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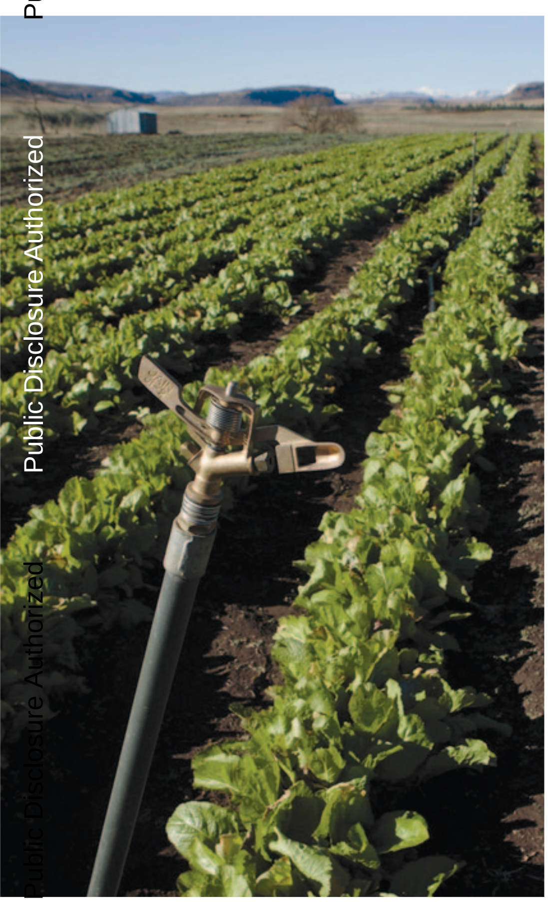
WATER GLOBAL PRACTICE



Lesotho WEAP Manual

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

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Acknowledgements

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 resources modeling and management, and 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). 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. The three 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 Commissioner of Water, the Department of Water Affairs, the Lesotho Meteorological Service, the Crops Department of the Ministry of Agriculture, and the Lesotho Highlands Development Authority.

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

The team also 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).

Abbreviations

DC	deep conductivity
DWC	deep water capacity
FAO	United Nations Food and Agricultural Organization
LHWP	Lesotho Highlands Water Project
MCM	million cubic meters
NSE	Nash-Sutcliffe Efficiency
ORASECOM	Orange-Senqu River Commission
PBIAS	percent bias
PFD	preferred flow direction
RDM	robust decision making
RRF	runoff resistance factor
RSA	Republic of South Africa
RZC	root zone conductivity
SC	sub-catchment
SEI	Stockholm Environment Institute
SWC	soil water capacity
WEAP	Water Evaluation and Planning

Chapter 1

The Water Evaluation and Planning (WEAP) System Basics

WEAP System Capabilities

Water management and allocation models are often used to help water managers make informed decisions. To support the robust decision making (RDM) process in Lesotho, this project used the Water Evaluation and Planning (WEAP) model to examine hydrologic dynamics in the Orange-Senqu river basin. This section describes the WEAP model's broad capabilities and the process for implementing the model in Lesotho.

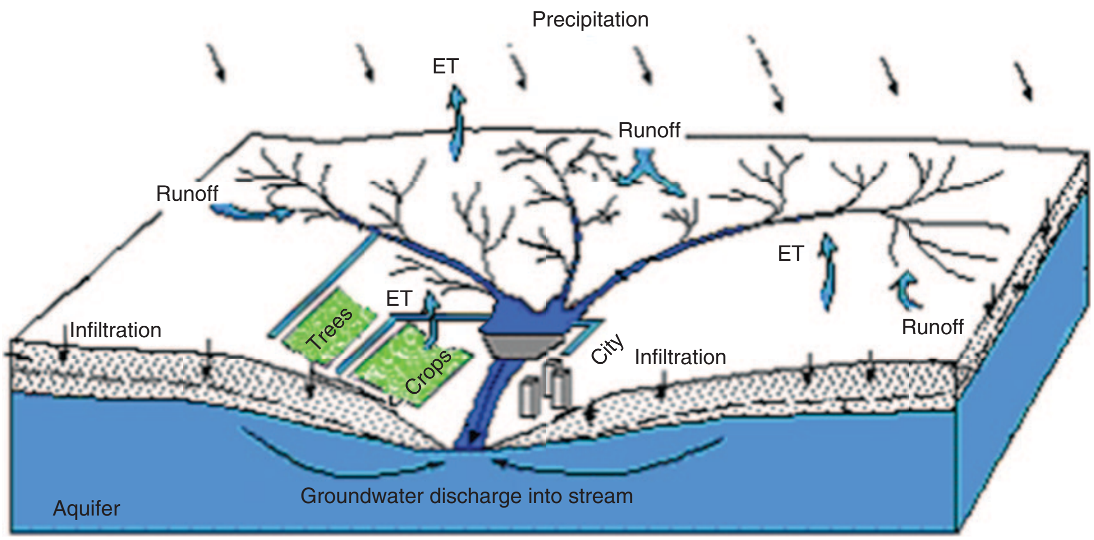
The WEAP system provides an integrated approach to water resources planning by linking hydrologic processes, system operations and end-use within a single analytical platform (Huber-Lee et al. 2003).[1]

The RDM process depends upon stakeholders engaging with the development and analysis of results. In additional to its complex operation capabilities, WEAP provides a comprehensive, flexible and user-friendly tool for water resources planning and policy analysis. As part of the Lesotho Project, team members lead capacity building trainings in WEAP both to provide Lesotho planners with the tool and to include them in the project's processes and results interpretations. WEAP's transparent structure facilitates the engagement of stakeholders in an open process to evaluate water development and management options, and consider the multiple and competing uses of water systems.

To model a water system's operation, WEAP integrates both water demand and supply by placing demand-side issues on an equal footing with supply-side dynamics. Demand estimates emerge from data regarding water use patterns, equipment efficiencies, re-use strategies, costs, and water allocation schemes, among others. WEAP models supply by reproducing both its managed components (streamflow diversions, groundwater pumping, reservoirs, and water transfers) and its natural components (e.g., evapotranspiration demands, runoff, baseflow) and its managed components. WEAP operates on the basic principle of a water balance and can be applied to a single watershed or complex trans-boundary river basin systems.

At the most basic level, WEAP's integrated hydrology/water allocation framework (Yates et al. 2005a, 2005b), recognizes that water supply is defined by the amount of precipitation that falls on a watershed (see figure 1.1). Further, this basic supply is depleted through natural watershed processes, where the watershed itself is the first significant point of depletion through evapotranspiration (Mahmood and Hubbard 2002). The water remaining in excess of evaporative demands throughout the watershed is the supply available to the water management system. Thus, as in the physical realm, there is a seamless link in the WEAP framework between climate, land use/land cover conditions, and the management of the water system (Purkey et al. 2007).

FIGURE 1.1 Conceptualization of Integrated Hydrologic Processes and Water Management Operations in WEAP



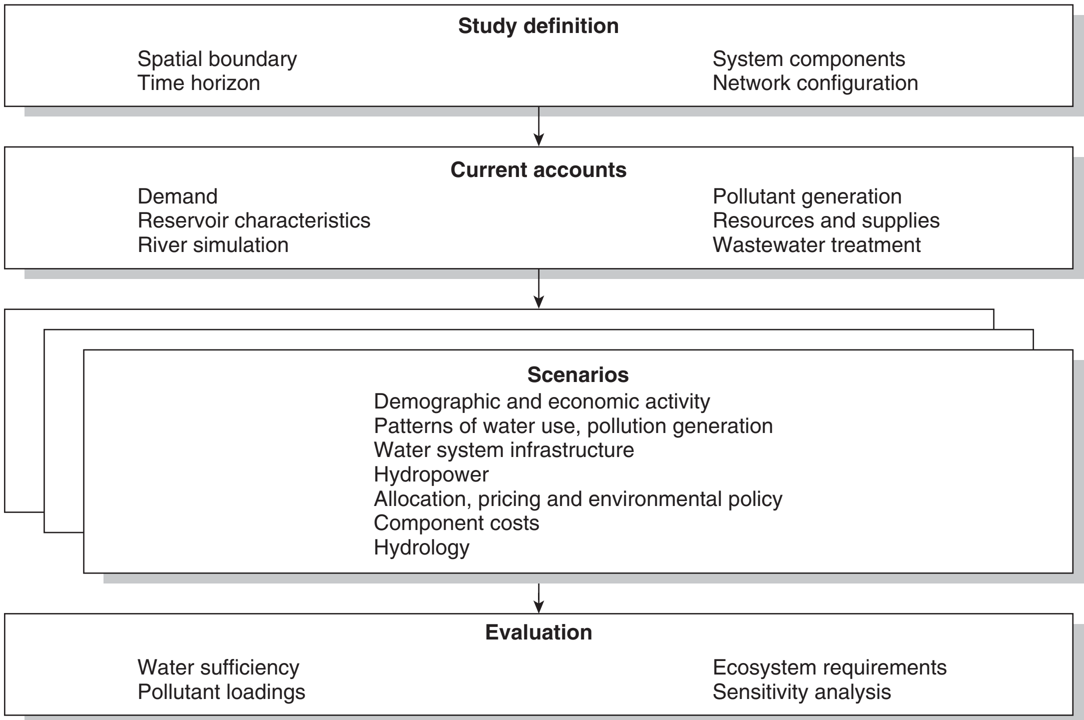
General Modeling Approach

WEAP is an integrated water resources planning tool that is used to represent current water conditions in a given area and to explore a wide range of demand and supply options for balancing environment and development objectives. WEAP is widely used to support 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 is 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. Finally the implications of these various policies can be evaluated with WEAP's graphical display of results.

Steps in Developing a WEAP Model

The development of the WEAP application in this study followed a standard modeling approach (see figure 1.2). The first step in this approach is the study definition, wherein the spatial extent and system components of the area of interest are defined and the time horizon of the analysis is set. Following this initial assessment, the "current accounts" is defined, which is a baseline representation of the system—including the existing operating rules for both supplies and demands. The current accounts serves as the point of departure for scenarios that characterize alternative sets of future assumptions pertaining to policies, costs, and factors that affect demands, pollution loads, and supplies. Finally, the scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets and sensitivity to uncertainty in key variables. The steps in the analytical sequence are described in greater detail in the following sections.

FIGURE 1.2 **Developing a WEAP Application**



Study Definition

Evaluating the implications of managing diversions and impoundments along a river requires the consideration of the entire land area that contributes to the flow within the river—the river basin. Within WEAP, it is necessary to set the spatial scope of the analysis by defining the boundaries of the river basin. Within these boundaries there are smaller rivers and streams (or tributaries) that flow into the main river of interest. Because these tributaries determine the distribution of water throughout the whole basin, it is also necessary to divide the study area into sub-basins such that we can characterize this spatial variability of river flows.

Current Accounts

The current accounts represent the basic definition of the water system as it currently exists. Establishing current accounts requires the user to "calibrate" the system data and assumptions to a point that accurately reflects the observed operation of the system. The current accounts include the specification of supply and demand data (including definitions of reservoirs, pipelines, treatment plants, pollution generation, etc.). This calibration process also includes setting the parameters for WEAP's rainfall-runoff module such that WEAP can use climatic data (i.e., temperature and precipitation) to estimate water supply (i.e., river flows, aquifer recharge) and demand (evaporative water demand) in the delineated basins.

Scenarios

At the heart of WEAP is the concept of scenario analysis. Scenarios are self-consistent story-lines of how a future system might evolve over time. The scenarios can address a broad range of "what if" questions. This allows users to identify unintended changes in the system and evaluate how these changes may be mitigated by policy and/or technical interventions. The result of these analyses guide the development of response packages, which are combinations of management and/or infrastructural changes that enhance the productivity of the system.

Evaluation

Once the performance of a set of response packages has been simulated within the context of future scenarios, the packages can be compared relative to key metrics identified by stakeholders in the XLRM activity of the RDM process. Often these relate to water supply reliability, water allocation equity, ecosystem sustainability, and cost, but any number of performance metrics and be defined and quantified within WEAP.

WEAP Calculations

At each time step, WEAP first computes the hydrologic flux, which it passes to each river. The water allocation is then made for the given time step, where constraints related to the characteristics of reservoirs and the distribution network, environmental regulations, and the priorities and preferences assigned to points of demands are used to condition a linear programming optimization routine that maximizes the demand "satisfaction" to the greatest extent possible (see Yates et al. 2005a for details). All flows are assumed to occur instantaneously; thus a demand site can withdraw water from the river, consume some, and optionally return the remainder to a receiving water body in the same time step. As constrained by the network topology, the model can also allocate water to meet any specific demand in the system, without regard to travel time. Thus, the model time step should be at least as long as the residence time of the study area. For this reason, the Lesotho project adopted a monthly time step for our study.

Rainfall-Runoff (aka Streamflow Generation)

WEAP offers three methods to simulate watershed hydrological processes such as evapotranspiration, runoff, and infiltration. These methods are (1) the Rainfall Runoff and (2) the Simplified Coefficient Approach, and (3) the Soil Moisture Method. This study used WEAP's Soil Moisture Method to estimate the rainfall-runoff processes at the sub-basin level throughout Lesotho.

The Soil Moisture module in WEAP is spatially continuous, with a study area configured as a contiguous set of sub-catchments that cover the entire extent of the river basin under examination. This continuous representation of the river basin is overlaid with a water management network topology of rivers, canals, reservoirs, demand centers, aquifers and other features (see Yates et al. 2005a, 2005b for details). Each sub-catchment (SC) is fractionally subdivided into a unique set of independent land use/land cover classes that lack detail regarding their exact location within the SC, but which sum to 100% of the SC's area. A unique climate-forcing data set of precipitation, temperature, relative humidity, and wind speed is uniformly prescribed across each SC.

