Technical Annex

Mara River Basin WEAP Model

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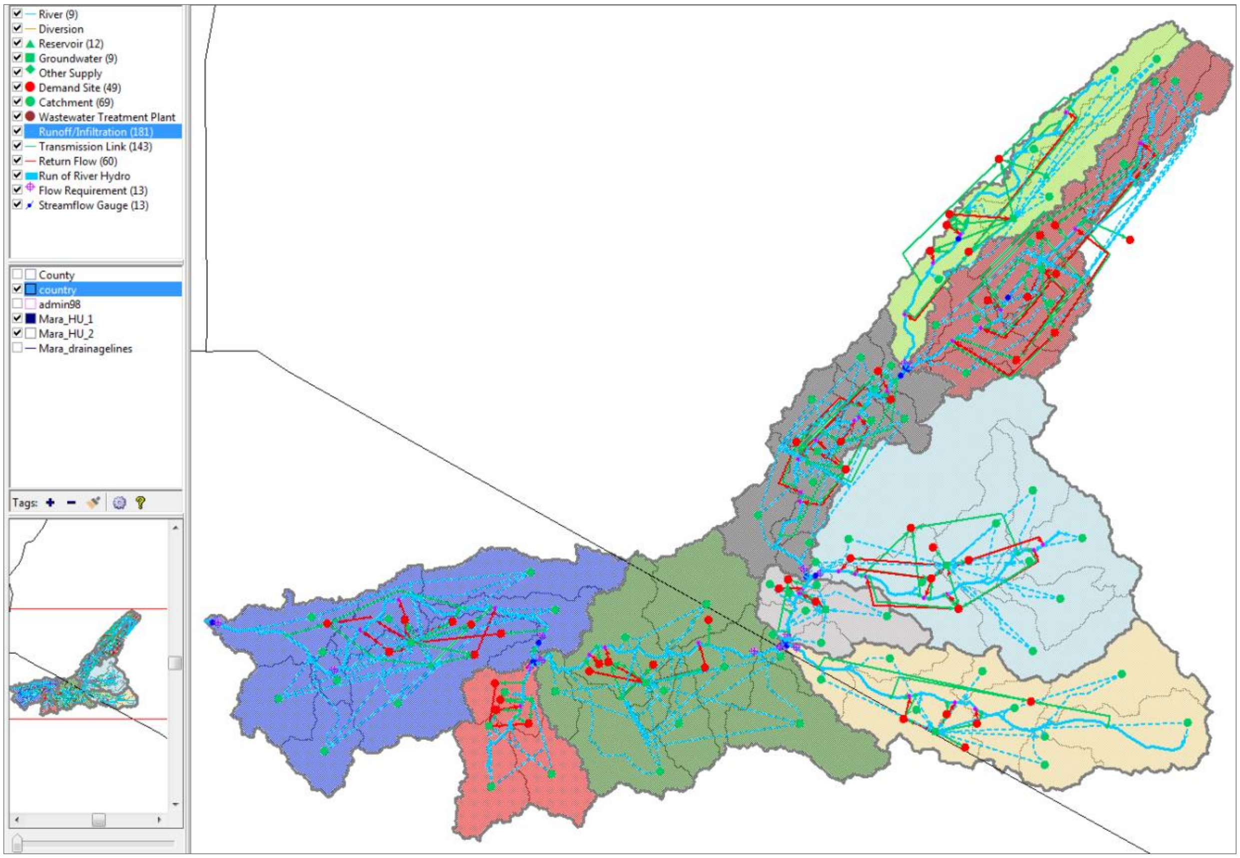


1. INTRODUCTION

1.1. THE MARA RIVER BASIN (MRB)

The Mara River Basin (MRB) covers an area of 13,750 square kilometers, with the upper 65 percent in Kenya and the lower 35 percent in Tanzania. The Mara River (Mara) originates in the western part of the Mau Escarpment at 2,930 meters above sea level. It flows for 395 kilometers before draining into Lake Victoria at 1,134 meters above sea level. The Mara is formed by the convergence of the Nyangores and Amala tributaries, both of which are perennial. It is joined downstream just before it reaches the border to Tanzania by the Olare Orok and Talek rivers, both seasonal tributaries. Once over the border, it is joined by the Sand River.

The MRB experiences bimodal rainfall, with longer rains between March and May and shorter rains between October and December. Rainfall in the basin varies from 1,500 millimeters per year at the headwaters of the Nyangores and Amala rivers, to below 700 millimeters per year in the Talek and Sand River sub-basins.

The Mara provides water for more than one million people in Kenya and Tanzania. Sustaining human livelihoods, livestock, and wildlife ecosystems, the flows of this river are critical to life throughout the basin. In the upper MRB, economic activities are dominated by forestry and rain-fed small-scale farming of maize, potatoes, beans, and tea. The central part of the basin is semi-arid. In this area, the Mara provides an important source of water for the pastoralist Maasai people. The lower MRB is home to the Maasai Mara National Reserve in Kenya and the Serengeti National Reserve in Tanzania, both of which serve as important sources of tourism revenue.

2. MODEL DEVELOPMENT: HISTORICAL AND BASELINE CONDITIONS

The WEAP model of the MRB was developed as a collaborative effort between IHE Delft Institute for Water Education (IHE) and SEI. The historical and baseline conditions are representative of our best understanding of the basin as it has existed and been used historically, as it exists and is used today, and how it will exist and be used into the future, without any major changes. The baseline run into the future, or business as usual, acts exactly as the historical representation of the model, but with growth trends on all water demands. The following sections describe this historical and business-as-usual representation in the Mara River WEAP model.

2.1. SCHEMATIC AND OVERVIEW OF MODEL AREA

The Mara River Basin model covers the entire area of the Mara River watershed, in both Kenya and Tanzania (Figure 1). The area of the basin is divided into nine hydrologic units (HU), which are each subdivided into sub-catchments (SC), for the purposes of hydrologic modeling. Figure 1 shows the division of the basin, with three HUs in Tanzania and six in Kenya. Figure 2 shows the WEAP schematic of the MRB model, which includes a representation of rivers, demands, catchments and reservoirs. The representation of these in WEAP are described in more detail in the following sections.

