerabilities of the *Plus Polihali* strategy (see figures 4.18 and 4.19). They confirm that the system with the Polihali Dam is very reliable under most climate scenarios and that deficits occur only in the very driest of future scenarios (16 of the 122 cases), in which precipitation is less than 725 mm per year (see figure 4.17).

4.5 The Lesotho Highlands Botswana Water Transfer

The governments of Botswana, Lesotho, and South Africa initiated a high-level planning study to evaluate the possible development and transfer of water resources from the highlands of Lesotho to the southern part of Botswana

FIGURE 4.7 Annual Summaries of Unmet Industrial Demand for the Baseline Strategy for 244 Climate and Demand Scenarios, 2016–50



and to communities adjacent to the conveyance system. A Memorandum of Understanding between the three countries was signed on March 1, 2013, and a Joint Study Management Committee was established to provide management and guidance for the high-level assessment.

The individual study is the first in a possible series of studies that could inform longer-term assessments of the potential regional costs and benefits associated with different regional supply options. The study is ongoing and will explore transfer options from the Lesotho highlands and the development of additional, sustainable revenue streams for Lesotho based on renewable water resources. The study will help Botswana make more informed decisions on securing water supplies, address water scarcity and security issues in parts of South Africa, and will consolidate Lesotho's position as the water tower of southern Africa. The regional concept builds on the historical foundations of bilateral agreements in the Orange-Senqu River basin and lays the foundation for a more strategic regional analysis of long-term water supply security considerations in southern Africa.

Several possible development scenarios were assessed using future scenarios of potential climate change to help understand the implications of any

FIGURE 4.8 Rainfed Maize Production for the Baseline Strategy for 122 Climate Scenarios, 2016–50

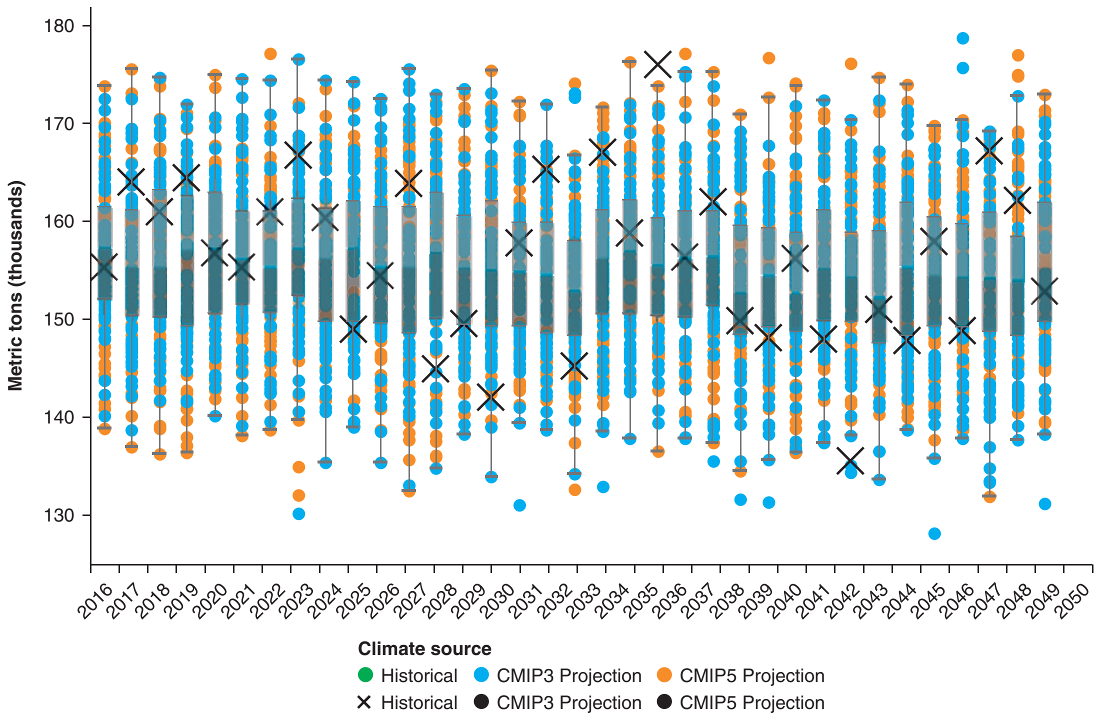


FIGURE 4.9 Total Rainfed Agricultural Production versus Average Annual Precipitation for 122 Climate Scenarios, 2041–50

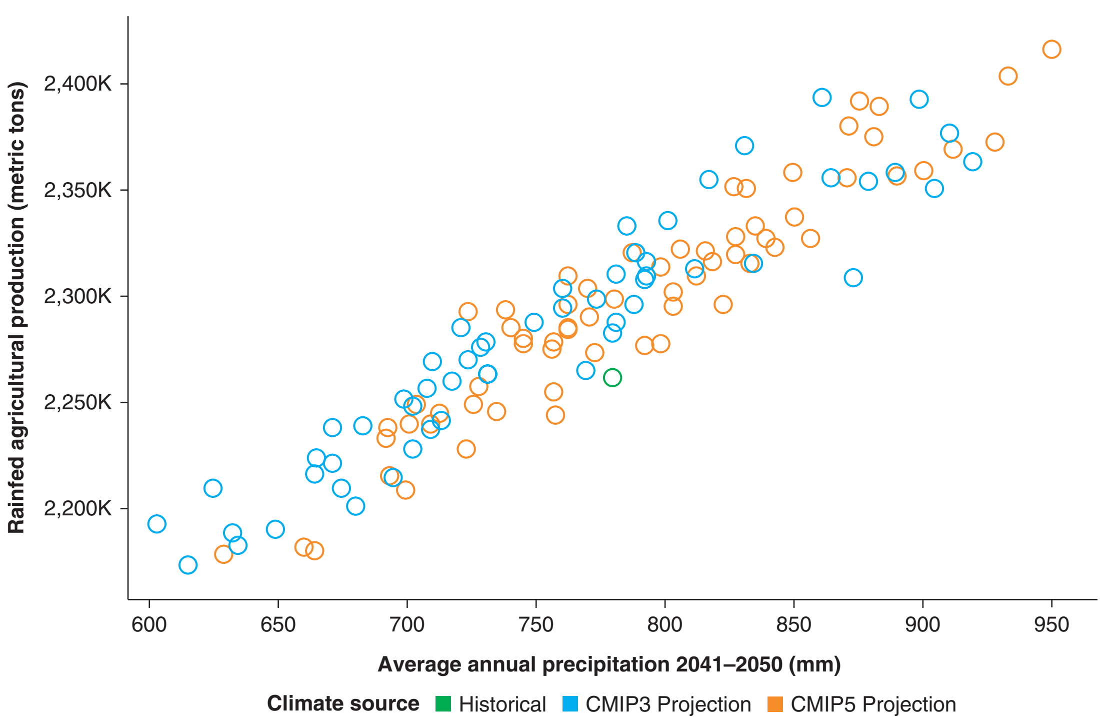


FIGURE 4.10 Per Capita Rainfed Plus Irrigated Agricultural Production for the Baseline Strategy for 121 Climate Projections, 2016–50

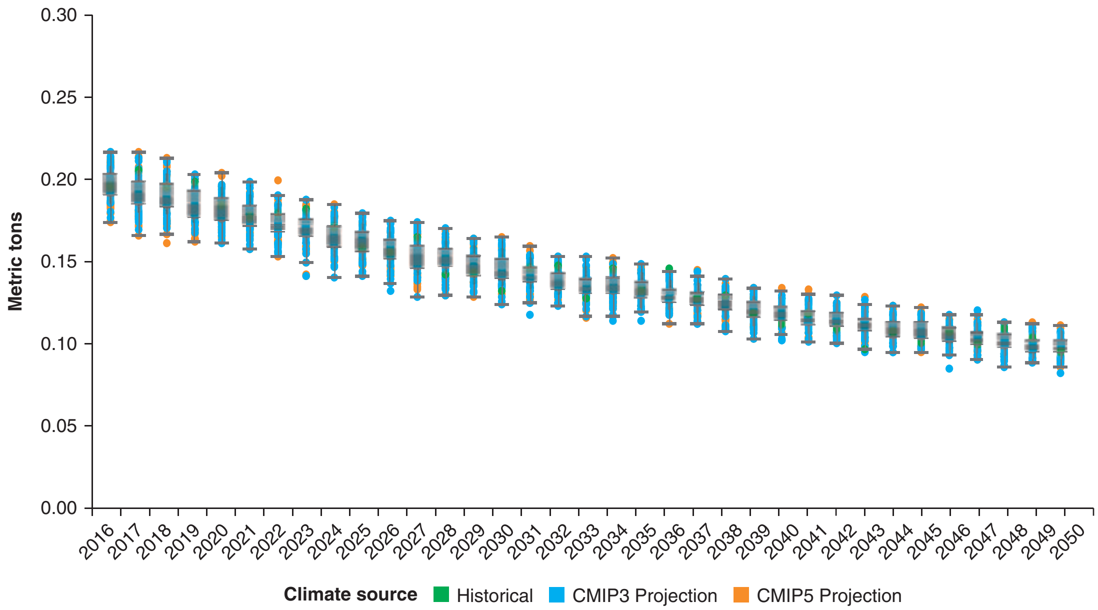


FIGURE 4.11 Net Hydropower Produced for the Baseline Strategy and Nominal Demand Projections for 122 Climate Scenarios, 2015–50