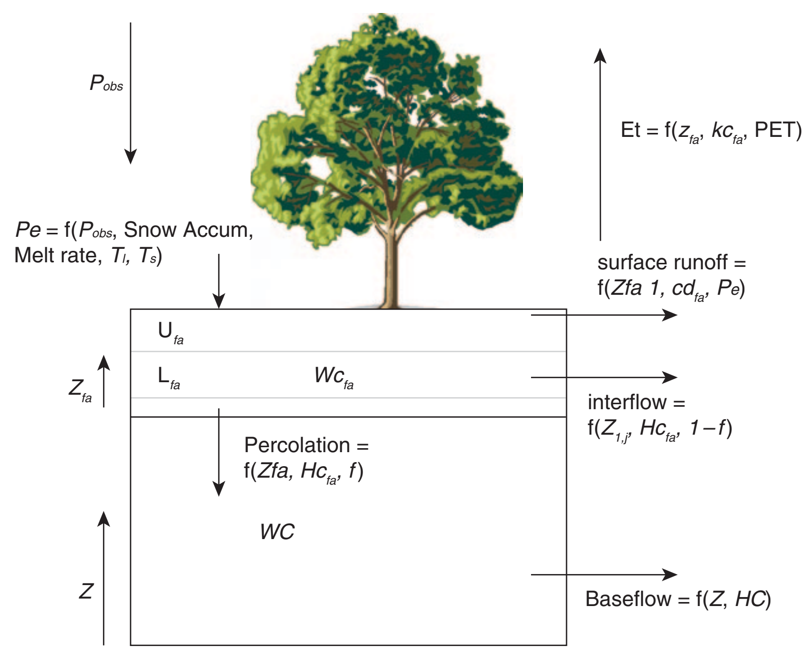
A one-dimensional, quasi-physical water balance model depicts the hydrologic response of each fractional area within a SC and partitions water into surface runoff, infiltration, evapotranspiration, interflow, percolation, and baseflow components (see equation 1.1 and figure 1.3). Values from each fractional area within the SC are then summed to represent the lumped hydrologic response, with the surface runoff, interflow and baseflow being linked to a river element and evapotranspiration being lost from the system.

Equation 1.1 Soil Moisture Model

$$Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{RRF\,j} - f_j k_{z,j} z_{1,j}^2 - (1 - f_j)k_{z,j} z_{1,j}^2$$

WEAP offers a default method for calculating the potential evapotranspiration that uses a modified Penman-Montieth equation or an alternate method that allows the user to define his/her own equation(s). Because the Penman-Montieth relies on variables that were not easily obtained for the suite of climate futures used in our analysis (i.e., wind speed and relative humidity), we chose to use a modified Hargreaves equation developed by Droogers and Allen (2002) that required only estimates of temperature and precipitation.

FIGURE 1.3 Diagram of the Two-Bucket WEAP Hydrology Model



Source: Yates et al. 2005a.

Water Allocation

Two user-defined priority systems are implemented to determine allocations of water supplies to demands (i.e., urban and agricultural), for instream flow requirements, and for filling reservoirs—demand priorities and supply preferences.

Demand priorities allocate water among competing demand sites and catchments, flow requirements, and reservoir storages. The demand priority is specified for every demand site, catchment, reservoir, or flow requirement. Priority numbers in WEAP range from 1 to 99, with 1 being the highest priority and 99 the lowest. Many demand sites can share the same priority, which is useful in representing a system of water rights, where water users are defined by their water usage and/or seniority. In cases of water shortage, higher priority users are satisfied as fully as possible before lower priority users are considered. If priorities are the same, shortage will be shared equally (as a percentage of their demands).

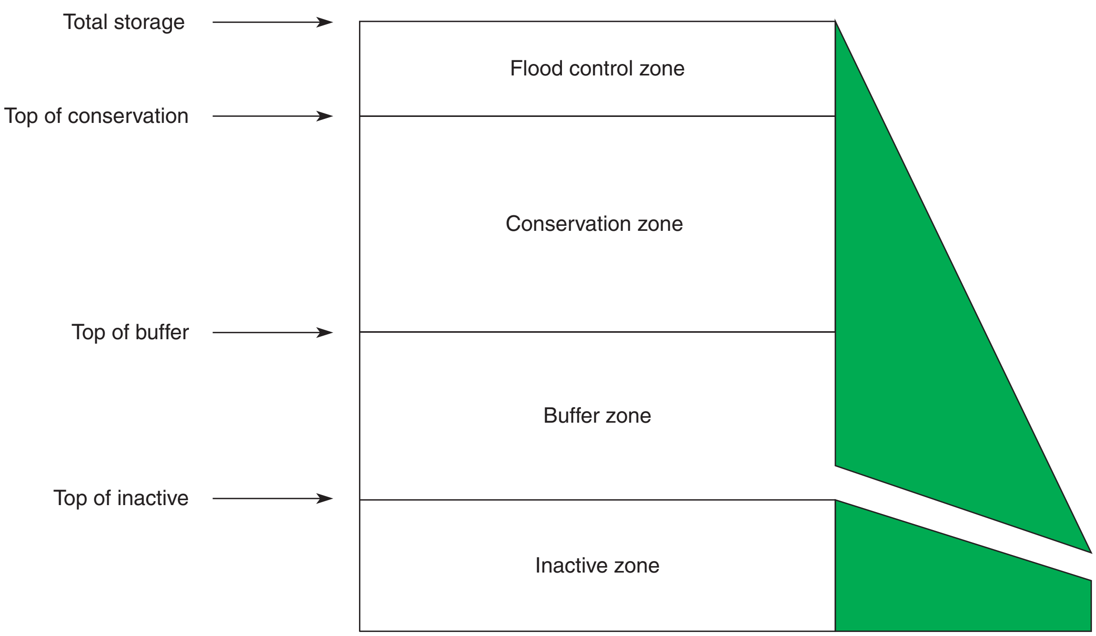
When demands sites or catchments are connected to more than one supply source, the order of withdrawal is determined by supply preferences. Similar to demand priorities, supply preferences are assigned a value between 1 and 99, with lower numbers indicating preferred water sources. The assignment of these preferences usually reflects some economic, environmental, historic, legal and/or political realities. In general, multiple water sources are present when the preferred water source is insufficient to satisfy all of an area's water demands. WEAP treats the additional sources as supplemental supplies and will draw from these sources only after it encounters a capacity constraint (expressed as either a maximum flow volume or a maximum percent of the demand) associated with the preferred water source.

WEAP's allocation routine uses demand priorities and supply preferences to balance water supplies and demands. To do this, WEAP must assess the available water supplies at any given time step. While total supplies may be sufficient to meet all of the demands within the system, it is often the case that operational considerations prevent the release of water to do so. These regulations are usually intended to hold water back in times of shortage so that delivery reliability is maximized for the highest priority water users (often urban indoor demands). WEAP can represent this controlled release of stored water using its built-in reservoir object.

WEAP uses generic reservoir objects that divide storage into four zones, or pools (figure 1.4). These include, from top to bottom, the flood-control zone, conservation zone, buffer zone and inactive zone. The conservation and buffer pools together constitute the reservoir's active storage. WEAP will ensure that the flood-control zone is always vacant—i.e., the volume of water in the reservoir cannot exceed the top of the conservation pool. The size of each of these pools can change throughout the year according to regulatory guidelines, such as flood control rule curves.

WEAP allows the reservoir to freely release water from the conservation pool to fully meet withdrawal and other downstream requirements. Once the storage level drops into the buffer pool, the release will be restricted according to the buffer coefficient, to conserve the reservoir's dwindling supplies. The buffer coefficient is the fraction of the water in the buffer zone available each month for release. Thus, a coefficient close to 1.0 will cause demands to be met more fully while rapidly emptying the buffer zone, while a coefficient close to 0 will leave

FIGURE 1.4 Reservoir Zones



demands unmet while preserving the storage in the buffer zone. Water in the inactive pool is not available for allocation, although under extreme conditions evaporation may draw the reservoir into the inactive pool.

Note

1. WEAP has been developed for the past 20 years by the Stockholm Environment Institute, (SEI) working in partnership with a number of agencies and organizations. WEAP is used by a large community of researchers, government officials, professionals, students and non-government organizations. They share their WEAP experiences in a User Forum (www.weap21.org).

Chapter 2

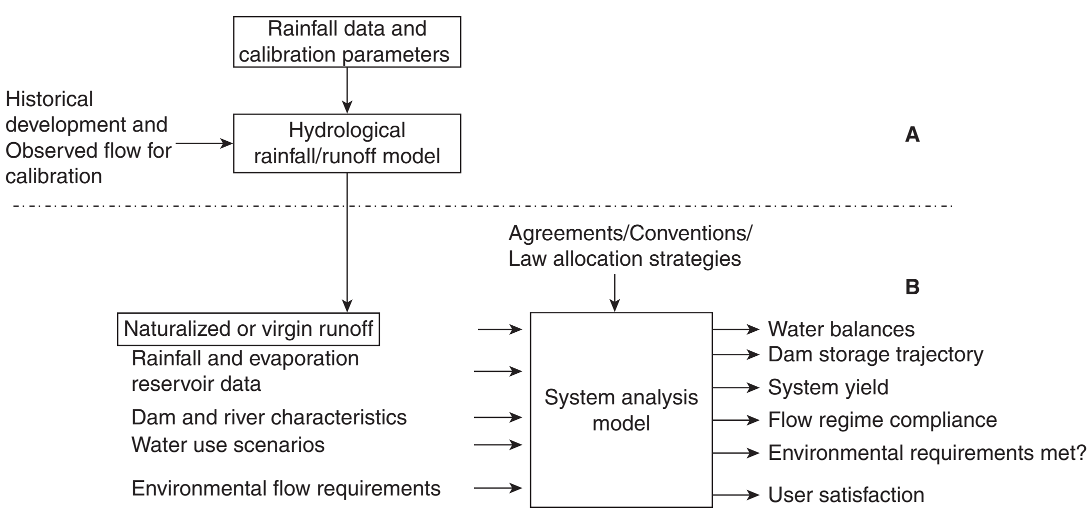
Lesotho Application of WEAP

This project developed a WEAP model to represent the main water supply and demand features for the Kingdom of Lesotho. The model was developed at a spatial scale appropriate to simulate major hydrologic flows; to represent major demographic trends; and to evaluate the effects of water management responses. Monthly observations between 1950 and 2005 were used to calibrate WEAP (See Annex A) to enable it to consider future climate and water management scenarios from 2010 to 2050.

The model is designed to evaluate the performance of water supply reliability for different water use sectors across a range of future climate conditions. These water use sectors include domestic and industrial water users, rainfed and irrigated agriculture, hydropower, instream flow requirements and water transfers to South Africa. For purposes of water allocation, the model assigns transfers to South Africa the highest priority. After that, the domestic water users have the highest priority for water deliveries; industrial water users the second highest priority; irrigation the third highest priority; instream flow requirements the fourth highest priority; and surface water storage behind dams holds the lowest priority for water. In the model, the current water supply system disconnects the demands in the Lesotho lowlands from the water supply system of the Lesotho Highlands Water Project (LHWP). Thus, under current operations, the deliveries to South Africa from the LHWP and the associated hydropower production are independent of water allocation in the lowlands.

The Lesotho WEAP model was developed using a two-step process (outlined in figure 2.1). The first step of this process focused on developing the rainfall/runoff routines and calibrating

FIGURE 2.1 Two-Step Process for Developing Lesotho WEAP Model



Source: Juizo and Linden 2010.

these to observed historical streamflow timeseries. The second step focused on adding representations of the existing and planned water management infrastructure to the model. These steps are explained further in the following two sub-sections.

Hydrology of Lesotho

In general, we used quaternary catchments from the South African Department of Water and Sanitation[1] as the basic unit used to define the spatial resolution of the hydrologic simulation. These catchments were often combined to form larger areas in cases where multiple catchments lay upstream of control points. For example, we combined quaternary catchments D11A through D11F, because they all lie upstream of Katse dam, which is the first control point that this study considered on the Malibamatso River (figure 2.2). This approach resulted in 34 catchments used in the WEAP model to represent hydrological processes within Lesotho. An additional 12 catchments were used to represent the hydrology of areas within South Africa that discharge into the Caledon River.

Each of the catchments shown in figure 2.2 contain climate data that are used as drivers for the routines that estimate the hydrological response (i.e., rainfall-runoff and baseflow) and the potential evapotranspiration for rainfed and irrigated agriculture. These data

FIGURE 2.2 WEAP Schematic Showing Catchment Objects Used to Simulate Basin Hydrologic Processes