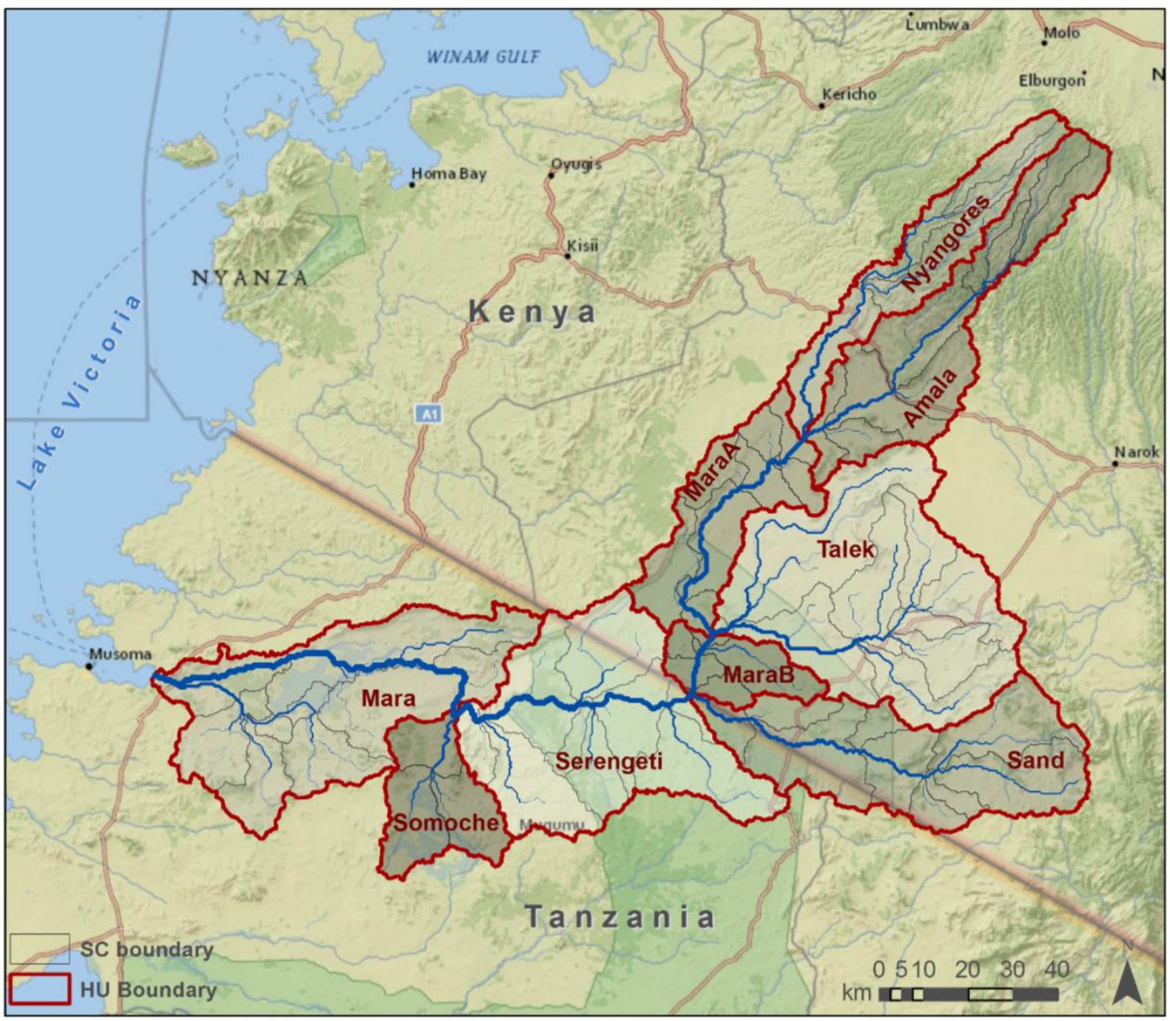


Figure 1 Map of the Mara River Basin, divided into HUs and sub-catchments.