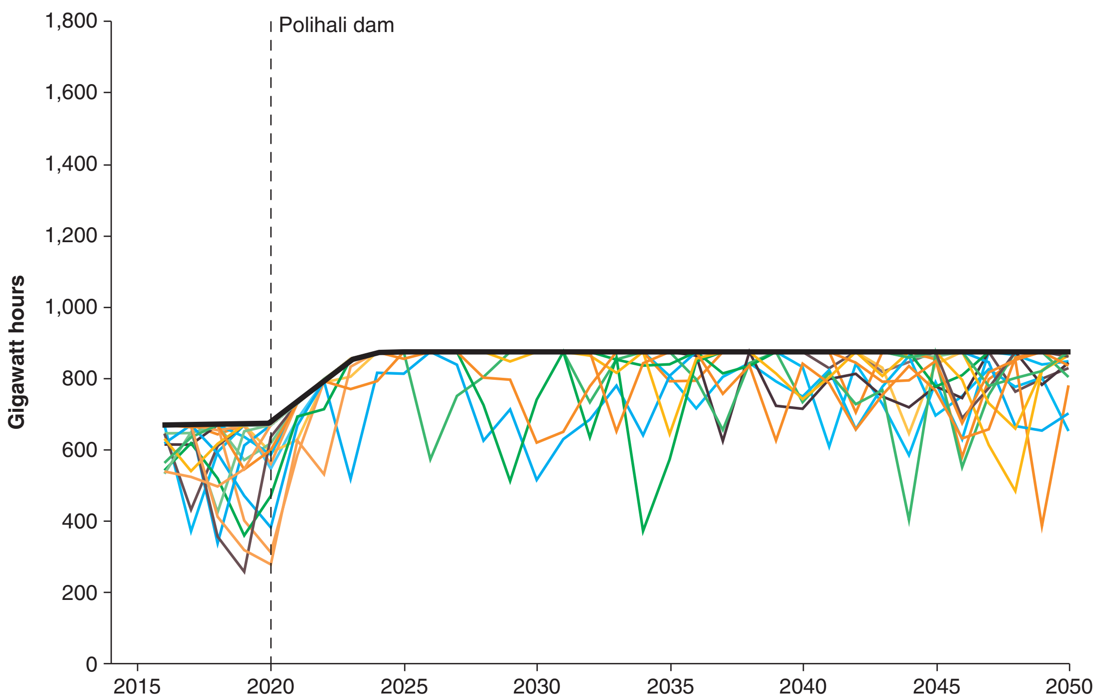


FIGURE 4.12 **Net Hydropower Production for the Plus Polihali Strategy and Nominal Demand Projections for 122 Climate Scenarios, 2015–50**

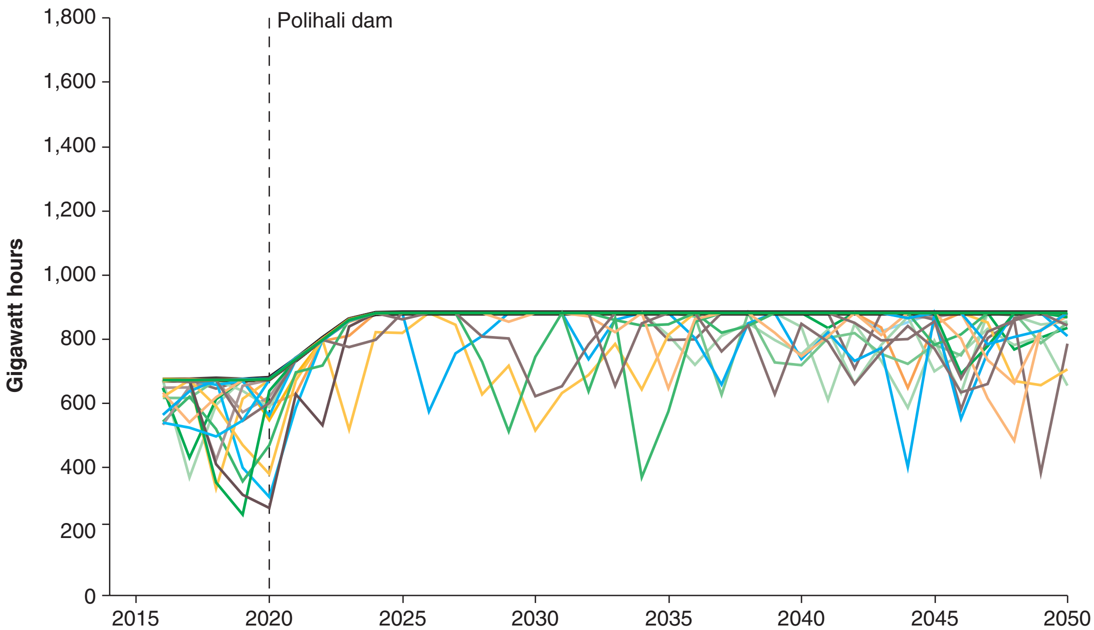


FIGURE 4.13 **Water Transfers to South Africa for the Baseline Strategy under a Repeat of Historical Conditions, 2015–50**

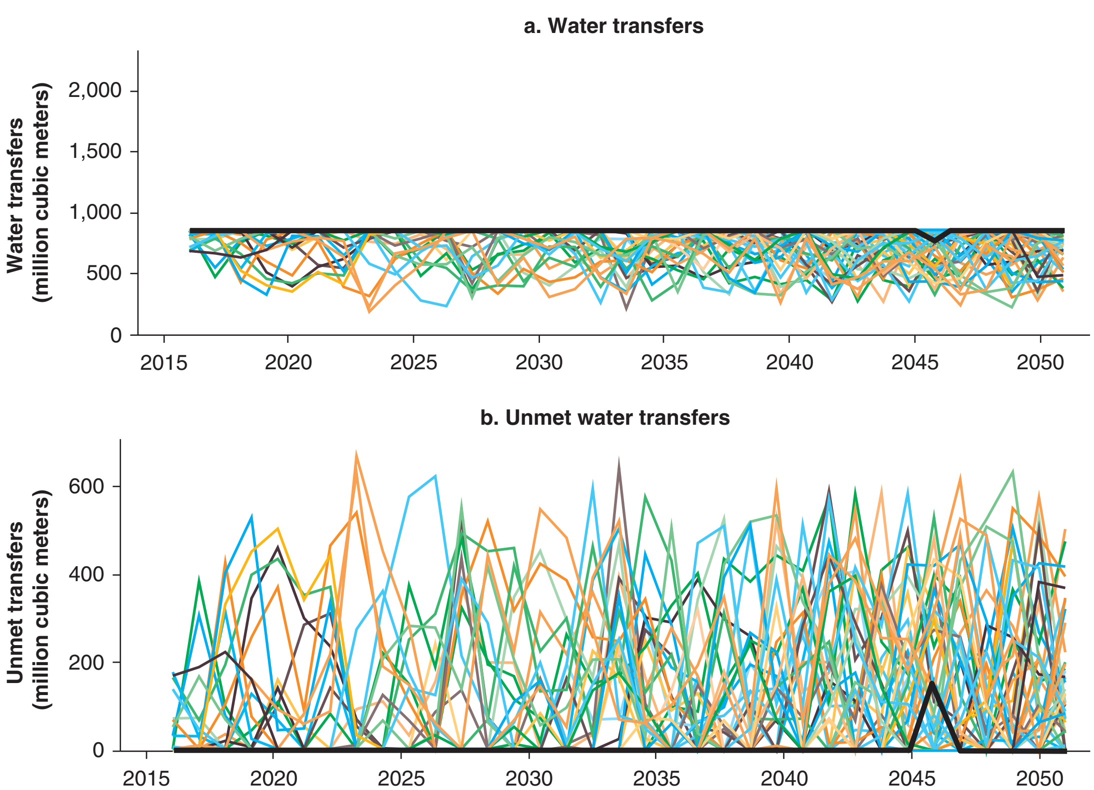


FIGURE 4.14 **Transfers to South Africa for the Baseline Strategy for 122 Climate Scenarios, 2015–50**