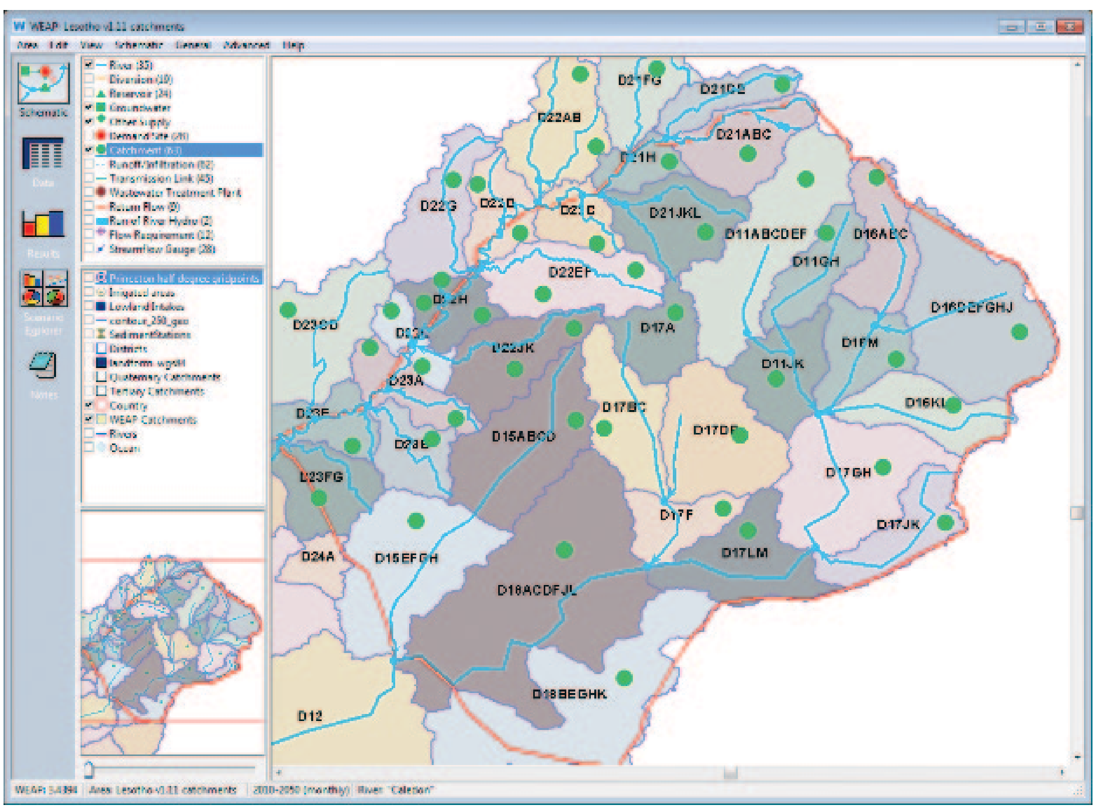
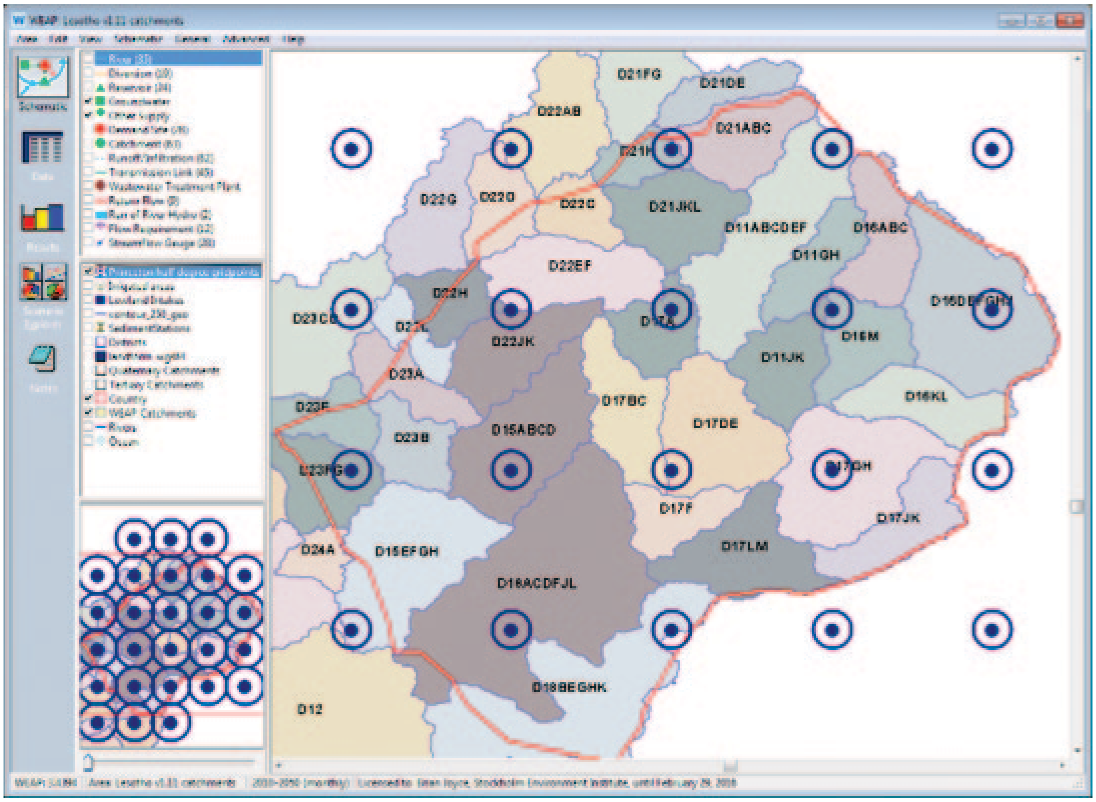


FIGURE 2.3 Climate Grid Points Used to Construct Climate Time Series for WEAP Model



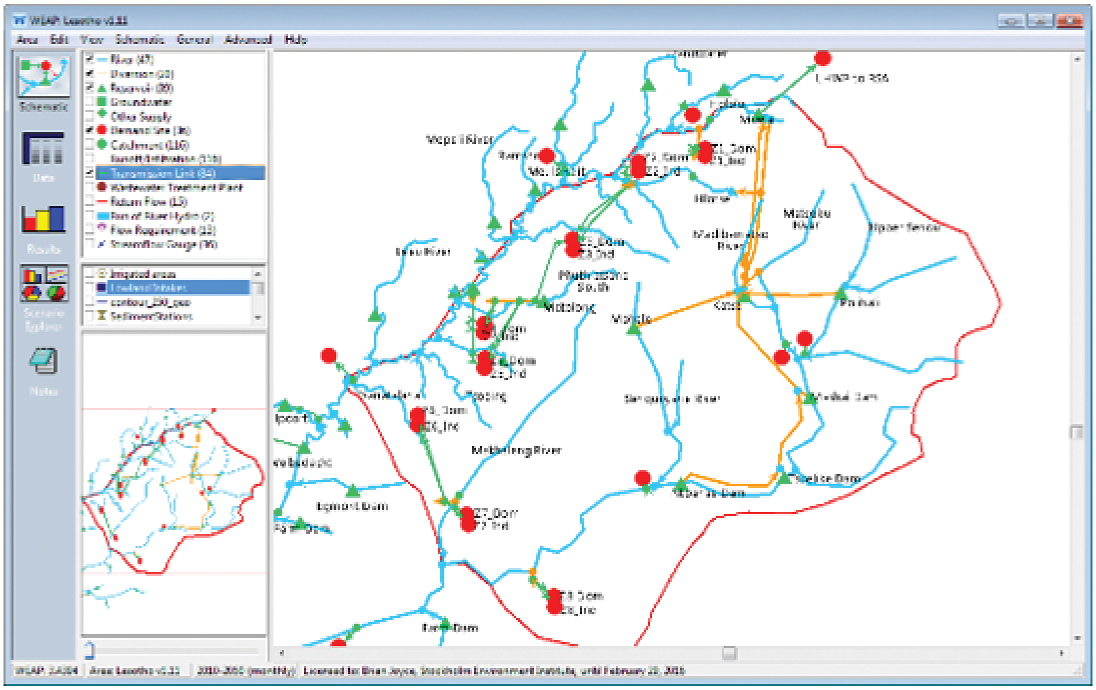
include time series of historical and projected monthly precipitation (mm), average temperature (deg C), minimum temperature (deg C), and maximum temperature (deg C). To construct these timeseries, we used historical climate data from 1948 to 2008, developed by the Terrestrial Hydrology Research Group at Princeton University (Sheffield et al. 2006). These data include climate sequences of monthly temperature and precipitation, spatially averaged for each hydrologically connected catchment. This dataset was developed at the 0.5 degree scale, resulting in 20 grid cells that overlay the Kingdom of Lesotho (figure 2.3). To calculate climate inputs for each catchment, we used weighted averages based on percentage of catchment polygons within each climate grid cells. This involved using GIS to intersect the grid cells with the catchment polygons.

Key Water Management Features of Lesotho

The model includes representations of the major water use sectors within Lesotho and the existing and planned infrastructure that serves them. The linkage of these supplies and demands is show in figure 2.4.

Inter-basin water transfers to the Republic of South Africa (RSA), shown in orange in figure 2.4, represent the largest single water use within the basin and are served by the LHWP. In fact, the main purpose of the LHWP is to provide water supply to South Africa and to generate

FIGURE 2.4 **WEAP Schematic Showing the Linkage of Water Supplies (Blue Lines) and Demands (Red Circles)**



hydropower for Lesotho. According to the treaty between Lesotho and South Africa, water transfers to South Africa from the LHWP increase with subsequent phases of the project. Currently, the project supplies 27.5 m^3s^{-1} (867 MCM/year) to South Africa and is expected to supply 40 m^3s^{-1} (1,261 MCM/year) once Phase 2 is fully operational. Transfers are expected to be capped at 70 m^3s^{-1} (2,207 MCM/year) once the project is fully developed. The project was originally envisioned in four phases that are described in the left of map 2.1 and shown in red in the map.

The first phase of the project (including Phase Ia and Ib) has been completed and includes Katse and Mohale dams as well as diversion structures to divert water into Katse from the Matsoku River and Mohale dam and a transfer tunnel to send water from Katse dam to Muela dam and subsequently South Africa. Phase II of the project, which is now under implementation, has been reconfigured to include a dam, Polihali, which was not part of the original design. It is expected to be complete by 2020. Further phases of the project face greater uncertainty and presently there are no reliable estimates for completion dates. For the purposes of the current study, we consider that the next phases will include the three dams planned for the main stem of the Senqu River downstream of the current facilities and they will be commissioned at regular intervals after the completion of Phase II. These are summarized in table 2.1.

For the purposes of this project, we assumed that these “transfer targets” to South Africa would be adjusted following the construction of each new facility and that they would increase over a five year period during the filling period of the new facility. Figure 2.5 shows the demand curve for South Africa water transfer targets.

MAP 2.1 Lesotho Highland Water Project

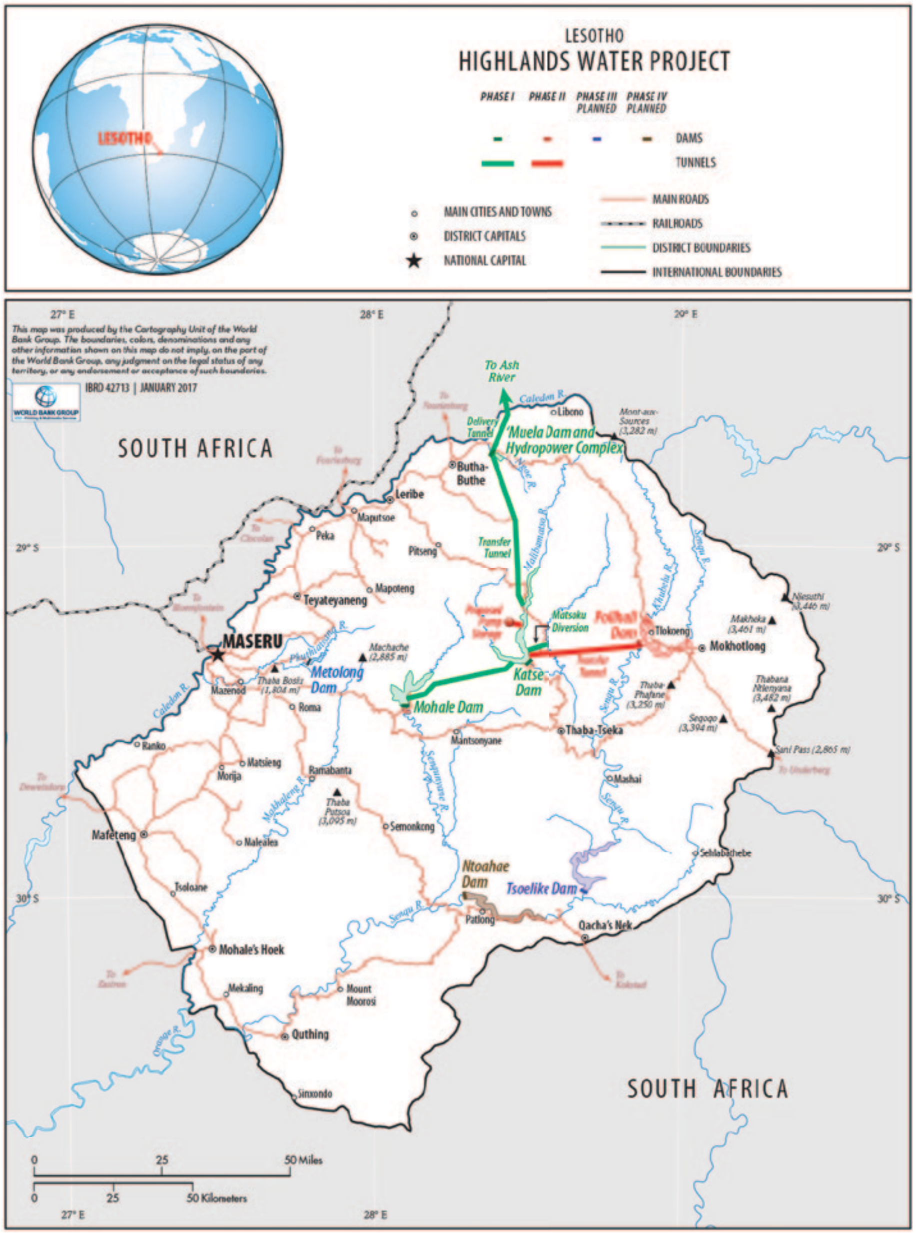
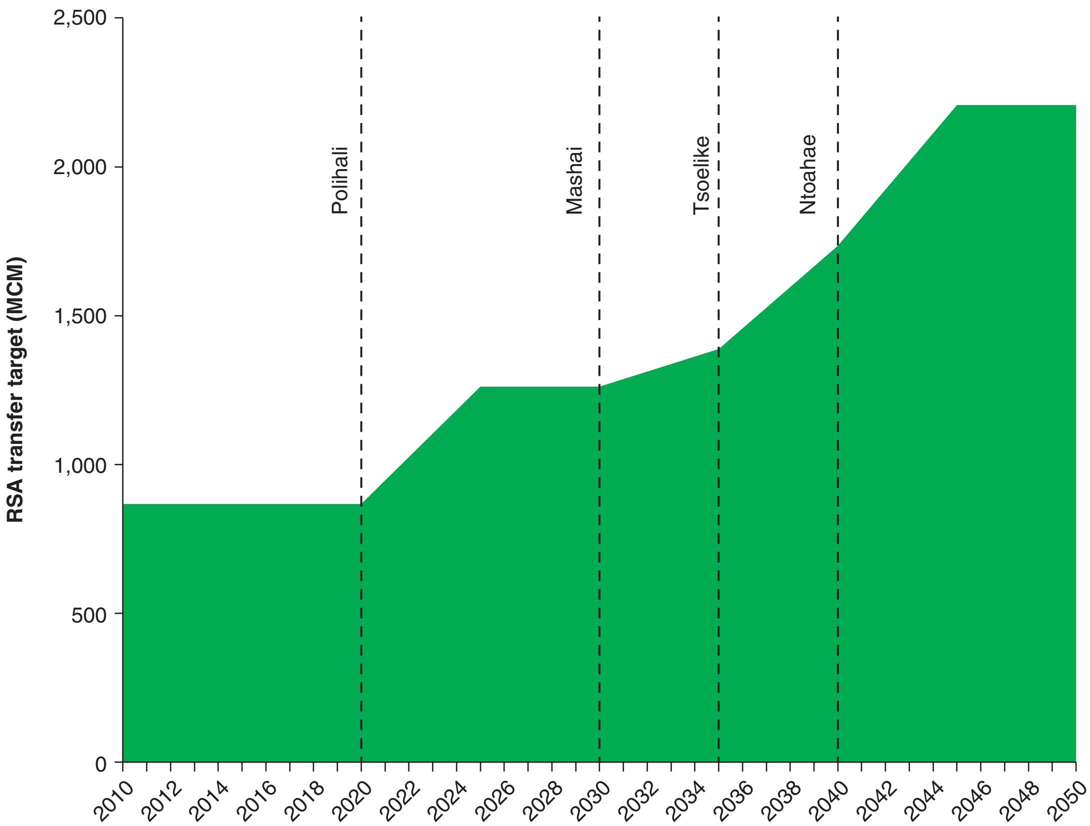


TABLE 2.1 Dams Included in WEAP Model as Part of Lesotho Highlands Water Project

Dam	Start year	Storage capacity (MCM)	Inactive storage (MCM)	Instream flow requirement (MCM/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

FIGURE 2.5 LHWP Water Transfer Targets to South Africa



Largely disconnected from the LHWP, most of the water usage within Lesotho is in the lowlands and is served by local surface water supply sources. Currently, there is another large water project in Lesotho—the Lesotho Lowlands Water Supply Scheme—that aims to enhance water supply reliability for the domestic, industrial, and agricultural water needs of the lowland districts. To define the location and pattern of water demands in the lowlands, we used data from the feasibility report for this project (2004), which organized demands in the lowlands into eight zones.