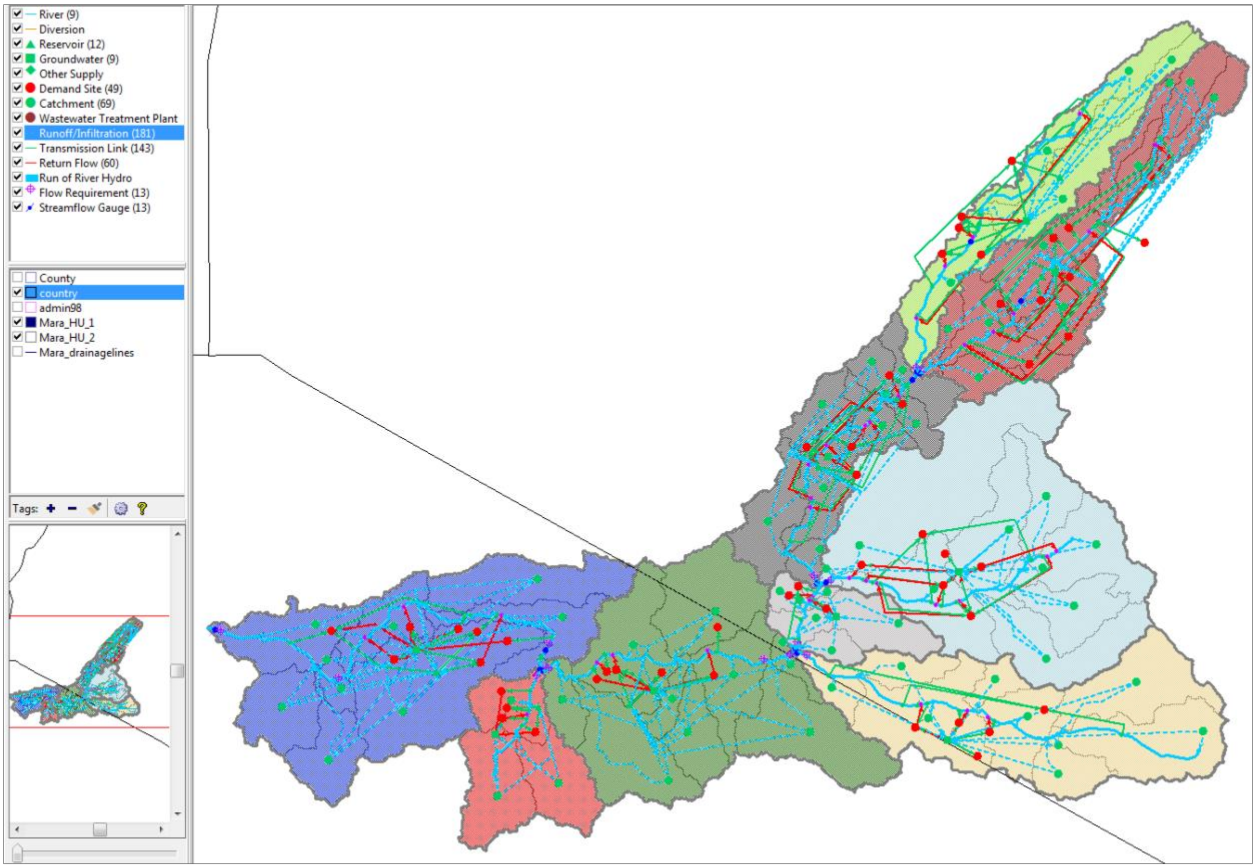


Figure 2. WEAP Schematic of the Mara River Basin model.

Prior to the development of the WEAP model, two assessments were carried out in each HU, in both Kenya and Tanzania by IHE Delft (see the full set of data on the Mamase website at: http://maps.mamase.org/documents/664). The abstraction survey aimed to measure all abstractions throughout each HU, identify their locations, sources of water, purpose of use and quantify abstractions. It was assumed that the abstraction survey was likely not a complete representation of water demand and use throughout the basin because it is unlikely every single abstraction site was visited. Because of this, a demand assessment was conducted which was informed by abstraction survey data as well as other data sources such as the most recent census, spatial data, and others. This assessment quantified the total demands in each HU. Both sources of information were inputs to the WEAP model. The historical period of the model runs from 1960-2009. This means the model has climate and land-use data covering this period. The future scenarios simulate the basin out to 2050.

2.2. CATCHMENTS AND HYDROLOGY

The nine HUs in the WEAP model are further subdivided into 69 sub-catchments (SC), represented with green dots, called catchments, in WEAP (Figure 2). In this model, WEAP's rainfall runoff soil moisture method is used to model the SCs and their contributions to streamflow and groundwater, which make up the watershed's hydrology. For each SC, climate data is entered, and as rain falls on the SC, the proportion of water that contributes to evapotranspiration, groundwater, or surface water is adjusted based on the SC's land use, slope, soil type, and other factors during a process called calibration. This process for the Mara River Basin model is further described in Section 3 of this document. Figure 3 shows how WEAP calculates the proportions of rainfall that end up as evapotranspiration, storage in the soil, baseflow to groundwater, interflow to the river, and surface runoff to the river in each time step.

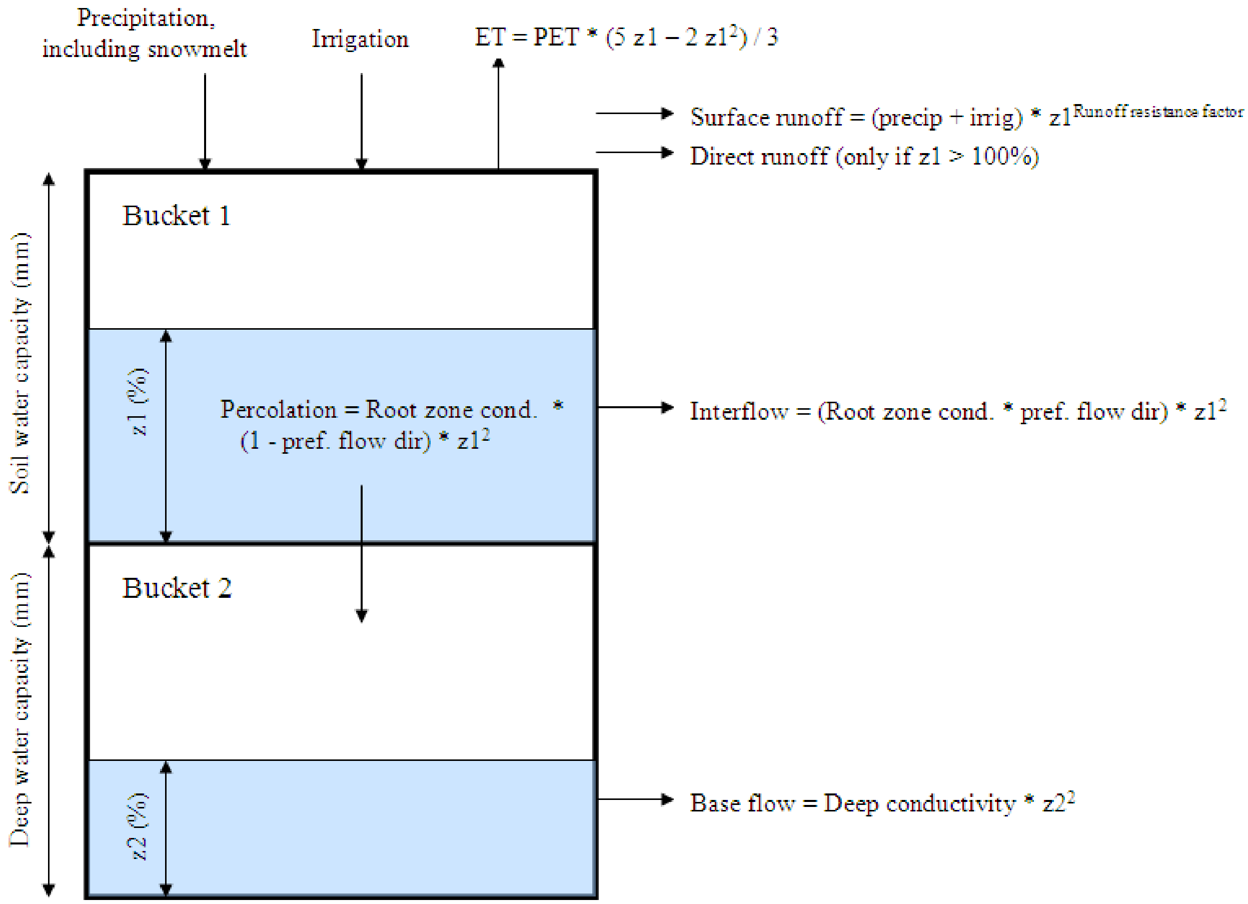


Figure 3. Conceptual diagram and calculations included in WEAP's soil moisture method for modeling catchment hydrology.