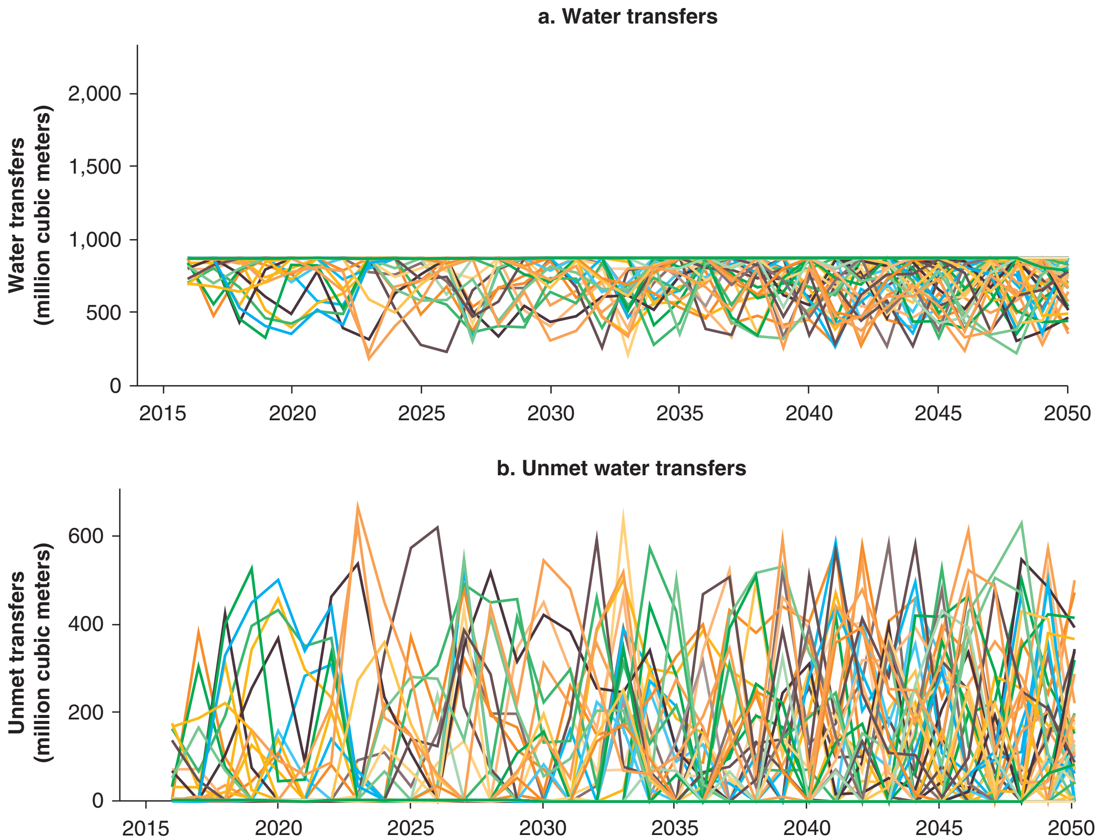


FIGURE 4.15 **Total Transfer Deficits for the Baseline Strategy for 122 Climate Scenarios, 2041–50**

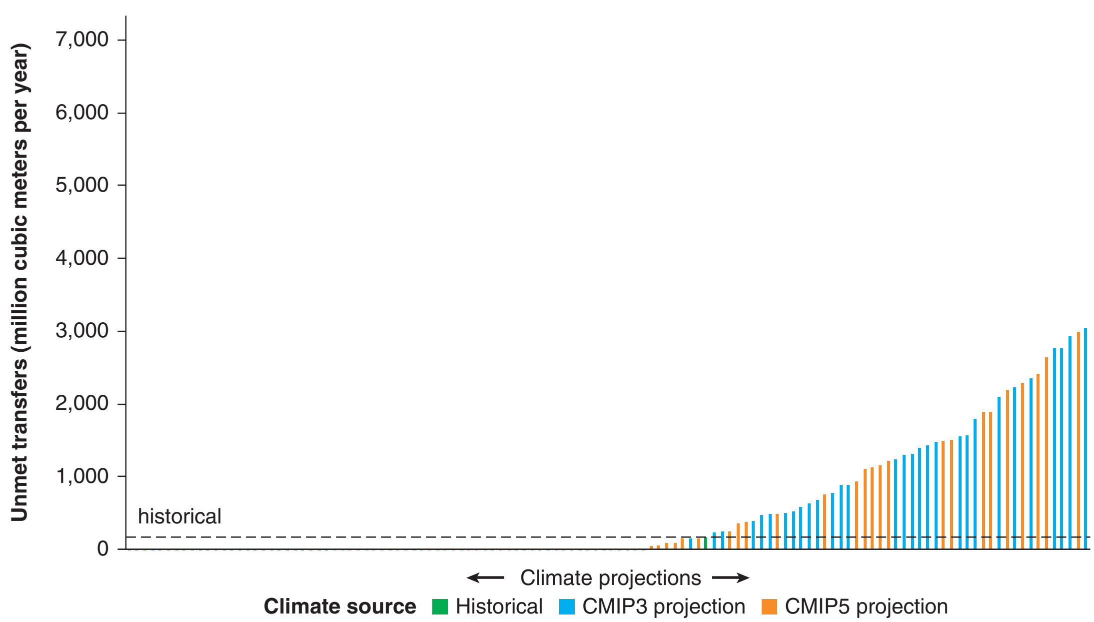
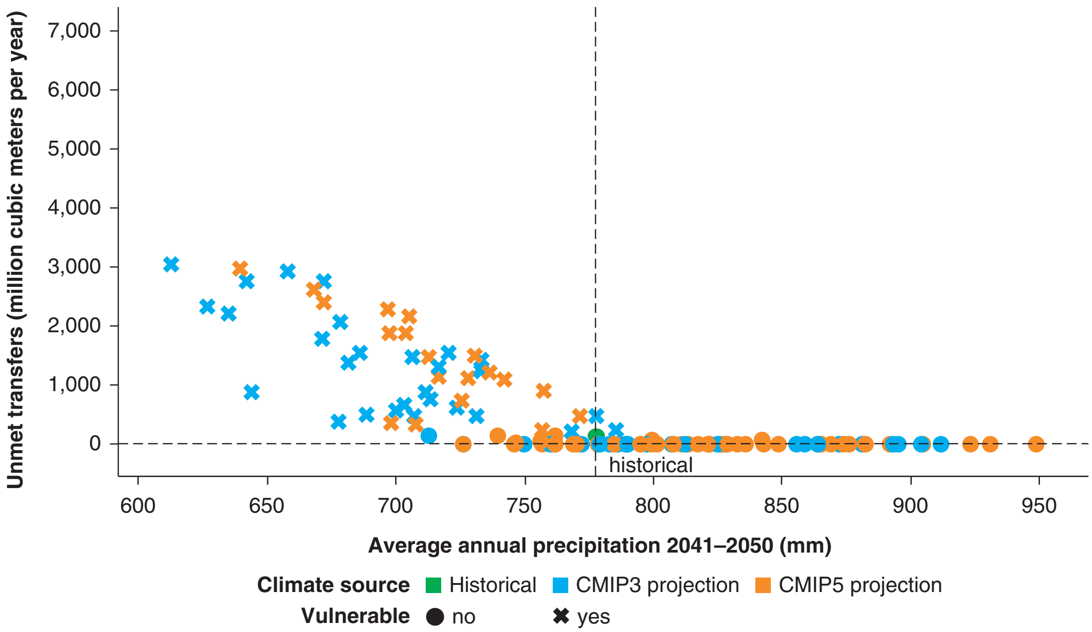


FIGURE 4.16 Transfer Deficits versus Precipitation for the Baseline Strategy for 122 Climate Scenarios, 2041–50



Note: "x" symbols indicate results in which transfer deficits are larger than a specified threshold of 154 MCM.

FIGURE 4.17 Transfers to South Africa for the Plus Polihali Strategy for 122 Climate Scenarios, 2015–50

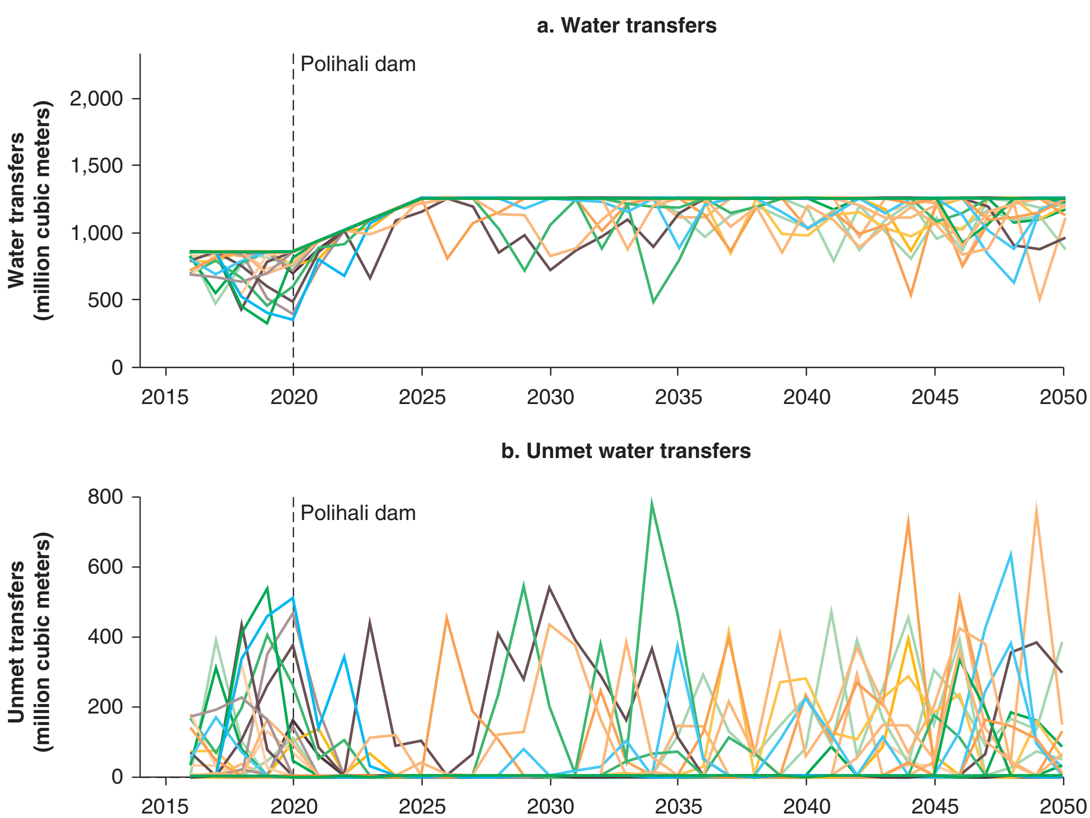


FIGURE 4.18 Total Transfer Deficits for the Plus Polihali Strategy for 122 Climate Scenarios, 2041–50