Figure 2.6 shows the configuration of the lowlands water demands within the WEAP schematic. Essentially, each zone consists of a pair of demand nodes (red circles)—domestic and industrial, which allows for WEAP to assign a higher priority to domestic users than to industrial/institutional users in each zone. Transmission links (green lines) connect demands to various water sources.

The Lowlands Water Supply Scheme feasibility study identified eight zones and five intakes from which water will be abstracted. These are summarized in table 2.2 and shown graphically in map 2.2. These abstraction points correspond to the diversion locations shown in figure 2.6.

TABLE 2.2 Location of Intakes for Lowland Demands

Zone	Service area	Water source	Coordinates (proposed intake)
1	Botha Bothe	Hololo river	Lat: 28°41’44.6”S Lon: 28°21’47.2”E
2&3	Maputsoe/Leribe	Hlotse river	Lat: 28°54’49.06”S Lon: 28°6’54.49”E
4&5	Maseru, TY, Morija	Metolong Dam	Lat: 29°21’10.81”S Lon: 27°44’20.24”E
6&7	Mafeteng, Mohale’sHoek	Makhaleng	Lat: 30°5’9.70”S Lon: 27°26’15.36”E
8	Quthing	Senqu	Lat: 30°21’59.21”S Lon: 27°43’14.84”E

MAP 2.2 Location of Intakes for Lowland Demands

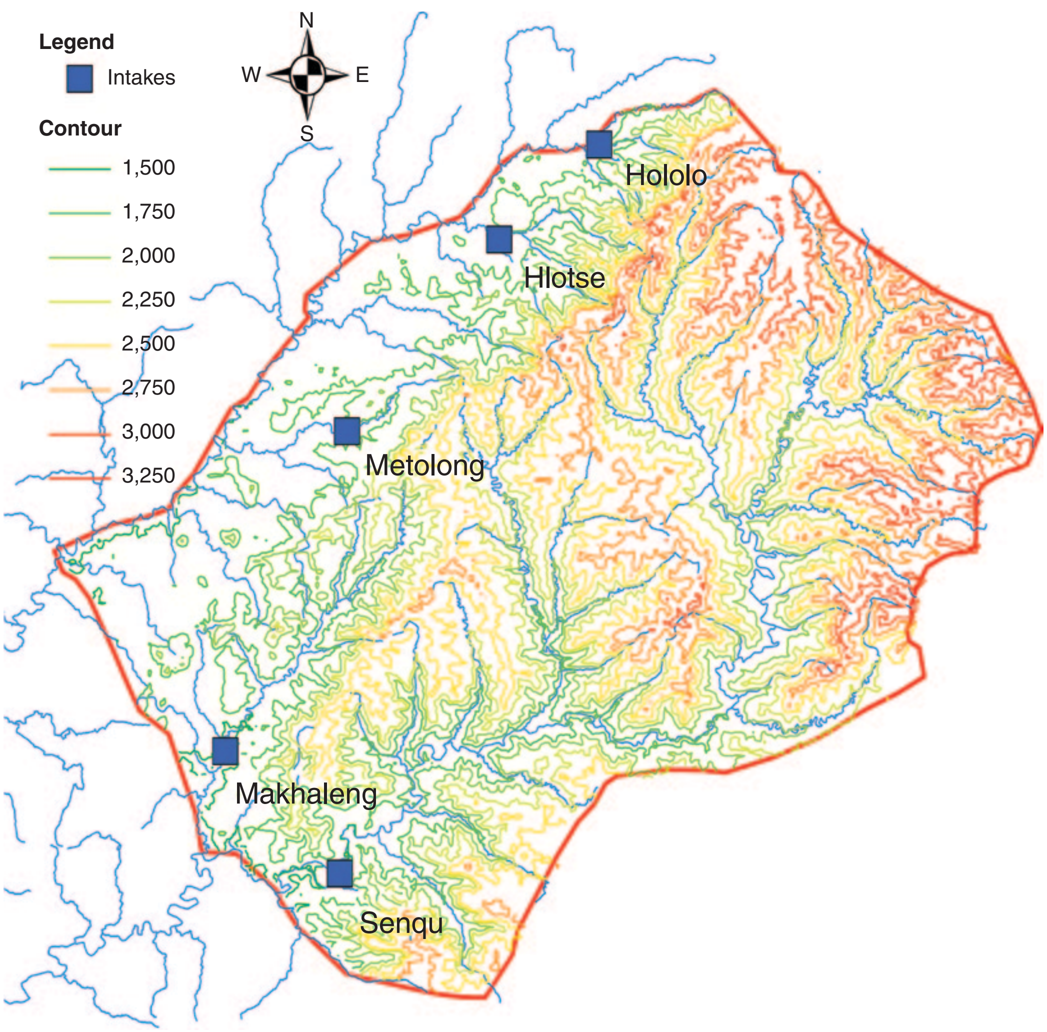
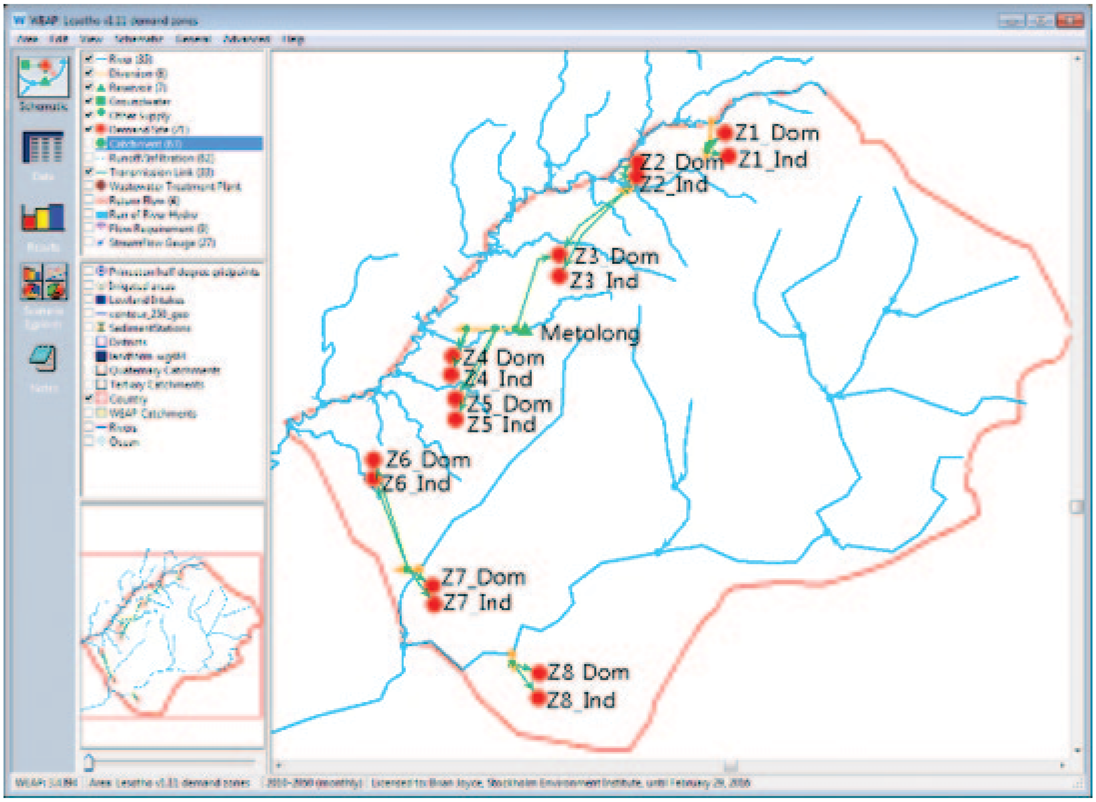


FIGURE 2.6 **WEAP Schematic Showing Configuration of Lowland Demand**



Building the Model for the Orange-Senqu River

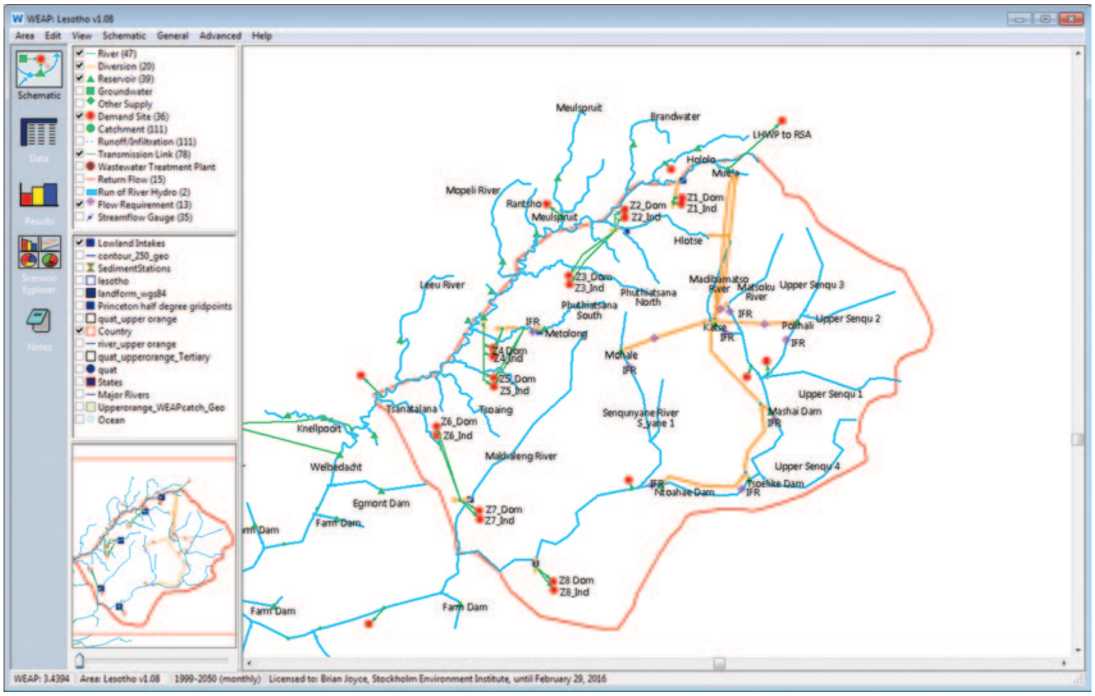
The WEAP model used in this study is a modified version of a tool developed for a previous World Bank project that examined the resilience of infrastructure throughout Africa in the face of climate change (Cervigni et al. 2015). A complete description of the development of this model, including descriptions of the spatial disaggregation of the basin and the main water management features, can be found in a forthcoming World Bank Report: Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors. This Annex provides a description of the enhancements made to the WEAP model under the current project to better represent water management in the Kingdom of Lesotho.

Lowland Demands

As part of the feasibility study of the Lesotho lowlands water supply scheme (2004), water demands were estimated for eight demand zones out to the year 2035. The location of these zones is shown in figure 2.7. The data are summarized in tables 2.3 and 2.4.

These data were reformatted to provide input to the WEAP model for Lesotho. Specifically, we calculated per capita water use by dividing the total domestic water demand by the population. Per capita waster use is then combined with population in WEAP to estimate total

FIGURE 2.7 WEAP Schematic Showing Configuration of Lowland Demands



domestic demands. This formulation was used so that we can explore different scenarios that adjust population and per capita water usage independently. Additionally, we applied a population growth rate of 1.5 percent after the year 2035, which generally continues the trend in the data between 2005 and 2035.

Industrial demands were estimated by taking the sum of industrial and institutional demands from table 2.3. Percent losses were estimated by dividing the total losses by the sum of domestic, industrial, and institutional demand. This resulted in a consistent estimate of 25 percent loss.

Metolong Dam Project

Metolong dam is represented in the WEAP model as a reservoir on the Phuthiatsana South River. It receives inflow from a catchment that is 348 km^2 large. The dam was commissioned in 2015 and came online in 2016. It has a storage capacity of 36.5 MCM (i.e., storage at 1,671 m elevation) and a dead (or inactive) storage level of 7.275 MC (i.e., storage at 1,635 m elevation). Its volume-to-elevation relationship is presented in figure 2.9. It is configured in the WEAP model to supply water to zones 4 and 5 (see figure 2.8). It is configured in the WEAP model to supply water to zones 4 and 5. In WEAP, the priority to store water in Metolong dam (priority 13) is set up such that it releases water only to meet domestic (priority 3) and industrial (priority 4) demands in zones 3, 4, and 5 and instream flow requirements (priority 5) on the Phuthitsana South river below the reservoir.