The first major input to catchments in WEAP for modeling hydrology is climate data (most importantly, precipitation and temperature). For the MRB model, we used monthly climate data collected from the Kenyan Meteorological Department and the Tanzanian Meteorological Agency's network of meteorological stations as inputs to the SCs. These data are summarized in Table 1 below.

Station Number	Station Name	Beginning Date	End Date	Total Number of Records	Percent Missing
9035228	KIPTUNGA FOREST STATION ELBURGON	Feb-61	Jul-09	546	6%
9035265	BOMET WATER SUPPLY	Feb-67	Jul-09	449	12%
9035284	MULOT	Nov-73	Dec-98	291	4%
9135013	KEEKOROK HYDROMET STATION NAROK	Feb-65	Jan-97	352	8%
9135019	LEMEK MAASAI FARM	Jul-66	Oct-93	233	29%
9135026	GOVERNORS CAMP	Mar-73	May-04	254	32%
9035031	DANSON K NGUGI SAW MILL	Feb-61	Jan-88	230	29%
9035079	TENWEK MISSION SOTIK	Feb-61	Mar-02	453	8%
9035085	OLENGURUONE	Feb-61	Jan-05	418	21%
9035227	DISTRICT OFFICE BOMET	Feb-61	Nov-92	354	7%
9035236	CHEPALUNGU FOREST STATION SOTIK	Feb-70	Jan-93	276	0%
9035241	BARAGET FOREST STATION	Aug-61	Jan-98	428	2%
9035260	KOIWA ESTATE KERICHO	Feb-70	Jan-93	276	0%
9035302	NYANGORES FOREST STATION	Sep-79	Jul-09	336	6%
9133000	MUSOMA METEO STATION	Feb-70	Jan-93	276	0%
9134008	NYABASSI	Feb-70	Jan-93	276	0%
9134019	KISII NTIMARU AGRIC HOUSE	Feb-70	Jan-93	276	0%
9134027	LOLGORIEN WS	Feb-70	Jan-93	276	0%
9134033	MUGUMU	Feb-70	Jan-93	276	0%
9135001	NAROK METEOROLOGICAL STATION	Feb-61	Jul-09	578	1%
9135008	KABOSON GOSPEL MISSION SOTIK	Feb-61	Aug-85	280	5%
9135010	AITONG HYDROMET STATION SOTIK	Feb-61	Apr-89	200	41%
9135022	AFRICA GOSPEL CHURCH NAIKARA	Feb-69	Jun-88	207	11%
9135025	ILKERIN INTEGRAL DEVELOPMENT PROJECT	May-73	Dec-99	268	16%
9135035	KICHWA TEMBO CAMP	Feb-88	Jan-03	122	32%

Table 1. Meteorological Stations within the Tara River Basin.

In addition to climate data, land-use information is another important input to WEAP catchments. Each SC is fractionally subdivided into a unique set of independent land-use/land-cover classes. For the Mara WEAP model we have used the European Space Agency's Climate Change Imitative Land Cover database (ESA-CCI-LC) to determine the land cover distribution within each catchment. These are shown in Figure 4 for each HU.

These data indicate that five land classes – grass, shrub, savanna, agriculture, and natural forest – account for the majority of the basin's area, which suggest that these land classes also largely control the hydrological response of the

MRB. A closer look at the data show that grass predominates in the middle part of the basin (HUs 3, 4, 5, 6, and 7) and that agriculture accounts for a larger portion of the area in the upper and lower parts of the basin, which are also more populous. Furthermore, the upper basin (HUs 8 and 9) also includes a higher proportion of natural forests than the rest of the basin, whereas the lower basin (HUs 1 and 2) include a higher proportion of savanna. The ESA land cover data is only available for the period 1992 to 2015, which does not coincide with the model's historical climate data record. For this reason, we have had to use a static land cover that is based on the average of the ESA dataset. This means the model does not have a representation of how land use changes in the basin overtime.

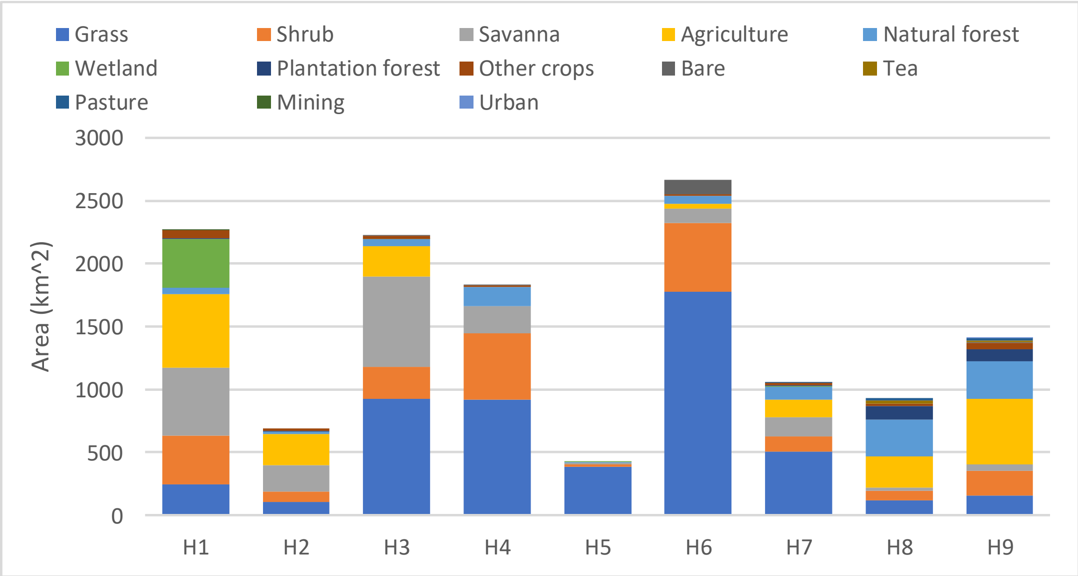


Figure 4. Total land cover within each hydrologic unit of the MRB.