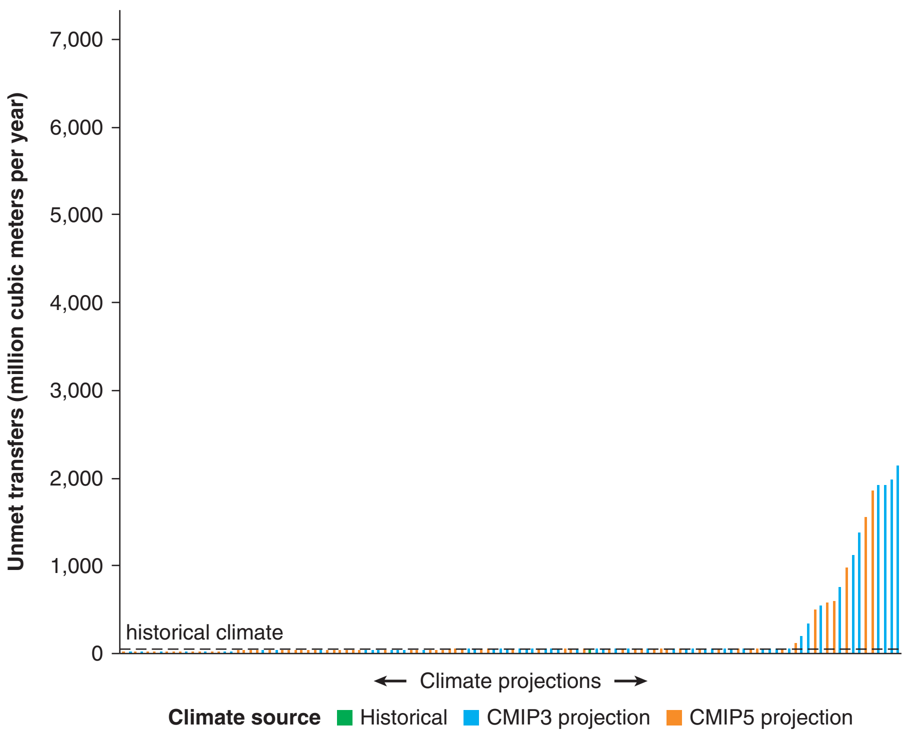
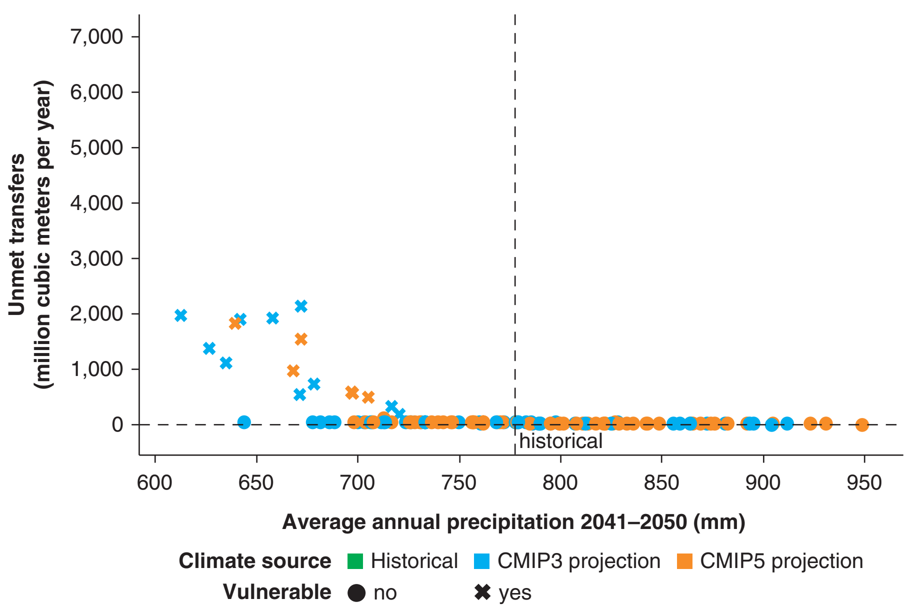
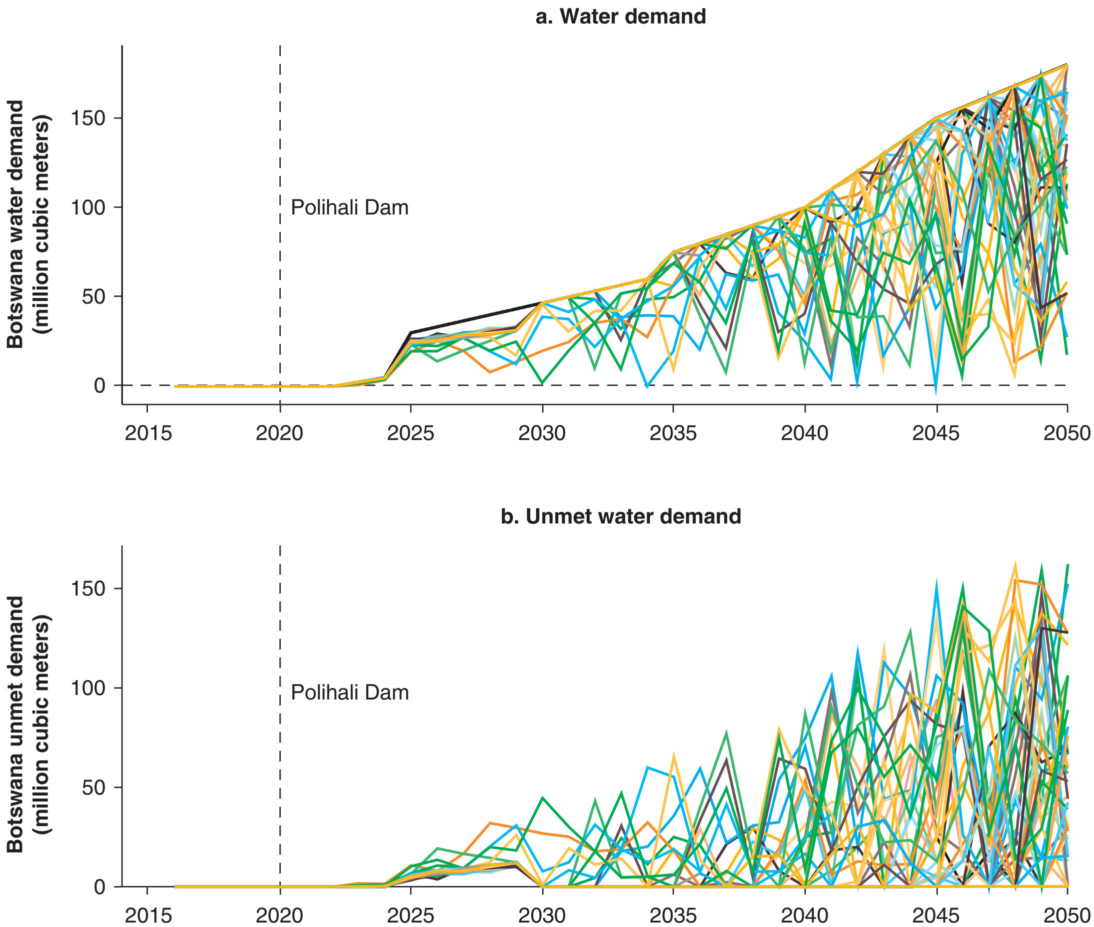


FIGURE 4.19 Transfer Deficits versus Precipitation for the Plus Polihali Strategy for 122 Climate Scenarios, 2041–50



Note: "x" symbols indicate results in which transfer deficits are larger than a specified threshold of 154 MCM.

FIGURE 4.20 Botswana Water Demand and Unmet Water Demand over Time for 122 Climate Scenarios, 2041–50



proposed transfer on the existing and planned water transfers to South Africa. The development scenarios were based on the following assumptions:

- Demands in Botswana start in 2024, and increase to 180 MCM by 2050 (as shown in figure 4.20)
- Two alternate scenarios for demand in South Africa:
  - o Only the Polihali Dam is built, with maximum demand of 40 m^3 per second
  - o The full build-out of the LHWP, with maximum demand of 70 m^3 per second
- Urban, industrial, and agricultural demand in Lesotho (with irrigated area expanded to 12,000 hectares) has a high priority
- Two scenarios with different priorities given to South Africa and Botswana

If the future climate is about the same as the historical climate, or wetter, the results suggest that the transfers to both South Africa and Botswana would be reliably met. Under drier climates, there is a tradeoff between meeting Botswana's and South Africa's transfer targets. The percentage impact is much lower on transfers to South Africa than to Botswana. When the transfers to Botswana are prioritized, they are very reliable, with shortfalls in only 4 of the 122 climates examined. With the construction of the Polihali Dam, the South African transfer targets are met under most, but not all, plausible future climate scenarios. Adding the transfers to Botswana increases the number of unmet transfers, but only under drier future projections, to 35 percent of future scenarios. Reducing the priority of transfers to Botswana partially mitigates the impact on South African transfers, but increases unmet Botswana targets to 40 percent of future scenarios.