TABLE 2.3 Demand Projections for Domestic, Industrial, and Institutional Consumers 2005–35

Year	2005	2010	2020	2035	2005	2010	2020	2035	2005	2010	2020	2035
	Zone 1—Butha-Buthe				Zone 2,3—Hlotse, Maputsoe				Zone 3—Teyateyaneng			
Total population	86,765	92,776	106,831	130,440	141,410	157,196	193,251	264,891	85,319	89,107	95,357	106,534
Domestic (m³/day)	4,586	5,052	6,154	8,007	8,061	9,264	12,032	17,553	4,402	4,662	5,081	5,822
Industrial (m³/day)	5,000	9,000	20,160	20,160	4,200	6,970	8,710	8,710	100	1,380	2,100	2,100
Institutions (m³/day)	259	299	394	554	675	760	948	1,309	593	631	696	810
Losses (m³/day)	2,392	3,519	6,608	7,111	3,172	4,186	5,360	6,831	1,253	1,648	1,948	2,162
Total demand (m³/day)	**12,237**	**17,870**	**33,316**	**35,833**	**16,108**	**21,180**	**27,050**	**34,403**	**6,349**	**8,321**	**9,825**	**10,895**
	Zone 4—Maseru				Zone 5—Morija, Matsieng				Zone 6—Mafeteng			
Total population	396,469	465,202	613,678	929,709	72,570	73,383	75,659	81,217	65,904	71,729	82,820	104,853
Domestic (m³/day)	32,442	39,230	53,875	85,057	2,737	2,775	2,881	3,134	3,906	4,364	5,240	6,983
Industrial (m³/day)	20,405	24,330	31,530	31,530	0	0	0	0	5,000	5,220	5,220	5,220
Institutions (m³/day)	5,566	6,652	8,990	13,917	152	159	177	215	243	280	352	495
Losses (m³/day)	14,452	17,401	23,447	32,475	674	685	716	789	2,246	2,425	2,662	3,133
Total demand (m³/day)	**72,865**	**87,613**	**117,842**	**162,979**	**3,564**	**3,620**	**3,774**	**4,138**	**11,395**	**12,290**	**13,473**	**15,832**
	Zone 7—Mohale'sHoek				Zone 8—Quthing				Total all zones			
Total population	40,514	44,539	52,216	67,486	41,047	42,079	44,253	48,542	929,998	1,036,013	1,264,065	1,733,673
Domestic (m³/day)	2,491	2,808	3,414	4,623	1,804	1,857	1,973	2,208	60,429	70,013	90,648	133,387
Industrial (m³/day)	2,000	11,860	31,000	31,000	0	0	0	0	36,705	58,760	98,720	98,720
Institutions (m³/day)	296	341	429	603	234	244	271	329	8,019	9,367	12,265	18,233
Losses (m³/day)	1,176	3,732	8,690	9,036	496	512	547	621	25,861	34,108	49,979	62,158
Total demand (m³/day)	**5,963**	**18,741**	**43,532**	**45,261**	**2,534**	**2,613**	**2,792**	**3,158**	**131,015**	**172,248**	**251,604**	**312,498**

TABLE 2.4 WEAP Inputs for Domestic and Industrial Water Demands

Year		2005	2010	2020	2035	2005	2010	2020	2035	2005	2010	2020	2035
		Zone 1—Butha-Buthe				Zone 2,3—Hlotse, Maputsoe				Zone 3—Teyateyaneng			
Domestic	Total population	86,765	92,776	106,831	130,440	141,410	157,196	193,251	264,891	85,319	89,107	95,357	106,534
	Water use rate (m^3/hd/yr)	19.29	19.88	21.03	22.41	20.81	21.51	22.73	24.19	18.83	19.10	19.45	19.95
Industrial	Total demand (Mm^3/yr)	1.920	3.394	7.502	7.561	1.779	2.821	3.525	3.657	0.253	0.734	1.021	1.062
Losses	Loss rate (percent)	24	25	25	25	25	25	25	25	25	25	25	25
		Zone 4—Maseru				Zone 5—Morija, Matsieng				Zone 6—Mafeteng			
Domestic	Total population	396,469	465,202	613,678	929,709	72,570	73,383	75,659	81,217	65,904	71,729	82,820	104,853
	Water use rate (m^3/hd/yr)	29.87	30.78	32.04	33.39	13.77	13.80	13.90	14.08	21.63	22.21	23.09	24.31
Industrial	Total demand (Mm^3/yr)	9.479	11.308	14.790	16.588	0.055	0.058	0.065	0.078	1.914	2.008	2.034	2.086
Losses	Loss rate (percent)	25	25	25	25	23	23	23	24	25	25	25	25
		Zone 7—Mohale'sHoek				Zone 8—Quthing				Total all zones			
Domestic	Total population	40,514	44,539	52,216	67,486	41,047	42,079	44,253	48,542	929,998	1,036,013	1,264,065	1,733,673
	Water use rate (m^3/hd/yr)	22.44	23.01	23.86	25.00	16.04	16.11	16.27	16.60	23.72	24.67	26.17	28.08
Industrial	Total demand (Mm^3/yr)	0.838	4.453	11.472	11.535	0.085	0.089	0.099	0.120	16.324	24.866	40.510	42.688
Losses	Loss rate (percent)	25	25	25	25	24	24	24	24	25	25	25	25

FIGURE 2.8 **WEAP Schematic Showing the Configuration of Metolong Dam**

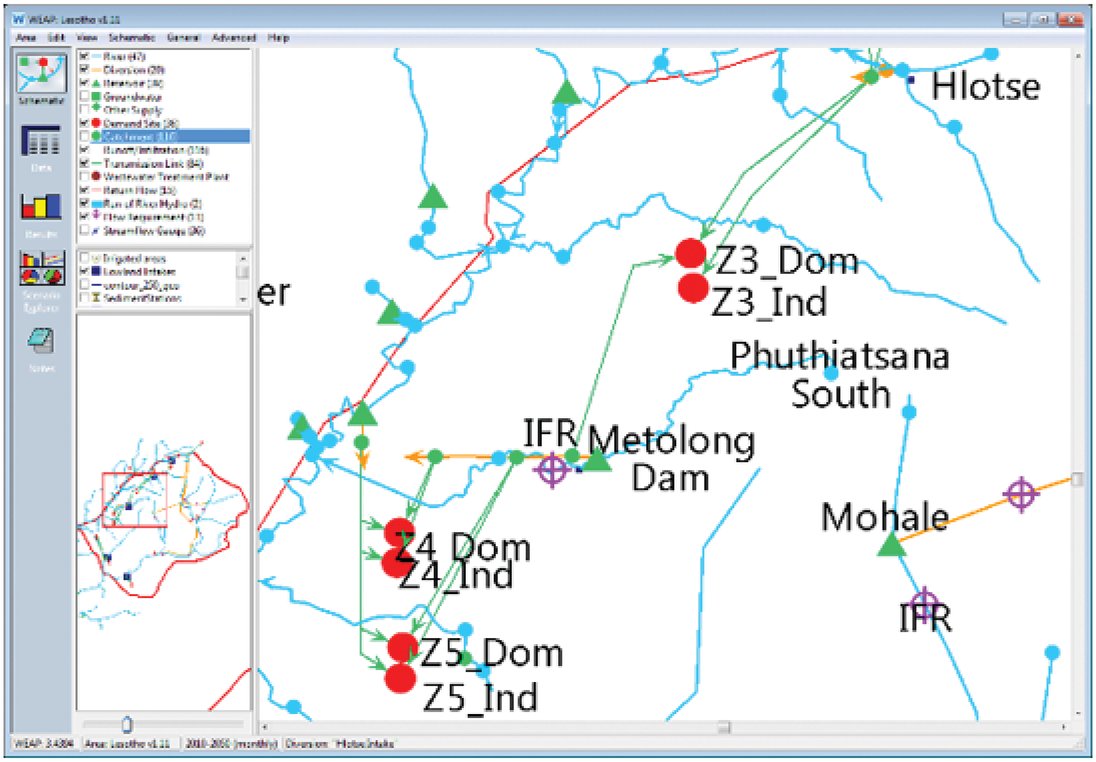
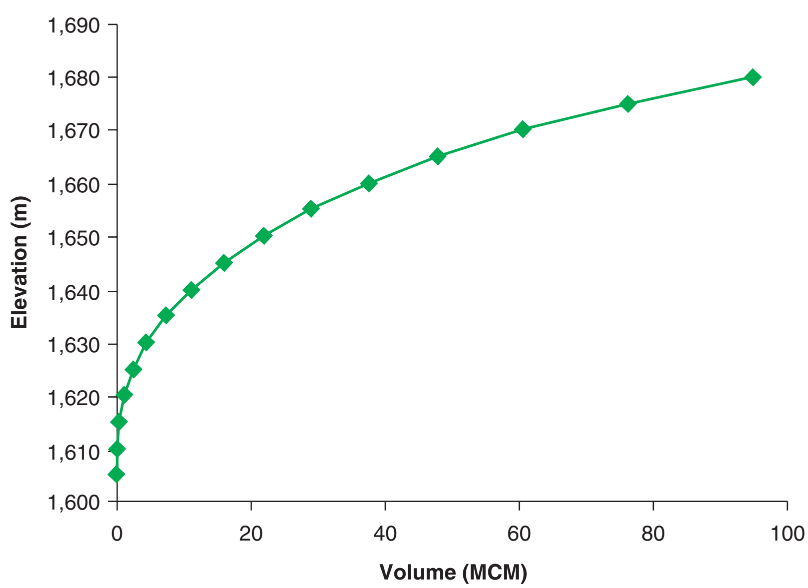


FIGURE 2.9 **Metolong Dam Volume-Elevation Relationship (Metolong Authority 2015)**

Volume (MCM)	Elevation (m)
0	1605
0.049889	1610
0.371365	1615
1.063319	1620
2.327759	1625
4.324348	1630
7.275344	1635
11.16614	1640
15.99169	1645
21.82331	1650
28.86547	1655
37.43851	1660
47.87276	1665
60.61116	1670
76.20036	1675
94.75504	1680



Metolong Instream Flow Requirement

An instream flow requirement exists below Metolong dam that is designed to provide low-flows and floods as specified in tables 2.5 and 2.6.

Irrigated Agriculture

Unfortunately, little data exist to describe the farming practices within existing irrigation schemes. It is known that farmers generally use sprinklers as a means of irrigation. However, no data were available to identify what crops are grown. Fortunately, ORASECOM maintains a water information system for the Orange-Senqu basin[2] that contains some general information on irrigated crops within twelve agro-economic regions throughout the basin (ORASECOM 2013). A screen capture of the tool is shown in figure 2.10.

The United Nations Food and Agricultural Organization (FAO) publishes information on many crop types that describe their crop water requirements, yield response to water, and crop water productivity information.[3] We used these data to describe the maximum potential yield and yield factors for each irrigated crop type. These are summarized in table 2.7.

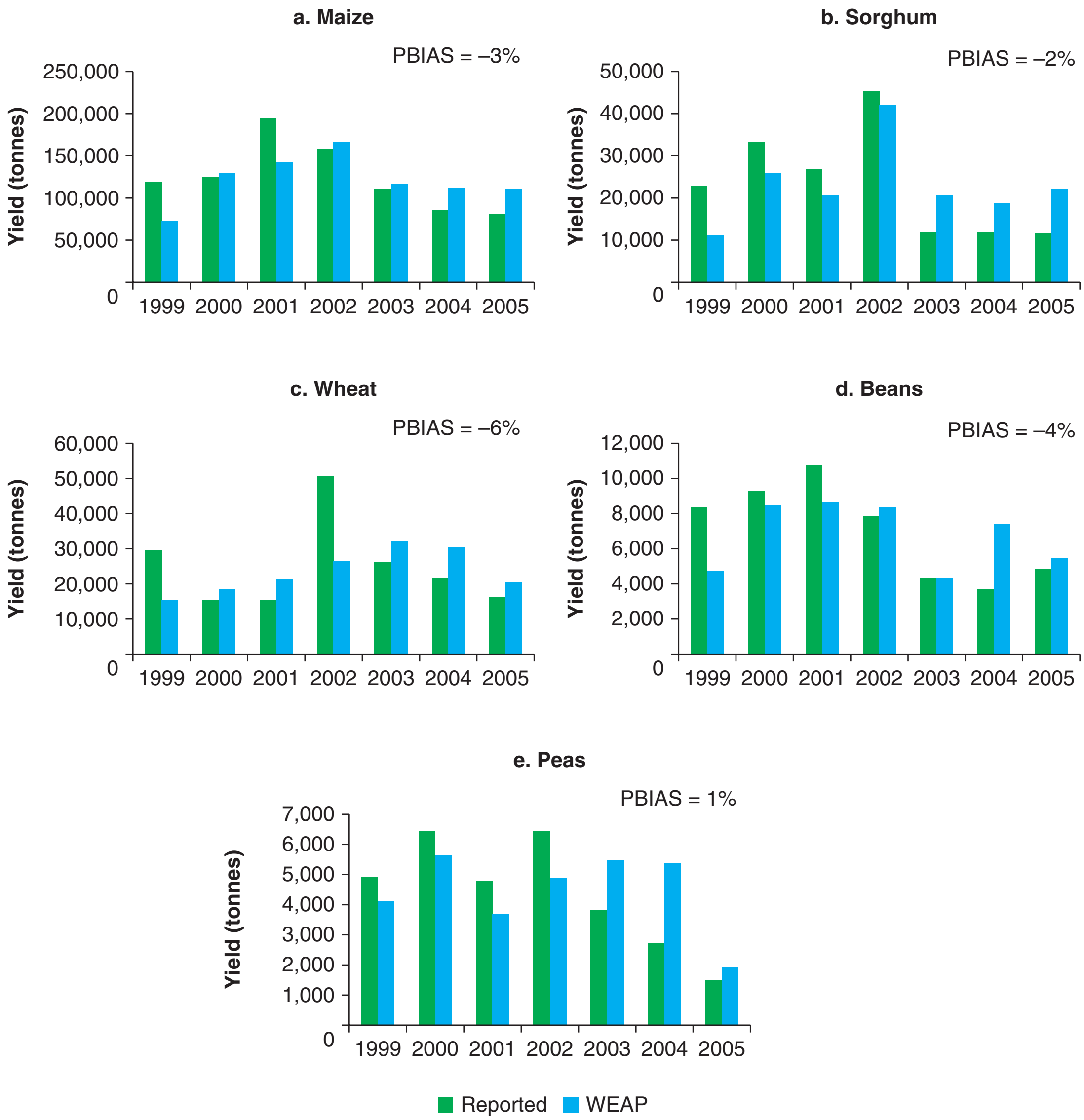
TABLE 2.5 Monthly Instream Flow Requirement from Metolong Dam (Metolong Authority 2015)