2.3. DEMANDS

Demands are represented in WEAP with red dots, called demand nodes (Figure 2). The model is developed so that there is one demand node per demand type (e.g. domestic, livestock, wildlife, etc.) for each HU, where those demands exist. All demands in the model were developed based on the water demand assessments and the abstraction surveys conducted in each country. For the most part, the demands are based on information in the demand assessment. In neither assessment were "other" demands included. These in the model are based on abstraction survey data. In some cases, the abstraction survey data and demand assessment did not agree. For example, there are extraction survey data for agriculture in the Mara B HU; however, the demand assessment did not indicate there were agriculture demands in this HU. When this occurred, the demand assessment was used.

Where possible, the demand is broken into an annual activity level which might be population, for domestic demands, or number of animals for livestock and wildlife demands, for example, as well as a water use rate, or a rate of use per unit in the annual activity level. For domestic demands, this is 50L/person/day, for example. In WEAP, the annual activity level is multiplied by the water use rate to get the total demand. The details of each demand set up are included in Table 2. Demands are divided by HU. The water use rates are saved in key assumptions in the model, so that they can easily be changed or modified. For example, if it was of interest to explore how the basin might look differently if the domestic rate of water use were only 25L/person/day, or increased to 70L/person/day, that change can easily be implemented in the key assumptions. From 1961 to the time that the annual activity level data were collected, the demand is constant. After the year the data were collected (For population in Tanzania, for example, this year is 2012, because data were collected for the 2012 census), the growth rate is applied into the future for the baseline scenario.

All demands are assumed constant throughout the year except agriculture, wildlife, and tourism. The monthly variation for tourism and wildlife was set for all catchments based on information provided in the TZ Demand Assessment: Half of the total population of wildebeest, zebras, gazelles, and eland is within the HUs from July-November. Therefore, the percentage of occupied tourism beds is 100 percent during these months and 50 percent during all other months. For agriculture, monthly variation in Tanzania is based on the information provided in the Demand Assessment. For Kenya, it is based on abstraction data provided by farmers.

Consumption is the amount of water that is sent to a demand, that is consumed. For demands like livestock and wildlife where the demand is solely for drinking water, it is assumed all water is consumed. For demands such as domestic and tourism, where some water is used for bathing and washing, this excess water is returned to the system. Assumed consumption rates are shown in Table 2. All consumption rates are saved in the key assumptions, so they can be easily changed as new information becomes available.

Total annual demands for Tanzania and Kenya are shown in

Table 3 through Table 5, compared with values from the Demand Assessment conducted in each country, which was the source for all demand information.

Demand category	Annual activity level	Water use rate	Growth Rate	Consumption
Domestic	Population[1]	50L/person/day[1]	Mara HU: 2.6[1] Somoche HU: 3.1[1] Serengeti HU: 3.1[1] All KE HU: 2.6[1]	65[2] Returns flow to groundwater and surface water
Agriculture	Because data about crop acreage for irrigated areas is not available, all crop demands for each HU are lumped into 1 production unit. [1]	Total annual demand for irrigation by HU[1]	Mara HU: 2.6[1] Somoche HU: 3.1[1] Serengeti HU: 3.1[1] KE: 1.1[3]	50[2] Returns flow to groundwater
Livestock	KE: Livestock units. 1 Livestock unit = 3 indigenous cows, 15 goats or sheep and 5 donkeys[1] TZ: Livestock units. 1 Livestock unit = 1 indigenous cow, 5 goats or sheep, 2 donkeys and 1 pig. [1]	KE: 50L/livestock unit/day[1] TZ: 30L/livestock unit/day[1,3]	KE: 1.1[1] TZ: 2.0[1]	100[2]
Wildlife	For migrating species, number of animals: wildebeest, zebra, thomson gazelle and eland. For resident population: lumped into 1 production unit due to the large variety of resident animals.[1]	Wildebeest: 12L/animal/day Zebra: 9L/animal/day Thomson gazelle: 23L/animal/day Eland: 1L/animal/day Resident population: Total demand for resident wildlife by HU[1]	Assumed population stays constant[1]	100[2]
Industrial (only exists in KE)	For Nyangores and Amala HUs: Number of shops and tea processing facilities lumped together as 1 annual activity level[1]	For Nyangores and Amala HUs: Shops: 100L/day/shop, for tea processing: total annual demand.[1]	1.1[5]	80[2] Returns flow to groundwater and surface water

Demand category	Annual activity level	Water use rate	Growth Rate	Consumption
	For Talek HU: Represents bottling, annual activity level is 1[1]	For Talek HU: total annual demand for bottling[1]		
Mining (only exists in TZ)	Number of mines[1]	In the Mara HU: For artisanal mines: 3.6 m^3/mine/day[1,3] For the Mara mine: 2760m^3/mine/day[1,3] In the Serengeti HU: For artisanal mines: 12m3/mine/day[1,3]	For Mara mine: no projected growth[1] For artisanal mines: 12.3[1]	80[2] Returns flow to groundwater and surface water
Tourism	Number of beds[1]	TZ: 84L/bed/day[1,3] KE: 40L/bed/day (average of range given in the KE Water Demand Assessment) [1]	3.2[1]	35[2] Returns flow to groundwater and surface water
Other	Because little data were available regarding these demands, other demands for each HU are lumped into 1 production unit.[4]	Total annual demand for other by HU[4]	1.1[5]	80[2] Returns flow to surface water

Table 2. Description of implementation of demands in WEAP.

[1]Data are sourced from the Demand Assessment for the respective country except in the case of tourism. No growth rate was provided for Kenya so it is assumed the same as Tanzania.
[2]All assumptions are made by model developers based on professional judgement as no information was directly available.
[3]This water use rate includes an additional 20 percent added per the draft Tanzania WAP guidelines. See the TZ Demand Assessment for more information.
[4]Data are sourced from the Abstraction Survey data
[5]No growth rate was indicated in the demand assessment, so a base rate of 1.1 was used.