Note

1 Lesotho's population is projected to increase from 1.15 million people in 2015 to 2.4 million people by 2050.

Chapter 5

Water Security Adaptations and Enhancements

The vulnerability assessment highlights the need to implement measures to improve water security and reduce the vulnerability of water management in Lesotho. The long-term vulnerabilities of the domestic and industrial sectors have the potential to impose significant drains on economic growth and development. Similarly, a failure to reduce the vulnerability of the agriculture sector to precipitation variability and to increase production to address increasing demand will undermine the prospects of the rural economy as well as of livelihoods.

Understanding the options for adaptation of the water management system in Lesotho and exploiting opportunities for closer integration with and without full development of the LHWP can provide the foundation for a more cohesive strategy for further developments. This approach could be used to guide prioritization of Lesotho's water resources development with respect to enhanced water, food, energy, and economic security. This section looks at a range of possible options for adaptation of the current water management strategy to potential future developments in Lesotho.

5.1 Securing Water for Domestic and Industrial Growth

Adaptation measures will enhance the security of water supplies in the lowlands of Lesotho to meet domestic and industrial demands. Implementation of the Lowlands project and the Polihali Dam project will provide additional water supplies to the Lesotho lowlands and significantly reduce unmet demand. Figure 5.1 summarizes unmet demand by year for 244 climate and demand future scenarios for the *Plus Polihali, Lowlands, and Irrigation* strategy. This can be compared with the baseline strategy illustrated in figure 5.2.

The analysis of unmet domestic water demand as a function of precipitation, from 2041–50, shows that the LLWSS effectively reduces unmet demand in the domestic sector (see figure 4.2). In contrast to the baseline strategy—in which the domestic sector was vulnerable in all future scenarios—with the

FIGURE 5.1 Annual Summaries of Domestic Demand and Unmet Demand for the Plus Polihali, Lowlands, and Irrigation Strategy for 244 Climate Scenarios, 2016–50

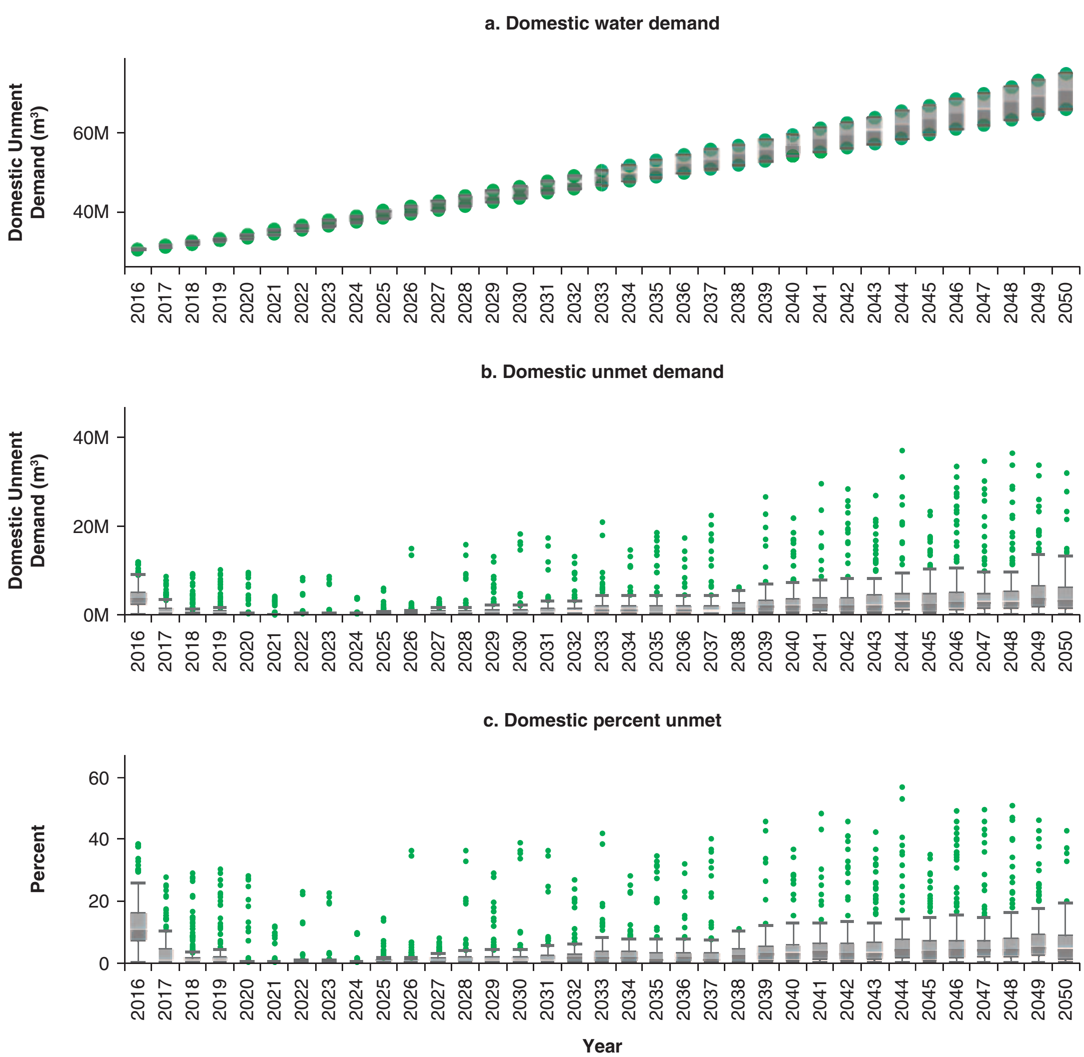
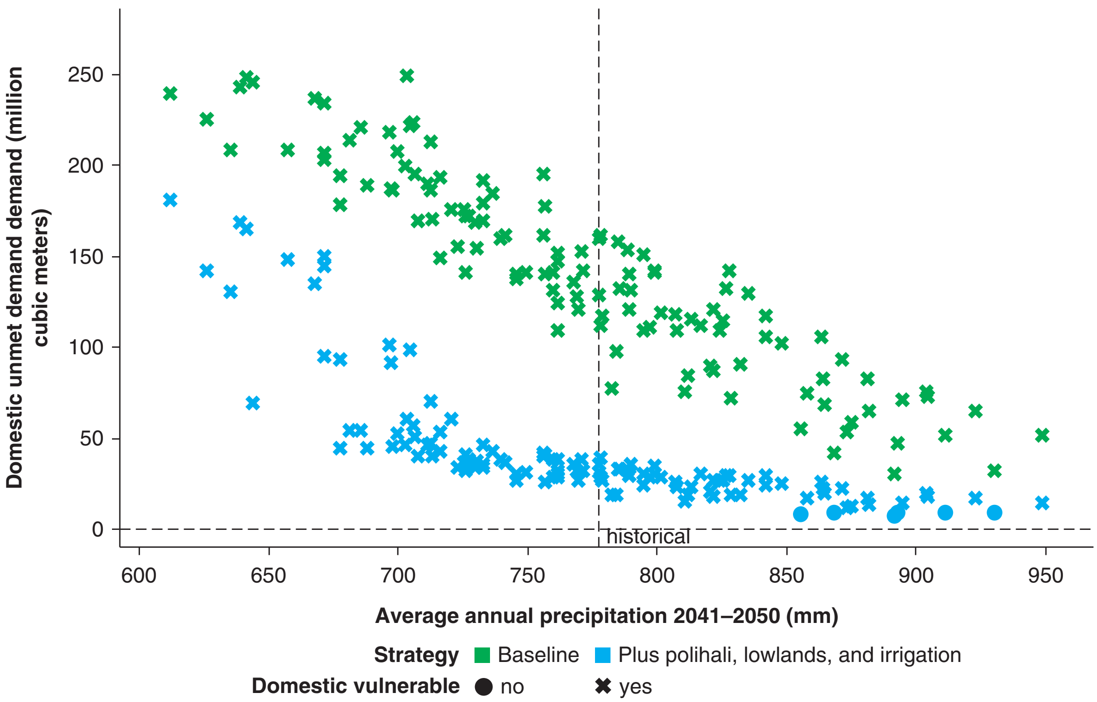


FIGURE 5.2 Unmet Domestic Demand versus Precipitation for the Baseline Strategy and the Plus Polihali, Lowlands, and Irrigation Strategy using the High Demand Projection for 122 Climate Scenarios, 2041–50



Note: "x" symbols indicate results in which unmet demand is larger than a specified unmet demand threshold of 10 MCM.

LLWSS, the domestic sector is more resilient to future scenarios in which precipitation is below 750 mm per year for 2041–50. Unmet demand still exceeds 10 MCM, but by much smaller amounts than under the baseline strategy.

The effects of this strategy under the nominal demand scenario (not shown) and for the industrial sector are equally effective at reducing vulnerabilities.