<table>
<tr><th rowspan="2">Month</th><th rowspan="2">Low-flow m^3s^{-1}</th><th colspan="3">Number of flood events</th></tr>
<tr><th>Class 1: 2.2 m^3s^{-1}</th><th>Class 2: 4.5 m^3s^{-1}</th><th>Class 3: 9.1 m^3s^{-1}</th></tr>
<tr><td>OCT</td><td>0.06</td><td rowspan="2">1</td><td></td><td></td></tr>
<tr><td>NOV</td><td>0.13</td><td></td><td></td></tr>
<tr><td>DEC</td><td>0.21</td><td></td><td rowspan="2">1</td><td rowspan="3">1</td></tr>
<tr><td>JAN</td><td>0.25</td><td></td></tr>
<tr><td>FEB</td><td>0.31</td><td></td><td rowspan="2">1</td></tr>
<tr><td>MAR</td><td>0.31</td><td></td><td></td></tr>
<tr><td>APR</td><td>0.34</td><td rowspan="3">1</td><td></td><td></td></tr>
<tr><td>MAY</td><td>0.31</td><td></td><td></td></tr>
<tr><td>JUN</td><td>0.27</td><td></td><td></td></tr>
<tr><td>JUL</td><td>0.13</td><td></td><td></td><td></td></tr>
<tr><td>AUG</td><td>0.07</td><td></td><td></td><td></td></tr>
<tr><td>SEP</td><td>0.05</td><td></td><td></td><td></td></tr>
</table>

TABLE 2.6 Flood Requirements (Metolong Authority 2015)

Flood type	Daily average peak (m^3s^{-1})	Duration (days)	Volume (MCM)	Number requested	Months
Class 1	2.2	3	0.6	2	Oct-Nov and Apr-May-Jun
Class 2	4.5	1.5	0.76	2	Dec-Jan and Feb-Mar
Class 3	9.1	3	2.1	1	Dec-Feb

FIGURE 2.10 **Simulated versus Reported Crop Production (1999–2005)**



Note: Calibration metric is based on percent bias (PBIAS), which is a measure of the model's ability to match the overall production.

TABLE 2.7 **Maximum Potential Yield and Yield Factors for Irrigated Crops**

Crop	Maximum potential yield (kg/ha)	Yield factor
Maize	6,000	1.25
Wheat	6,000	0.85
Vegetables	25,000	1.10
Pasture	3,500	0.90
Alfalfa	2,000	1.10

Rainfed Agriculture

The African Development Bank publishes data on crop production in Lesotho.[4] These data were obtained for five primary crop types (maize, sorghum, wheat, beans, and peas) and are summarized in the table 2.8.

These data are generally consistent with FAO estimates of cultivated land,[5] which was 209,000 ha in 1994. FAO data also suggest that the vast majority of these lands are rainfed. For this reason, we used the data in table 2.9 to estimate areas for rainfed agriculture throughout Lesotho.

However, the data in tables 2.8 and 2.9 are reported for the ten districts within Lesotho, whereas WEAP represents rainfed agriculture at the scale of quaternary hydrologic catchments, shown in map 2.3.

The simplest approach to allocating the areas from map 2.3 would be to assume that the crops are uniformly distributed within each district. However, given the topography of the country and the concentration of people within the lowlands, it is more likely that cropped areas are positively correlated to population density. For this reason, we used

TABLE 2.8 Crop Factor Coefficients throughout the Years

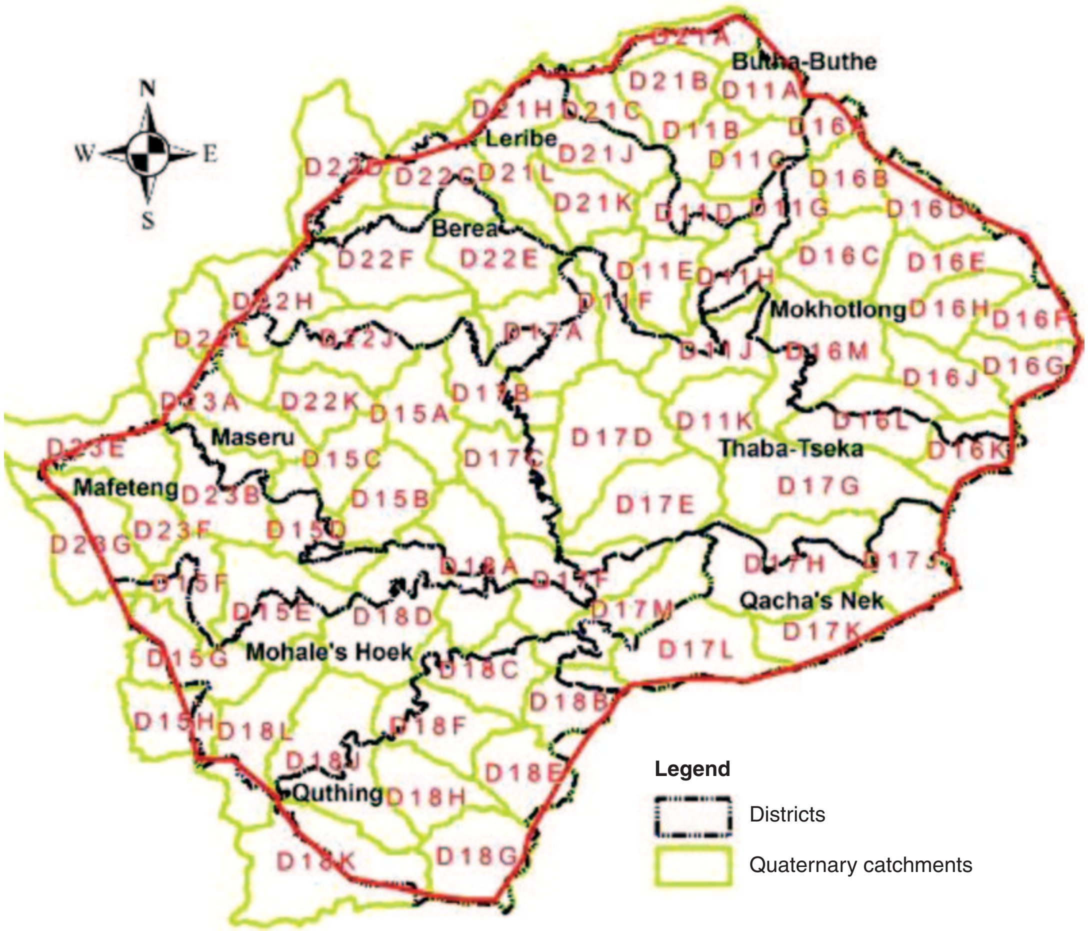
Crop	Crop mix (%)	Crop factor											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize	30	0.91	0.30	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.51	0.91	1.10
Wheat	20	n/a	n/a	n/a	n/a	n/a	0.15	0.34	0.79	1.00	0.87	0.18	n/a
Vegetables	20	0.99	1.00	0.65	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.29	0.70
Pasture	20	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
Alfalfa	10	0.80	0.80	0.70	0.50	0.40	0.30	0.30	0.40	0.50	0.70	0.80	0.80

Note: n/a = not applicable

TABLE 2.9 Total Area Planted, ha (2007)

	Maize	Sorghum	Wheat	Beans	Peas	Total (ha)
Berea	32,535	9,776	3,131	4,289	545	50,276
Botha-Bothe	8,176	2,482	360	2,710	32	13,760
Leribe	29,616	6,397	6,807	7,279	718	50,817
Mafe-teng	26,519	6,008	5,488	3,245	1,505	42,765
Maseru	26,134	8,082	3,409	4,891	534	43,050
MohalesHoek	31,777	6,762	3,128	3,276	789	45,732
Mokho-tlong	6,482	460	1,837	768	462	10,009
Qacha's Nek	6,970	2,168	1,116	765	59	11,078
Quthing	8,415	2,265	2,866	1,986	211	15,743
Thaba-Tseka	13,974	3,791	1,671	4,574	51	24,061
Total (ha)	190,598	48,191	29,813	33,783	4,906	307,291

MAP 2.3 **Quaternary Catchments Used for Hydrological Routines**



2010 population density maps from Columbia University (CIESIN 2011) to estimate the distribution of crops within each district (map 2.4). We then intersected these estimates with quaternary catchments to estimate the total cropped area for each crop within each catchment.

The African Development Bank also provides data on total crop production for a few recent years (table 2.10). These data were used to calibrate the agricultural yield routine within WEAP (figure 2.10).

Re-Calibration of Hydrology

The WEAP models are often calibrated to historical streamflows using a combination of manual methods and computer algorithms, such as the PEST software (Doherty 2002). In general, eight land use parameters are adjusted to achieve calibration to streamflow. These parameters are the evapotranspiration coefficient (Kc), soil water capacity (SWC), deep water capacity (DWC), runoff resistance factor (RRF), root zone conductivity (RZC), deep conductivity (DC), and preferred flow direction (PFD). Model simulations are most sensitive to SWC, RZC, RRF, and PFD. Thus, initial

MAP 2.4 Population Density (CIESIN 2011)

TABLE 2.10 Total Yield, Tonnes (1999–2005)

Crops	1999	2000	2001	2002	2003	2004	2005
Maize	118,679	124,549	194,338	158,194	111,205	85,032	80,898
Wheat	29,641	15,426	15,545	50,755	26,250	21,805	16,216
Sorghum	22,815	33,340	26,807	45,354	11,919	11,953	11,482
Beans	8,376	9,273	10,740	7,860	4,360	3,701	4,831
Peas	4,904	6,429	4,800	6,429	3,825	2,717	1,496

calibrations should focus on these four parameters. Further refinements to the shape and timing of the resulting hydrographs may be accomplished by adjusting the remaining parameters.

The Nash-Sutcliffe Efficiency (NSE) coefficient is commonly used in hydrologic modeling to evaluate how well modeled stream flow matches observed data. The NSE indicates how well a plot of observed versus simulated data fits to a 1:1 line. NSE ranges from $-\infty$ to 1.0. If NSE = 1, there is a perfect match between the observed and modeled, if NSE = 0, the modeled is only as good as the observed mean of the data, and NSE <0 indicates the model performs worse than the mean. Generally in hydrologic modeling, NSE > 0.6 is desired, while NSE > 0.8 is good. The mathematical form of NSE is:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - \overline{Y^{obs}} \right)^2} \right]$$

Where Y_i^{obs} is the *i*th observation, Y_i^{sim} is the *i*th simulated value, $\overline{Y^{obs}}$ is the mean of the observed data, and *n* is the total number of observations.

While NSE is a useful one-value indicator of model performance, it is biased by high flows. Additionally, it only captures certain aspects of the model flow deviations from observed. To fully understand and evaluate model performance, NSE must be used in conjunction with other metrics that consider seasonal variation, flow duration curves, and annual totals of the modeled and observed flows. To this end, we often consider the ratio of the root mean squared error to the standard deviation (RSR) as a measure of how much the simulated flows deviated from the observed hydrographs. We consider the ratio of simulated versus observed flow standard deviation (SDR) as a measure of how well the simulated flows match the flow variability within the historical record. Lastly, we consider the percent bias (PBIAS) as a measure of the model's ability to match the total volume of flow. In general, the model can be judged as satisfactory if the NSE ≥ 0.5, PBIAS ±25%, RSR ≤ 0.7, and 0.9 ≤ SDR ≤ 1.1 (Moriasi et al. 2007). The equations for PBIAS, RSR, and SDR are as follows:

$$PBIAS = 100 * \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)}{\sum_{i=1}^{n} \left(Y_i^{obs} \right)} \right]$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - \overline{Y^{obs}} \right)^2} \right]}$$

$$SDR = \frac{STDEV_{sim}}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{sim} - \overline{Y^{sim}} \right)^2} \right]}{\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - \overline{Y^{obs}} \right)^2}}$$

There are a number of stream flow-gauging stations within the basin that are operated by either DWA or the Lesotho Ministry of Water (see figure 2.11). The data from these stations were used as the basis for calibrating the hydrology of the basin. The results of this calibration are summarized in table 2.11 and figures 2.12–2.22.