	Projected domestic demand (m^3/day) (as presented in Table 4-5 of the Tanzania Demand Assessment)					Projected domestic demand (m^3/day), as calculated in the MRB WEAP Model[1]				
HU	**2012**	**2018**	**2023**	**2028**	**2038**	**2012**	**2018**	**2023**	**2028**	**2038**
Serengeti	2,349	2,823	3,294	3,846	5,256	3,915	4,702	5,477	6,381	8,659
Somoche	1,424	1,750	2,078	2,469	3,482	2,373	2,850	3,320	3,867	5,248
Mara	6,405	7,398	8,349	9,428	12,047	10,674	12,452	14,157	16,095	20,805
Total	10,177	11,972	13,721	15,743	20,785	16,962	20,003	22,954	26,343	34,712

Projected livestock demand (m^3/day) (as presented in Table 4-13 of the Tanzania Demand Assessment)					Projected livestock demand (m^3/day), as calculated in the MRB WEAP Model[2]			
HU	**2018**	**2023**	**2028**	**2038**	**2018**	**2023**	**2028**	**2038**
Serengeti	2,283	2,569	2,854	3,425	2,283	2,521	2,783	3,393
Somoche	2,099	2,362	2,624	3,149	2,099	2,318	2,559	3,120
Mara	8,646	9,727	10,808	12,969	8,646	9,546	10,540	12,848
Total	13,029	14,657	16,286	19,543	13,029	14,385	15,882	19,360

	Projected small-scale irrigation demand (m^3/day) (as presented in Table 4-17 of the Tanzania Demand Assessment)				Projected small scale irrigation demand (m^3/day), as calculated in the MRB WEAP Model[2]			
HU	**2018**	**2023**	**2028**	**2038**	**2018**	**2023**	**2028**	**2038**
Serengeti	0	0	0	0	0	0	0	0
Somoche	3	3	5	10	3	4	4	6
Mara	593	660	735	910	620	705	801	1,035
Total	596	663	740	920	623	708	806	1,041
	Projected tourism demand (m^3/day) (As presented in Table 4-27 in the Tanzania demand assessment)				**Projected tourism demand (m^3/day), as calculated in the MRB WEAP Model[2]**			
HU	**2018**	**2023**	**2028**	**2038**	**2018**	**2023**	**2028**	**2038**
Serengeti	61	71	83	114	58	67	79	108
Somoche	0	0	0	0	0	0	0	0
Mara	5	6	8	10	5	6	7	9
Total	66	77	91	124	62	73	86	117
	Projected mining demand (m^3/day) (As presented in Table 4-37 of the Tanzania Water Demand Assessment)				**Projected mining demand (m^3/day) as calculated in the MRB WEAP Model**			
HU	**2018**	**2023**	**2028**	**2038**	**2018**	**2023**	**2028**	**2038**
Serengeti	12	21	38	122	12	21	38	122
Somoche	0	0	0	0	0	0	0	0
Mara	2,873	2,963	3,122	3,914	2,873	2,962	3,120	3,910
Total	2,885	2,984	3,160	4,036	2,885	2,983	3,159	4,032

	Projected wildlife demand (m^3/day) (as presented in Table 4-32 of the Tanzania Demand Assessment)	Projected wildlife demand (m^3/day) as calculated in the MRB WEAP Model[3]
HU	**All Years**	**All Years**
Serengeti	4,823	9,683
Somoche	0	0
Mara	0	0
Total	4,823	9,683

Table 3. Demands in Tanzania, compared between the Tanzania Demand Assessment and the MRB WEAP model.

[1]The demand in the WEAP model is nearly double that in the Demand Assessment because the WAP includes 20L/person/day of the demand in the reserve, and only 30L/person/day in Table 4-5. The full demand (50L/person/day) is included in the demand site in WEAP.

[2]Slight differences between the Demand Assessment and WEAP values occur because applying the growth rate as indicated in the assessment yielded slightly different results in WEAP.

[3]In a revised version of the Tanzania Demand Assessment, an assumption was added that only half the population of animals would be in any given hydrologic unit at a time. This assumption was not built into the WEAP model and, as such, demands are double those in the demand assessment. Despite this, demands for wildlife are very small relative to flows in the river.

HU	2017 domestic demand from population data (m^3/day) (As presented in section 4.1 of the Kenya Water Demand Assessment)	2017 domestic demand (m^3/day) as calculated in the MRB WEAP Model
Nyangores	12,455	12,455
Amala	15,572	15,572
Talek incl. Lemek	2,309	2,309
Sand River	1,901	1,901
Mara A	4,248	4,248
Mara B	0	0
Total	36,485	36,485

HU	2017 Tourism demand based on the results of the abstraction survey (m^3/day) (As presented in section 4.2 of the Kenya Water Demand Assessment)	2017 tourism demand (m^3/day) as calculated in the MRB WEAP Model
Nyangores	0	0
Amala	0	0
Lemek	27	381
Talek	354	
Sand River	77	77
Mara A	107	98
Mara B		8
Total	**565**	564

HU	2017 Livestock demand (m^3/day) (As presented in section 4.4 of the Kenya Water Demand Assessment)	2017 livestock demand (m^3/day) as calculated in the MRB WEAP Model
Nyangores	1,539	1,557
Amala	2,339	245
Talek incl. Lemek	9,081	9,180
Sand River	1,777	1,796
Mara A	6,369	6,439
Mara B	0	0
Total	21,104	19,217

HU	Wildlife water demand (m^3/day) (As presented in section 4.5 of the Kenya Water Demand Assessment)	Wildlife demand (m^3/day) as calculated in the MRB WEAP Model[1]
Nyangores	0	0
Amala	13	6
Talek incl. Lemek	385	252
Sand River	38	26
Mara A	408	381
Mara B	102	95
Total	946	760
HU	**2017 Industrial and Commercial demand (m^3/day) (As presented in section 4.6 of the Kenya Water Demand Assessment)**	**2017 Industrial and Commercial water demand (m^3/day) as calculated in the MRB WEAP Model**
Nyangores	161	161
Amala	249	245
Lemek	0	0
Sand River	0	0
Mara	0	0
Talek	2	2
Total	412	408

Table 4. Demands in Kenya, compared between the Kenya Demand Assessment and the MRB WEAP model.

	Other demands included in the WEAP model (m^3/day)			
	2,018	**2,023**	**2,028**	**2,038**
Mara	322	340	359	401
Serengeti	2	2	2	3
Sand	6	6	6	7
Talek	2	2	2	3
Nyangores	157	166	175	195
Amala	8	9	9	10

Table 5. Other demands which were not presented in Demand Assessments, but were presented in abstraction survey results and therefore are included in the MRB WEAP model.

[1] Differences are likely due to differences in migration assumptions. Monthly populations and demand estimations were not provided in the demand assessment, so assumptions were made in the WEAP model based on the Tanzania Demand Assessment.