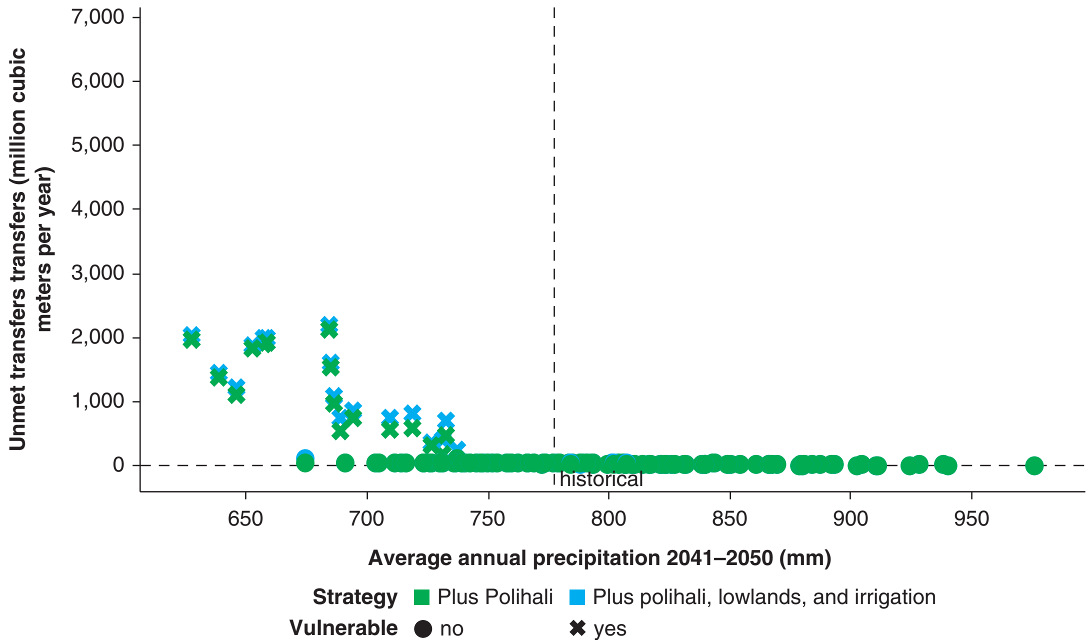
It is worth noting that providing this needed water supply to the domestic sector from the LLWSS does not affect transfers to the highlands project. Figure 5.3 shows transfer deficits for 2041–50 as a function of precipitation for the *Plus Polihali* and *Plus Polihali, Lowlands, and Irrigation* strategies across all 121 climate projections, but only very slight increases, between 2 percent and 3 percent, in transfer deficits for the driest climate projections.

5.2 Enhancing Agricultural Productivity through Irrigation

Adaptation measures will also enhance the security of water available to support agricultural development in Lesotho.

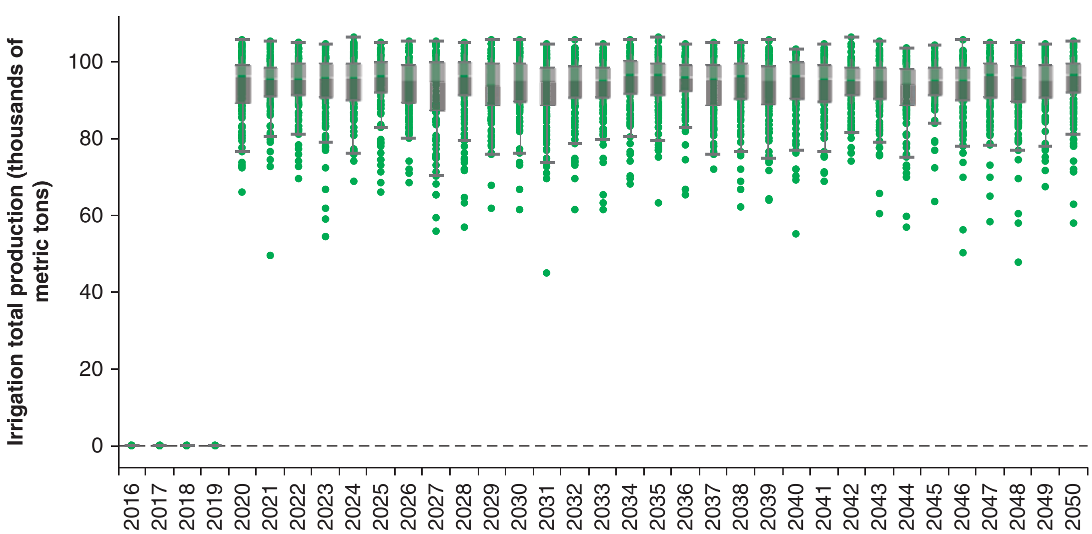
The addition of 12,000 hectares of irrigation under the *Plus Polihali, Lowlands, and Irrigation* strategy significantly increases crop production

FIGURE 5.3 Transfer Deficits versus Precipitation for the Plus Polihali Strategy and the Plus Polihali, Lowlands, and Irrigation for 122 Climate Scenarios, 2041–50



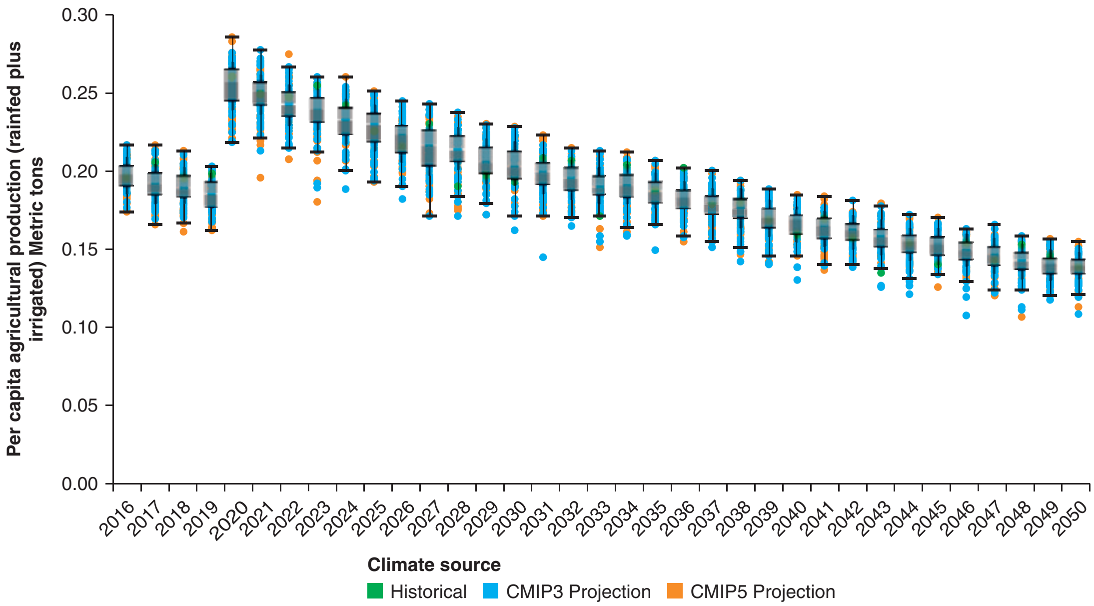
Note: "x" symbols indicate results in which transfer deficits are larger than a specified threshold of 154 MCM.

FIGURE 5.4 Irrigated Crop Production for the Plus Polihali, Lowlands, and Irrigation Strategy for 121 Climate Projections, 2016–50



in Lesotho. Figure 5.4 shows additional production under irrigation across climate projections ranging from 70,000 metric tons to over 100,000 metric tons. Although the yield is still variable across years, this added production is significant when compared to the rainfed production—200,000 metric tons to 270,000 metric tons—an increase of almost 50 percent. This additional production also reduces the decline in per capita production by a factor of two (see figure 5.5).

FIGURE 5.5 **Per Capita Total Crop Production for the Plus Polihali, Lowlands, and Irrigation Strategy for 121 Climate Projections, 2016–50**



The FAO has reported that maize imports from South Africa between April 2014 and mid-January 2015, reached about 90,000 metric tons, almost double that of the previous year (GIEWS 2015). Any improvement in agricultural production will reduce the number of food insecure households in Lesotho as well as enhance security against global price fluctuations in maize in particular.

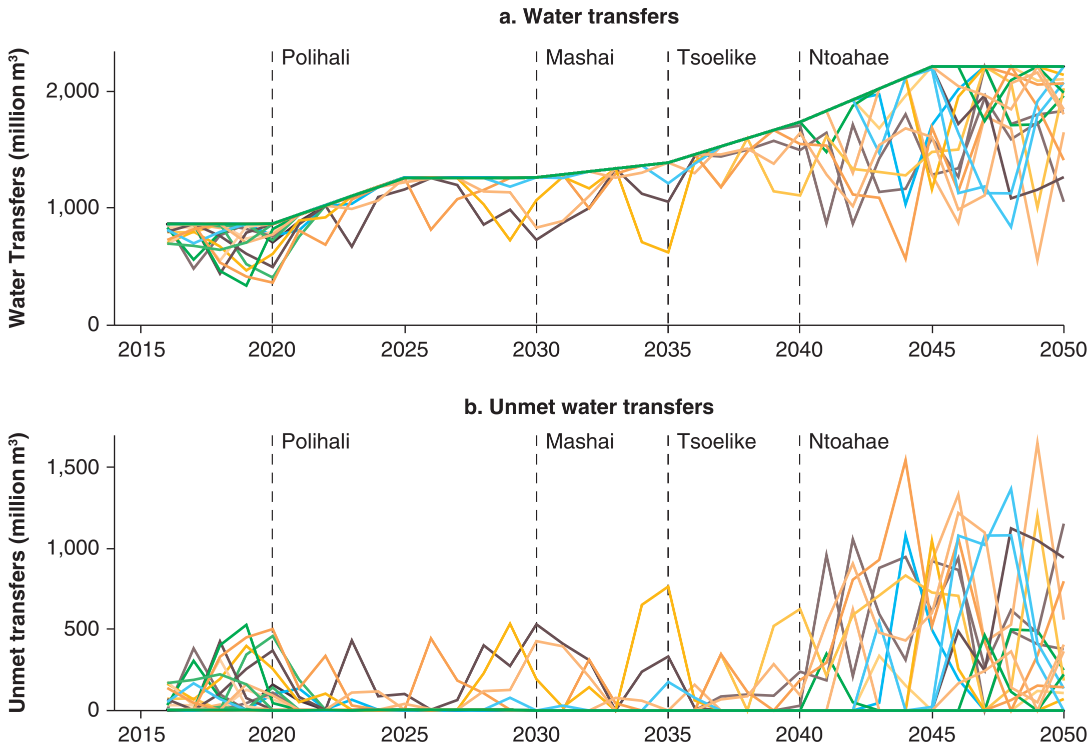
The analyses show how critical expanded irrigation is for the development of Lesotho, not only increasing incomes, but providing desperately needed food security for a largely agriculture-dependent population.