FIGURE 2.11 WEAP Schematic Showing Streamflow Calibration Locations

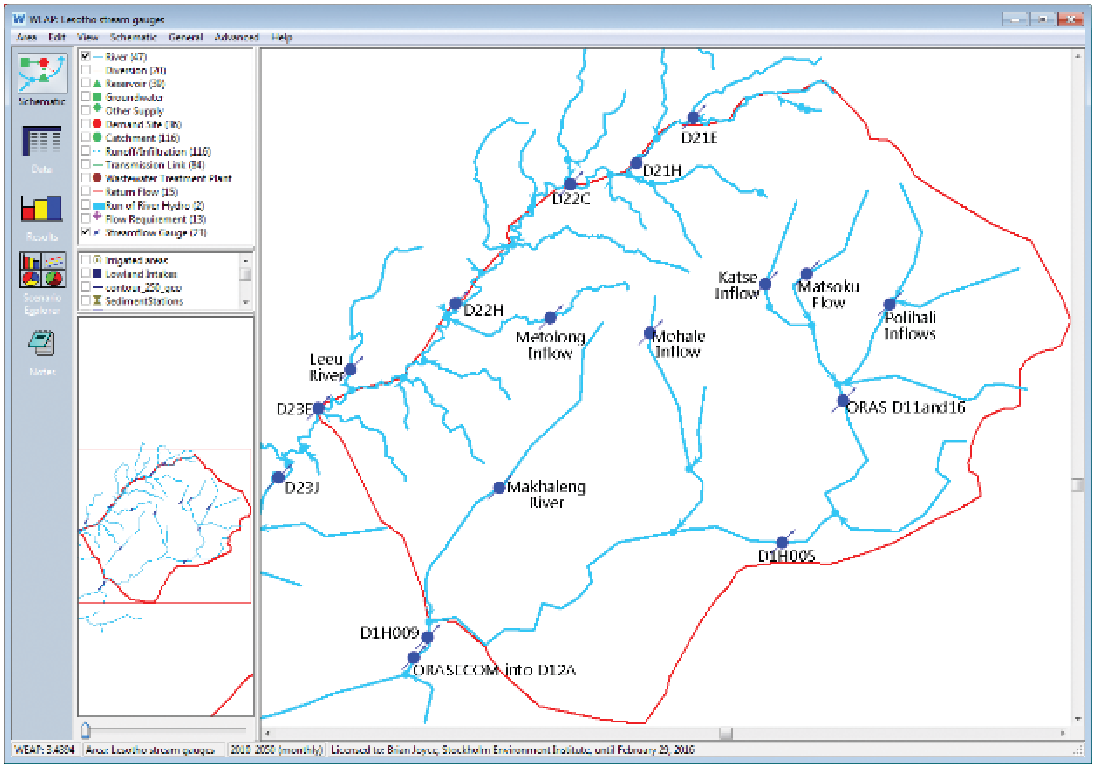


TABLE 2.11 Statistics for Observed Data Used for WEAP Calibration

Site	WEAP comparison	Records used	NSE	Annual bias (%)	SDR	RSR
Katse inflow	ORASECOM	1949–2000	0.16	−2.1	1.07	0.92
Mohale inflow	ORASECOM	1949–2000	0.27	0.03	1.01	0.85
Matsoku weir inflow	ORASECOM	1949–2000	0.02	6.7	0.92	0.99
Polihali inflow	ORASECOM	1960–96	0.20	1.0	0.93	0.89
Makhaleng river at Qaba	Observed	1981–2007	0.4	−3.5	0.97	0.07
D21E	ORASECOM	1960–89	0.23	3.0	1.11	0.88
D21H	ORASECOM	1960–89	0.31	−2.1	1.14	0.83
D22C	ORASECOM	1960–89	0.31	0.2	1.18	0.83
D22H	ORASECOM	1960–89	0.33	0.6	1.21	0.81
D23E	ORASECOM	1960–89	0.43	7.0	1.23	0.75
D23J	ORASECOM	1960–89	0.54	7.5	1.22	0.68

FIGURE 2.12 WEAP versus ORASECOM Results for D11 A-F (Inflows to Katse Dam)

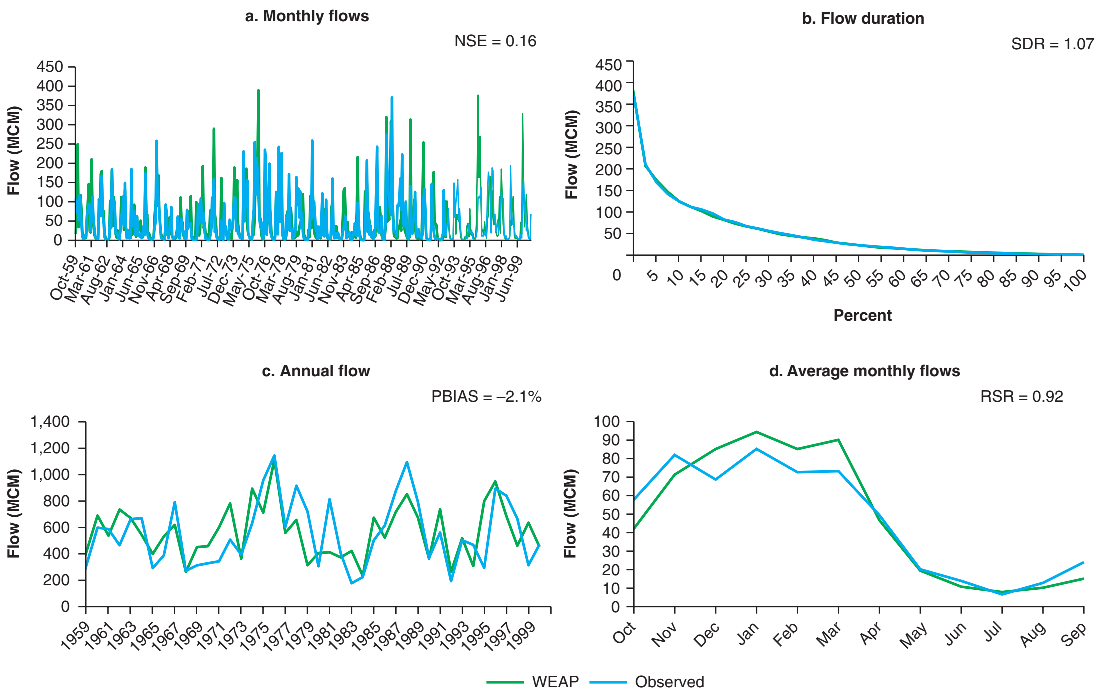


FIGURE 2.13 WEAP versus ORASECOM Results for D17A (Inflows to Mohale Dam)