2.4. WATER SUPPLIES

The MRB model simulates surface water flow and groundwater storage based on catchment hydrology and water use. Surface water supplies include rivers and water pans. In addition to the mainstem of the Mara River, the model simulates flows on the major tributaries, which include the Amala, Nyangores, Talek, Sand, and Somoche rivers. Storage in water pans is aggregated for each HU in the model, as is groundwater storage.

2.4.1. SURFACE WATER

WEAP simulates water flow in rivers using the rainfall-runoff approach described in section 2.2. Water reaches the rivers from catchment objects (green circles) via runoff/infiltration links in WEAP which connect catchments to the river. These are depicted by dotted blue lines in the model schematic (Figure 2).

Water pans are depressions in the landscape that collect rainfall and provide seasonal water supplies. They are primarily used to support livestock but may also be used for domestic and agricultural use. According to the Water Abstraction Survey Report, water pans currently exist in all three HUs in Tanzania (Table 6). In Kenya, water pans are currently only identified in the Mara A catchment. This is likely an underestimation, however. Quantitative data were not available to support other assumptions. Water pans in WEAP are represented as local reservoirs, or reservoirs that are not located on a river. These are depicted by green triangles.

To estimate the total capacity of water pans in Kenya, it was assumed that abstractors use their pans at the rate indicated in the water abstraction survey for two-thirds of the year (243 days). This was multiplied by the rate to get an estimated total volume of all pans in each HU (Table 6). It was assumed pans are 1-2 meters deep.

In Tanzania, total water pan capacity was estimated by assuming the water pans had sufficient storage to meet demands that use them (Table 6) in June, July and August for most areas, but additionally to meet demands in September in the Somoche HU. This is because without the added storage, significant shortage occurred in the Somoche HU due to high reliance on water pans. Total capacities are shown in Table 6. With these assumptions, there are close to no unmet demands in Tanzania the baseline historical period, meaning between the water pans and other water sources, sufficient water is available to meet demands in nearly all months. Some exceptions are in dry years when there is not enoughwat in the pans to meet the demands of livestock in every month. It was assumed pans are 1-2 meter deep.

The total capacity of all water pans increases with time at the same rate that agricultural demands increase. This is based on the assumption that as demands grow, new water pans will be developed. All water pans are filled with precipitation and affected by modeled evaporation. In Tanzania, water pans also divert water from the rivers to fill, while in Kenya they only fill from runoff and precipitation. In Tanzania, when the reserve is enforced, water pans are not able to fill from river water. The reserve is not enforced in the baseline scenario.

Because there is little information available to accurately describe the water pans, there is much uncertainty around modeling them. This uncertainty includes measurements such as their size or total capacity, the amount of water that flows into them from runoff, and the amount of water that evaporates from them. As such, we have included all assumptions regarding the water pans as Key Assumptions within the WEAP model. This way we may easily update the model as more information becomes available, and also test the sensitivity of these assumptions.

HU	Water Pan Abstractions, according to Abstraction data (m3/day)	Assumed Water Pan Total Capacity as implemented in the MRB model (m3)	Demands met with Water Pans, according to Abstraction data	Demands met with Water Pans as implemented in the MRB model
Somoche (TZ)	34	257,330	None according to the raw data, but pans are indicated as used in the Abstraction Survey Report	Livestock, Agriculture
Serengeti (TZ)	323	570,218	Livestock	Domestic, Livestock
Mara (TZ)	8182	1,860,752	Domestic, Livestock, Irrigation, Mining, Other	Domestic, Livestock, Agriculture, Other (assumed all “water pan” sources from mining are actually sourced originally from groundwater)
MaraA (KE)	23	5,589	Domestic, Tourism	Domestic, Tourism

Table 6. Explanation of water pan assumptions and representation in WEAP.

2.4.2. GROUNDWATER SUPPLIES

The Mara River WEAP model accounts for groundwater as a supply for water users and as a contributor to streamflow. These groundwater nodes in the model represent shallow, unconfined aquifers that are physically linked to catchments. The catchments act as a source of percolation to the water table, and to rivers. The rivers can either be a source of groundwater recharge, in the case of a losing river reach, or a sink for groundwater outflow when groundwater levels exceed the height of the river reach’s height above riverbed. Groundwater nodes are linked by way of transmission links to water demands to represent groundwater pumping.

The WEAP model uses a simplified, physically-based approach for simulating groundwater levels and lateral flows between the aquifer and the river. This is represented as a wedge that is symmetrical about the river, such that recharge or extraction from one side of the wedge represents half of the total rate (Figure 5).

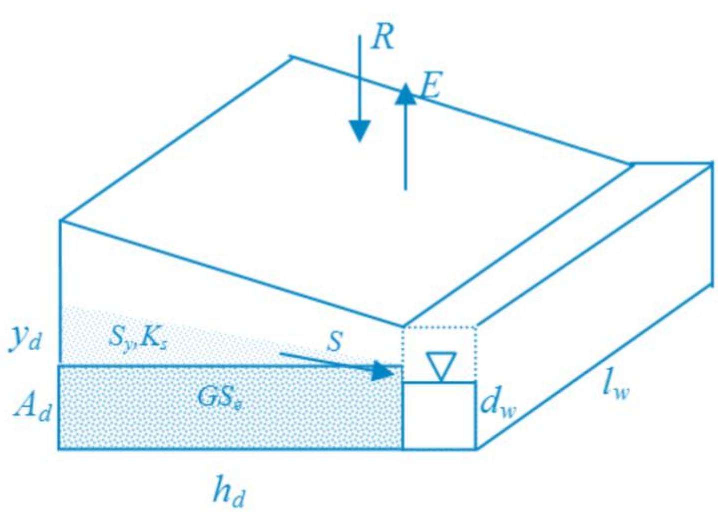


Figure 5. WEAP's groundwater 'wedge' model.

Because sufficient data is lacking to adequately calibrate groundwater levels, the model has been calibrated such that storage levels remain stable over the historical period of simulation (1971-1990). The calibration process set the length of the stream-aquifer interface (l_w) equal to values estimated using GIS and set the specific yield (S_y) uniformly to 0.4, which is generally suitable to groundwater in the region. The wetted depth of the stream-aquifer (d_w) and the horizontal distance from the stream to the centroid of the contributing area of the aquifer (h_d) were adjusted until groundwater storage levels were stabilized for the historical period of simulation.