5.3 Sustaining Economic Options through the LHWP

Adaptation measures to sustain the continued contribution of water to the overall economy of Lesotho include support for the further development of water resources in the highlands of Lesotho. The LHWP can continue to provide valuable income to Lesotho from South Africa, and there are options to implement reliable transfers to Botswana through bulk pipes, as discussed in section 4.5.

The full build-out of the LHWP affects the quantity and reliability of transfers to South Africa, and the assessment looked at whether inclusion of the LLWSS project and irrigation affects the results. Figure 5.6 shows that with the implementation of the *Plus All Highlands* strategy, transfers to South Africa increase with each additional facility. As under the *Plus Polihali*

FIGURE 5.6 Transfers to South Africa for the Plus All Highlands Strategy for 122 Climate Scenarios, 2015–50

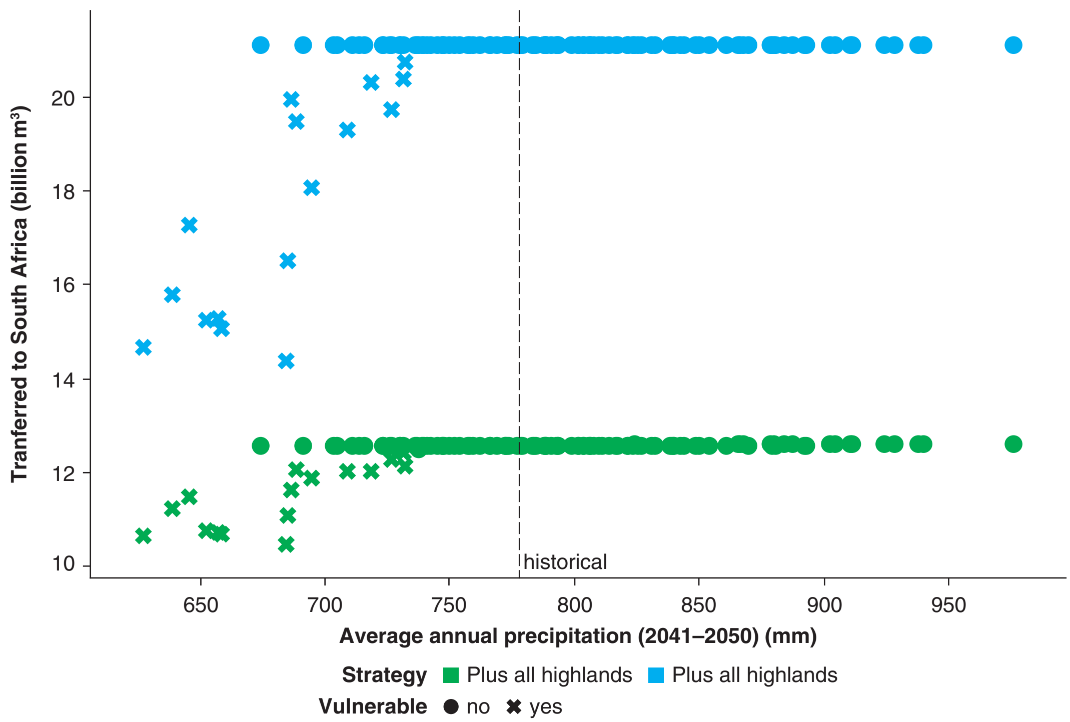


strategy, unmet demand is infrequent across the climate projections, even as demand for transfers increases with the additional infrastructure projects.

With the implementation of additional components of the LHWP, transfers increase in all future scenarios, although the vulnerability of transfers grows in absolute amounts (see figure 5.7). For example, for future scenarios in which no deficits occur, the *Plus Highlands* strategy would deliver 8.5 BCM more water than the *Plus Polihali* project (21.1 BCM versus 12.6 BCM). For future scenarios in which deficits occur for both strategies, the additional amount delivered by the *Plus Highlands* strategy declines to as low as 3.9 BCM. Although this increase of 3.9 BCM is greater than the *Plus Polihali* strategy decline of 2 BCM, it is significantly lower than the expected increase of 8.5 BCM. Thus, while the *Plus Highlands* project remains resilient to all but the driest climate future scenarios (precipitation less than 733 mm per year), it is more vulnerable to absolute and proportional reductions than the *Plus Polihali* strategy because the total transfer increases dramatically. More stressful climates will decrease the value of the additional project elements in the *Plus Highlands* strategy.

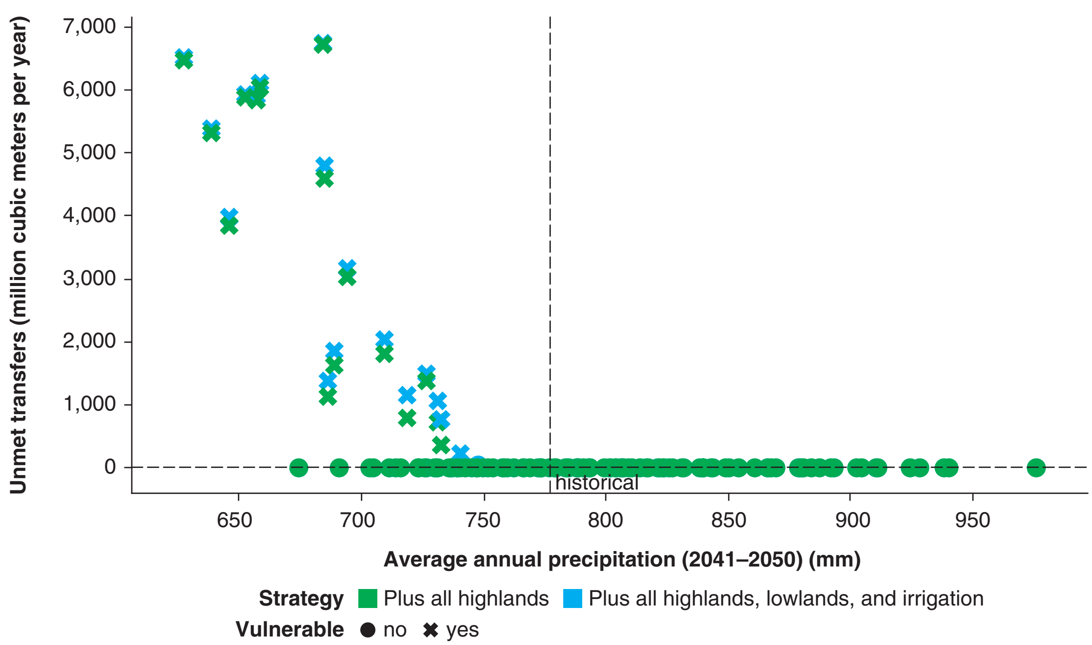
The last evaluation compares deliveries with all the LHWP elements with and without the LLWSS and irrigation projects. Figure 5.8 shows that for all future scenarios, adding these two elements to benefit the Lesotho lowlands has a negligible impact on transfers to South Africa.

FIGURE 5.7 Water Transferred to South Africa under Plus Polihali Strategy and Plus Highlands Strategy for 122 Climate Scenarios, 2041–50



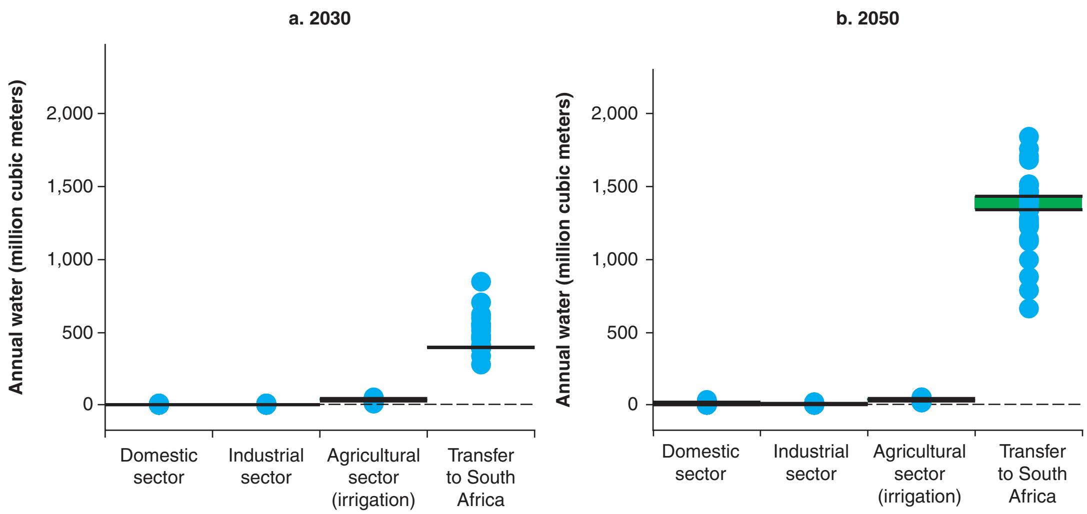
Note: "x" symbols indicate results in which transfer deficits are larger than a specified threshold of 154 MCM.