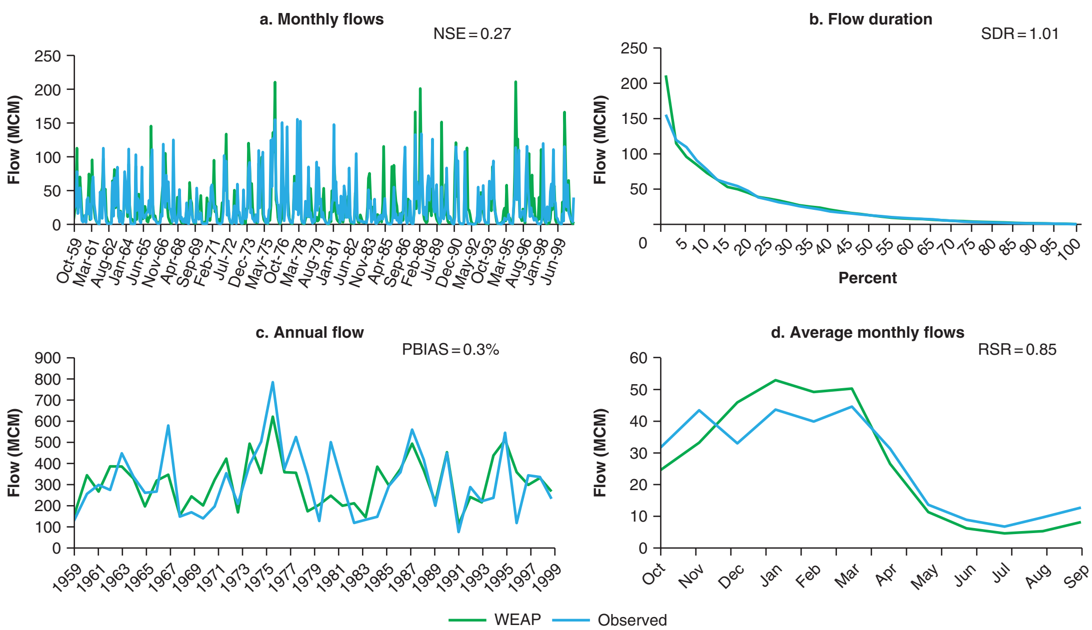


FIGURE 2.14 WEAP versus ORASECOM Results for Matsoku River

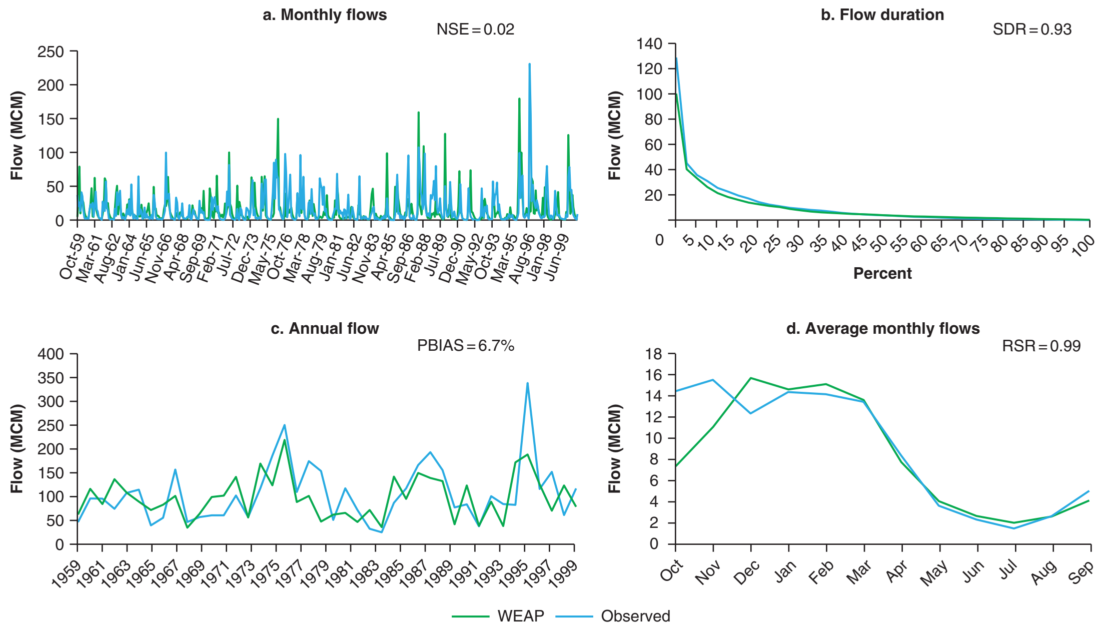


FIGURE 2.15 WEAP versus ORASECOM Results for Senqu River Flows into Polihali

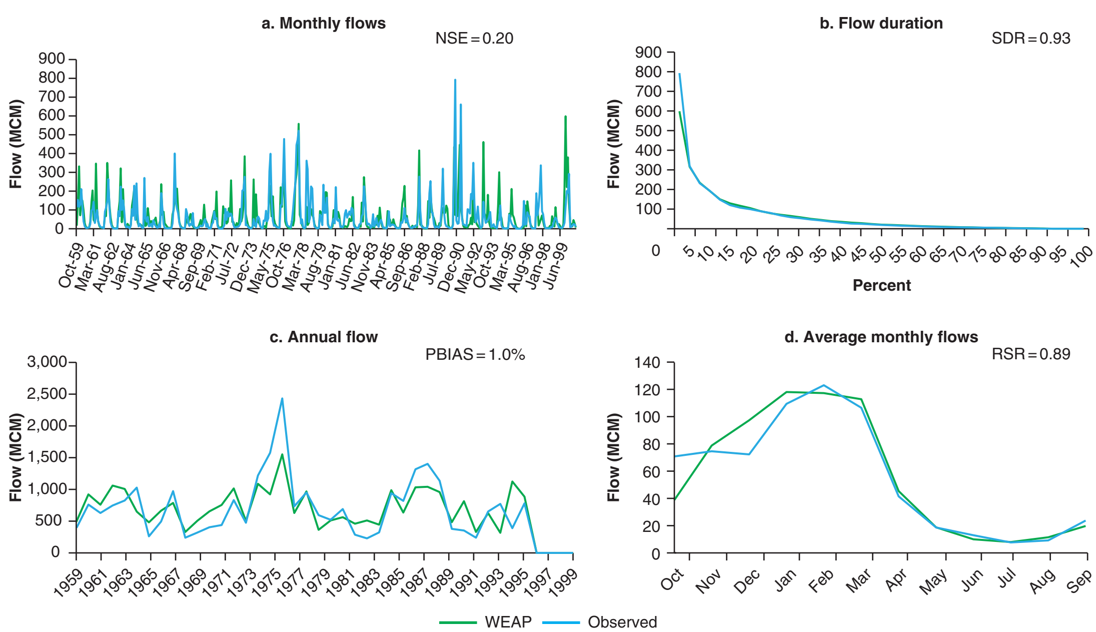


FIGURE 2.16 WEAP versus Observed Makheleng River Flows at Qaba

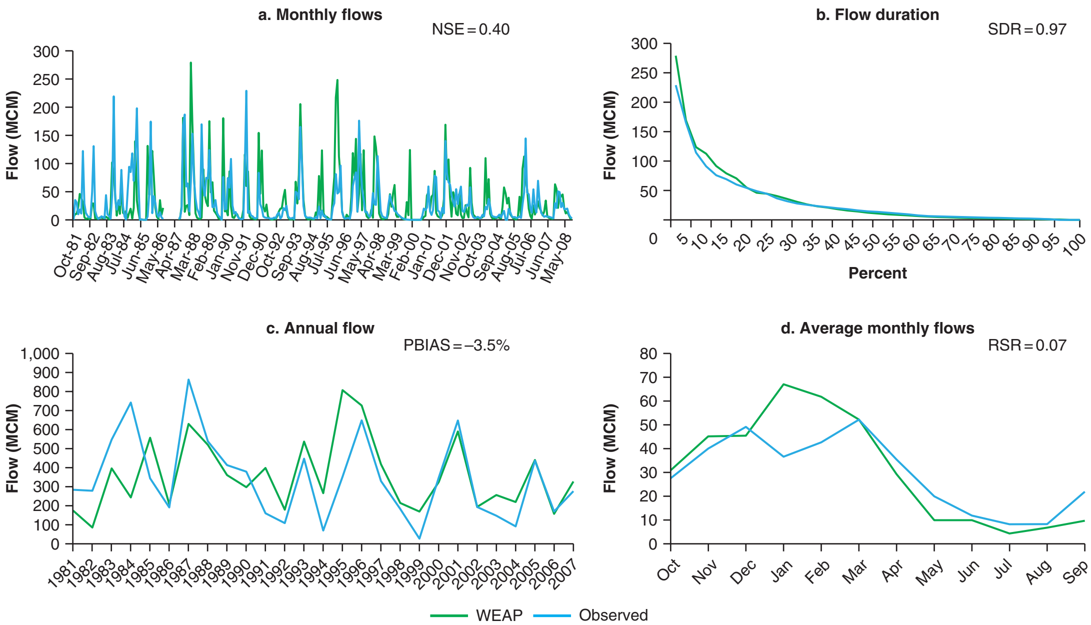


FIGURE 2.17 WEAP versus ORASECOM Results for D21E

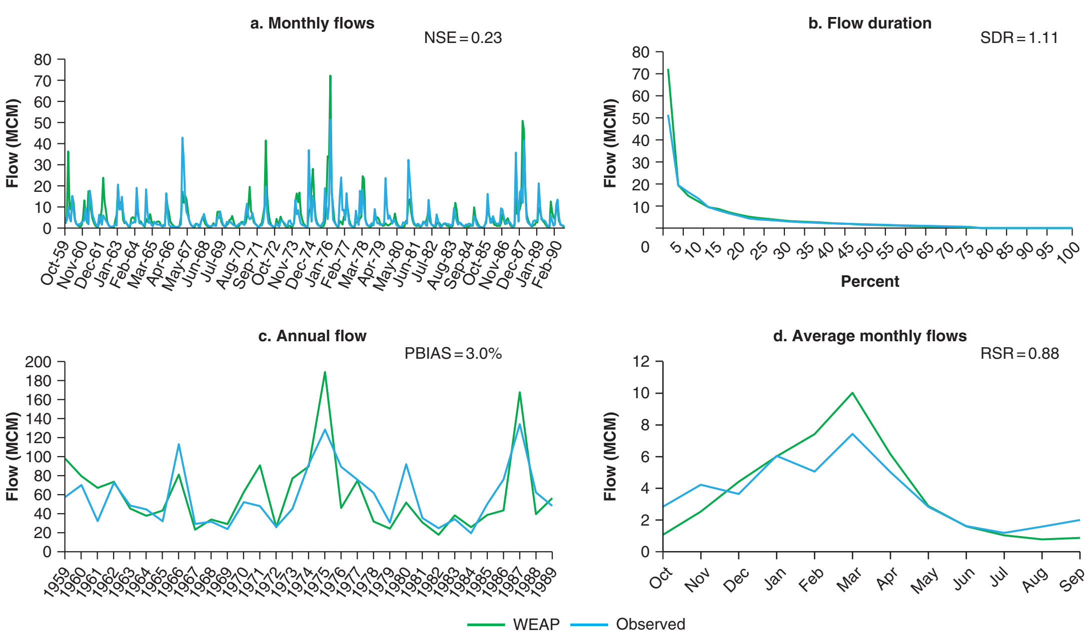


FIGURE 2.18 WEAP versus ORASECOM Results for D21H

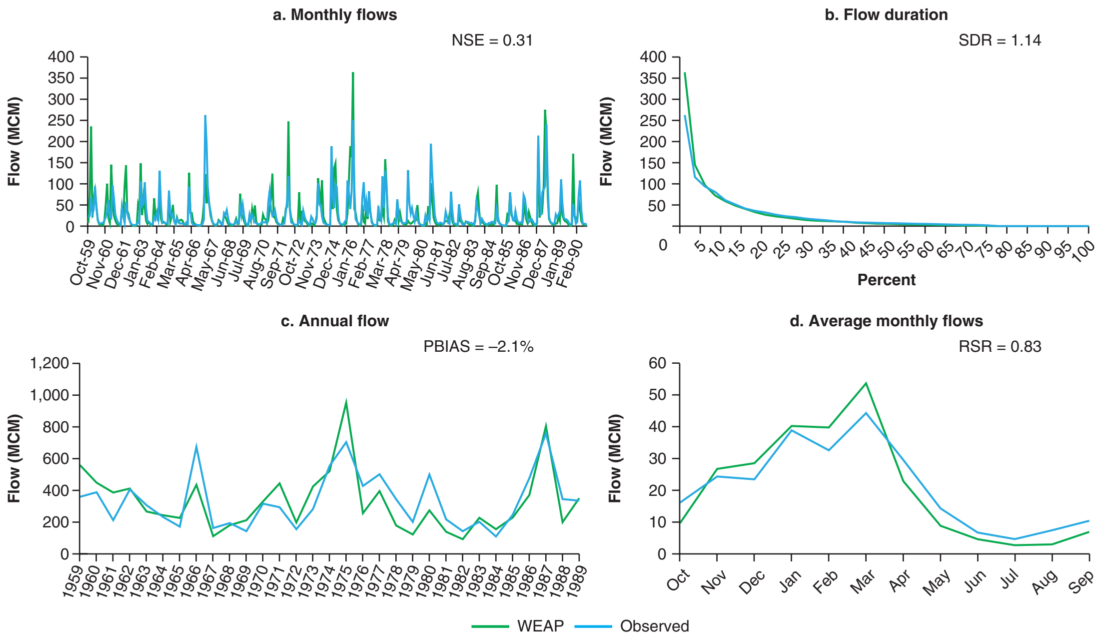


FIGURE 2.19 WEAP versus ORASECOM Results for D22C

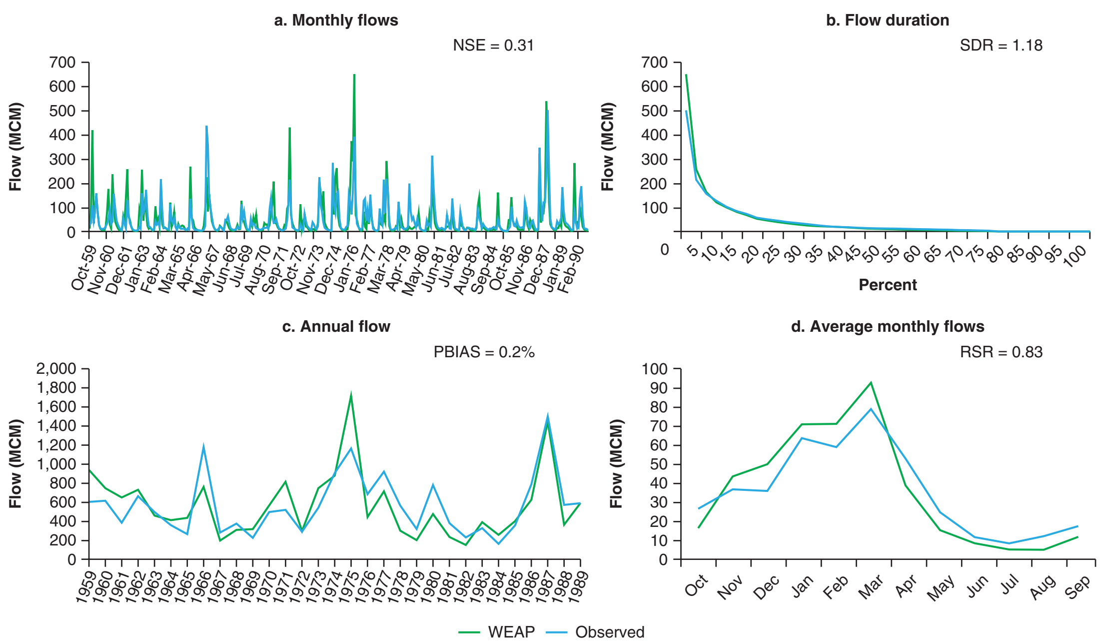


FIGURE 2.20 WEAP versus ORASECOM Results for D22H

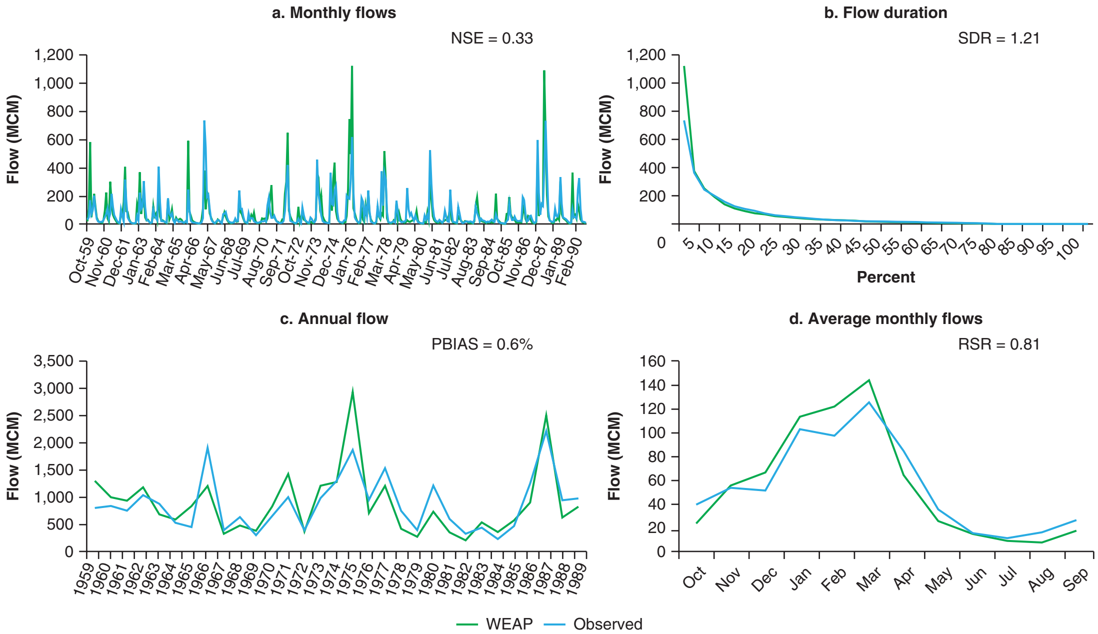


FIGURE 2.21 WEAP versus ORASECOM Results for D23E

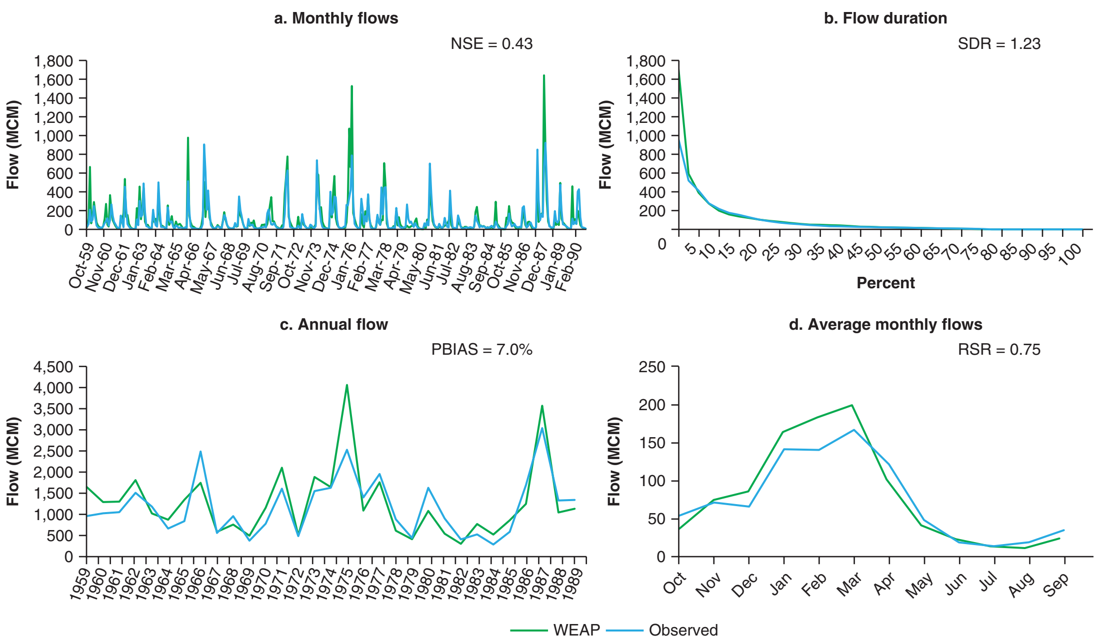
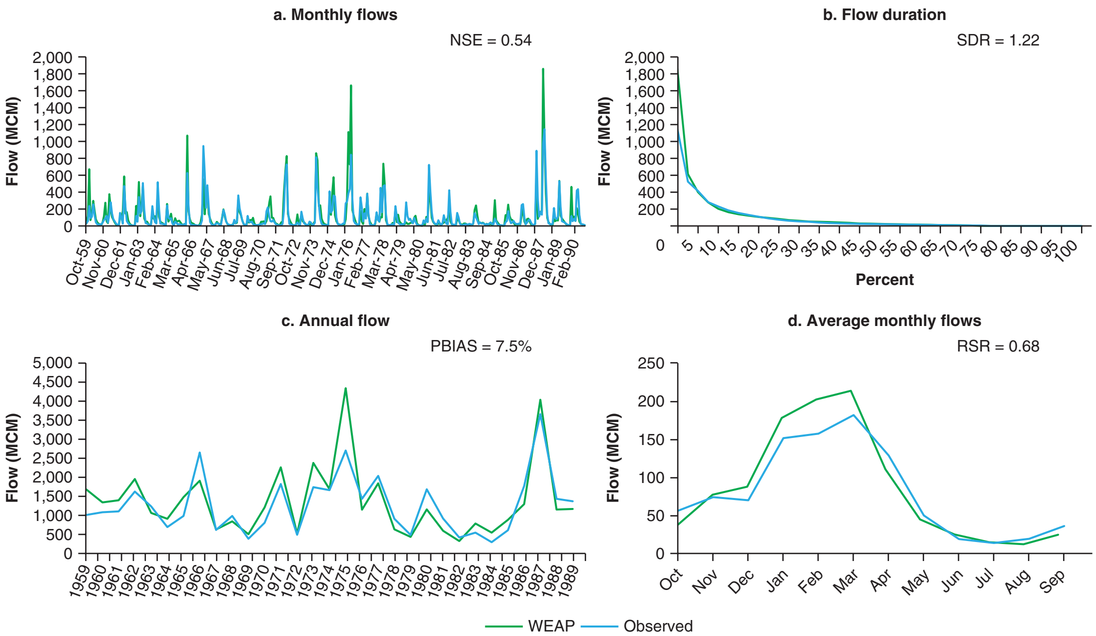


FIGURE 2.22 WEAP versus ORASECOM Results for D23J



Notes

1. https://www4.dwa.gov.za/wma/.
2. Orange-Senqu Water Information System: http://wis.orasecom.org/. Information on irrigated agriculture was obtained from http://wis.orasecom.org/irrigation-water-demand-management-wp6/.
3. FAO Crop Water Information available at http://www.fao.org/nr/water/cropinfo.html.
4. Sources: World Bank - WDI Nov. 2014; ADI 2013; FAO - Production Statistics Aug. 2014; Food Balance Sheets 2014 http://lesotho.opendataforafrica.org/rqgdlhd/lesotho-agriculture-sheet.
5. http://www.fao.org/docrep/v8260b/V8260B0z.htm.

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

SKU K8830