FIGURE 5.8 Transfer Deficits versus Precipitation for the Plus Highlands Strategy and the Plus Highlands, Lowlands, and Irrigation Strategy for 122 Climate Scenarios, 2041–50



Note: "x" symbols indicate results in which transfer deficits are larger than a specified threshold of 154 MCM.

FIGURE 5.9 Allocation of Additional Water Supplied, by Sector, for the Plus All Highlands, Lowlands, and Irrigation Strategy Compared to the Baseline Strategy for All 122 Climate Scenarios, 2030 and 2050



5.4 Summary of Adaptation Strategies

It is illuminating to see how the additional water developed through the LHWP and the adaptations described in this study is allocated across the sectors. Figure 5.9 shows that the vast majority of the total water development for each strategy would go to transfers to South Africa. An important but very modest amount would be used to meet Lesotho's in-country water needs.

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Chapter 6

Key Findings and Recommendations

Water remains one of Lesotho's greatest natural assets. It provides for human dignity and well-being and is embedded into the cultural fabric of the Kingdom. It provides sustainable revenues that have driven economic growth and development across the country. The water transfers to South Africa represent 3 percent of GDP and 10 percent of total government revenues, a considerable resource for the funding of development projects in Lesotho.

Ensuring the continued sustainable development of Lesotho's water resources requires an integrated and strategic long-term approach to inform a long-term vision that can respond to the challenges of climate change. Decision makers need to balance the revenue streams afforded by the geographic proximity to demand centers with national development needs to provide water for the people and to provide the foundations for continued development of wet industries.

A detailed water management model has been developed to help facilitate robust decision making. This model has been developed through an iterative consultative process led by key water resources management agencies in Lesotho. The model allows for the assessment of vulnerabilities in water supply reliability across water use sectors, including domestic, agriculture, hydropower, and industrial. The model also evaluates water management strategies aimed at reducing vulnerabilities and improving livelihoods.

A range of future scenarios has been defined using a sampling of many climate projections obtained from publicly available datasets. Temperature is consistently predicted by all of the models to increase between 0.8˚C and 2.9°C over the next 20 to 30 years. This will have implications for water supply availability by potentially altering the seasonal snow melt, runoff, and soil moisture content. The amount of water required for irrigation will increase with rising temperatures. However, it is also possible that opportunities for increased irrigation might arise in Lesotho if temperature increases result in longer growing seasons or more favorable growing conditions for new cash crops.

The future climate projections do not agree on precipitation trends, with roughly an equal number of projections predicting both increases and decreases in average annual precipitation. Precipitation demonstrates a variable response among the future scenarios advocating for flexible yet robust mechanisms to facilitate decisions relating to the development of water resources.

Climate change and demand growth will have significant effects on Lesotho's ability to meet domestic and industrial demand. More than half of the future scenarios evaluated show unmet domestic demand of 20 percent or more for the 2041–50 period. Future demand and climate uncertainty produce a wide range of projected unmet demand, ranging from zero to 250 MCM per year by 2041–50. Demand uncertainty explains about 48 MCM per year of this variation with the balance due to climate uncertainty.

Implementation of the LLWSS and other potable water supply infrastructure investments, along with the Polihali Dam project, can reduce domestic and industrial vulnerabilities.

Agricultural production will remain vulnerable to interannual variability over the coming decades. Production, which is largely rainfed, is highly variable and fluctuates with precipitation. As precipitation trends over time relative to interannual variability are small the dominant pattern of highly fluctuating agricultural output from year to year will continue into the future under all climate projections. Per capita production declines as population rises.

Development of irrigation can be implemented without significant reductions in the reliability of water transfers to South Africa under the LHWP.

Hydropower development will continue to rely on water transferred through the LHWP at the 'Mulea outlet. Further development of the 'Mulea Hydropower Project should be positioned within the long-term demand projections for South Africa to enable expansion at the appropriate decision point along the supply-demand curve.

The LHWP demonstrates a high degree of resilience to predicted future climate change scenarios. Over the coming decades, the transfer of water to South Africa will be reliably met unless climate conditions are 5 percent drier than the historical record.

Implementation of Phase 2 of the LHWP increases the potential water available for transfer to South Africa and the reliability of transfers and includes the construction of the Polihali Dam.

In contrast, the ability of the highlands project to deliver supply to South Africa or to produce hydropower is less affected by climate change, especially with the implementation of the Polihali project—there are projected transfer deficits in only 13 percent of future climate projections.

Further development of the water resources in the highlands of Lesotho increases transfers and can support the LLWSS and irrigation development, but it also introduces economic risks. Findings for the Botswana transfer show that targets can be met in all but four of 122 future climate projections.

Effective planning under conditions of future uncertainty requires continued investment to enhance and maintain development capacity. Three major categories: better data, improved capacity within Lesotho, and additional analyses.

Investments in data integrity and enhancements are required to strengthen the underlying assumptions in the analysis and monitor the predicted outcomes. One of the key challenges is working with datasets with obvious integrity issues. The best data were most likely climate-related—precipitation and temperature—but even these data had many gaps. The weakest data are in the agricultural sector. The following data requirements should be given priority:

- Agricultural areas, cropping patterns, yields, and inputs
- Current withdrawals by South Africa from the Caledon River
- Future demand by South Africa caused by climate change
- Value of water inside Lesotho and outside its borders across sectors
- Capital, operation, and maintenance costs of planned infrastructure
- Sedimentation and related processes that contribute to increased sediment loads to rivers

Capacity enhancement is a continuous process that needs dedicated, sustained investment within a strategic framework aligned to national needs. The development and application of the tools used in the analysis (such as R, WEAP, and Tableau) as well as the methods for interpreting climate statistics, understanding effects and vulnerabilities, and robust strategies have been carried out using a highly intensive, participatory process with staff from five key agencies involved in water management and climate monitoring in Lesotho. The agencies included the Office of the Commissioner of Water, the Department of Water Affairs, the Meteorological Service, the Ministry of Agriculture, and the LHDA.

Investments in continued development of the human resources, technological, and resource capacity required to sustain the development and application of these tools is critical to ensure a sustainable, strategically aligned water management system that can provide a basis for the continued socioeconomic development of Lesotho.

Investment in addition analyses will also support effective planning. Further development and adaption of the WEAP model could extend its application to the evaluation of operational strategies for water allocation among competing uses. The WEAP model is currently based on a monthly time step. Although sufficient for the purposes of the analysis, further development of the model to allow for a shorter time step, such as one day, would allow the model to be used to evaluate operational strategies of water allocation among competing uses. This would provide an operational model that can assess implications for water delivery, the timing for domestic and agricultural use, and hydropower generation. Further development of the model would also allow for a more detailed examination of how climate extremes, such as extended drought periods and changes in the intensity and frequency of rainfall, might affect Lesotho.

Application of available analyses to the agricultural sector could assist in setting priorities for instituting adaptation measures that would contribute to food security in Lesotho. A closer examination of the potential effects on agricultural production of changes in climate, such as increasing atmospheric carbon dioxide (CO_2) concentrations, rising temperatures, and water stress, would inform decisions relating to adaptation measures. A better understanding of these dynamics could help develop the agricultural strategy that is best suited for the climatic changes under way, for example, by identifying plants that might be better adapted to warmer conditions and more susceptible to enhanced CO_2 fertilization. Although it is possible that Lesotho could benefit from changes in climate, the capacity of small-scale farmers to take advantage of these opportunities is very limited. Information on their ability to do so could enable a program to incorporate the traits of such plants into desirable crop production cultivars to improve yield.

Further evaluation and extension of the different adaptation measures identified in this study could enhance the robustness of the findings to improve the decision-making process. Additional iterations of the vulnerability and adaptation analysis could be extended to the end of the 21st century and explore individual climate projections with more scientific rigor. Incorporating an economic evaluation into the assessment of climate risks and weighing the tradeoffs would require identification of cost and valuation data to support a cost-benefit analysis across the wide range of climate conditions. These data can be integrated into the current RDM framework to evaluate the economic implications of the various options available to decision makers.

Using a deliberate, inclusive process with Lesotho managers, this project incorporated Lesotho's most pressing needs to demonstrate the vulnerabilities, challenges, and opportunities in the Lesotho water management system. With the new quantification of options for improving system robustness, managers can move forward with plans that are most aptly positioned to support their objectives.

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An initiative of the African, Caribbean and Pacific Group, funded by the European Union and managed by GFDRR

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