2.5. CONNECTING WATER SUPPLIES AND DEMANDS

A single demand node in WEAP can be connected to multiple water sources by way of transmission links (green lines in Figure 2). WEAP decides which of these sources to draw from based on assigned preferences, which vary between demand types and in reality, are generally determined by cost, availability, and/or water quality considerations. The extent to which any one source can be accessed may also depend on physical and/or permitted limitations. In WEAP, these considerations are represented though preferences and limitations on transmission link flows as a maximum percent of demand.

In the MRB model, preferences and limitations on transmission link flows were set based on water abstraction survey data and are presented in Table 7 below, where under preference, '1' represents the highest preference and '3' represents the lowest. Limitations on transmission link flows are expressed as a percentage of water demand. In WEAP, water is first taken from the source with the highest preference until that supply is no longer available, or until the maximum percent of demand allowed from that source is met. Then, the next preferred source is used and so on. All wildlife demands are met with river water and are not shown in Table 7.

Table 7. Water supply preference and maximum percent of demand that can be met from different water sources.

Hydrologic Unit	Demand Type	Preference			Maximum Percent of Demand		
		Ground-water	Water Pan	River	Ground-water	Water Pan	River
HU1 (Mara)	Domestic	2	1	-	-	-	-
	Livestock	1	2	3	11	-	-
	Agriculture	-	1	2	-	6	-
	Mining/Industrial	1	-	2	99	-	-
	Tourism	1	-	-	-	-	-
	Other	2	1	-	-	-	-
HU2 (Somoche)	Domestic	2	-	1	-	-	-
	Livestock	-	1	2	-	-	-
	Agriculture	-	1	2	-	-	-
	Mining/Industrial	N/A	N/A	N/A	N/A	N/A	N/A
	Tourism	N/A	N/A	N/A	N/A	N/A	N/A
	Other	N/A	N/A	N/A	N/A	N/A	N/A
HU3 (Serengeti)	Domestic	2	1	-	-	2	-
	Livestock	-	1	-	-	-	-
	Agriculture	N/A	N/A	N/A	N/A	N/A	N/A
	Mining/Industrial	-	-	1	-	-	-
	Tourism	1	-	-	-	-	-
	Other	-	-	1	-	-	-

HU4 (Sand)	Domestic	1	-	2	98.2	-	-
	Livestock	1	-	-	-	-	-
	Agriculture	N/A	N/A	N/A	N/A	N/A	N/A
	Mining/Industrial	N/A	N/A	N/A	N/A	N/A	N/A
	Tourism	1	-	2	95.8	-	-
	Other	1	-	2	10.7	-	-
HU 5 (Mara B)	Domestic	N/A	N/A	N/A	N/A	N/A	N/A
	Livestock	N/A	N/A	N/A	N/A	N/A	N/A
	Agriculture	N/A	N/A	N/A	N/A	N/A	N/A
	Mining/Industrial	N/A	N/A	N/A	N/A	N/A	N/A
	Tourism	1	-	2	58.3	-	-
	Other	N/A	N/A	N/A	N/A	N/A	N/A
HU6 (Talek)	Domestic	1	-	2	42.6	-	-
	Livestock	1	-	-	-	-	-
	Agriculture	N/A	N/A	N/A	N/A	N/A	N/A
	Mining/Industrial	1	-	-	-	-	-
	Tourism	1	-	2	93.5	-	-
	Other	1	-	-	-	-	-
HU7 (Mara A)	Domestic	1	2	3	59.3	-	-
	Livestock	-	1	2	-	-	-
	Agriculture	-	1	2	-	-	-
	Mining/Industrial	N/A	N/A	N/A	N/A	N/A	N/A
	Tourism	1	2	3	68.8	-	-
	Other	N/A	N/A	N/A	N/A	N/A	N/A
HU8 (Nyangores)	Domestic	1	-	2	21.9	-	-
	Livestock	1	-	2	94.6	-	-
	Agriculture	N/A	N/A	N/A	N/A	N/A	N/A
	Mining/Industrial	1	-	2	1.3	-	-
	Tourism	N/A	N/A	N/A	N/A	N/A	N/A
	Other	1	-	2	74.2	-	-
HU9 (Amala)	Domestic	1		2	41.7	-	-
	Livestock	1	-	2	71.2	-	-
	Agriculture	1	-	2	0.4	-	-
	Mining/Industrial	1	-	2	1.3	-	-
	Tourism	N/A	N/A	N/A	N/A	N/A	N/A
	Other	1	-	2	62.5	-	-

There were a few assumptions made in the model regarding the sources available to each demand. For mining in the Mara HU, the abstraction survey indicated water pans are largely used. It was assumed that the original source of water pan water is groundwater; therefore, groundwater is the only source available to the mining demand in the Mara HU. No water pans were visited in the Somoche HU during the abstraction survey, and therefore there are no abstraction data. However, the Abstraction Survey report indicates water pans are used. In the model, it was assumed these pans are used for livestock. In WEAP, borehole, spring, and shallow well are all combined as groundwater. To set rules for how much water each demand can take from each source, the following assumptions were made:

- If a demand takes water from groundwater, surface water, and water pans, the groundwater is used first (preference 1 Table 7). It is constrained, however, by the maximum percent of demand, which is calculated as the proportion of groundwater used from abstraction survey results (see Table 7, farthest right three columns). After this, water pans are used if water is available (preference 2), then surface water is used if additional water is needed to meet the demand (preference 3).

- If a demand takes water from groundwater and surface water, the groundwater is used first (preference 1, Table 7) but is constrained by the maximum percent of demand, which is calculated as the proportion of groundwater used from abstraction survey results (see Table 7, farthest right three columns). Surface water is then used if more water is needed (preference 2, Table 7).
- If a demand takes water from groundwater and water pans, water pans are used first if available (preference 1, Table 7), then groundwater is used if additional water is needed (preference 2, Table 7).
- If a demand takes water from surface water and water pans, water pans are used first (preference 1, Table 7), then surface water is used if additional water is needed (preference 2, Table 7).

There are two exceptions to these rules. Agriculture in the Mara HU only meets 6 percent of its demands with water from water pans according to the abstraction survey results. Domestic in the Serengeti HU only uses 2 percent from water pans. Because these are so small and they share the water pans with other demands, the allowable withdrawal from water pans for these two demands is constrained to this percentage of their demand. Because all water pans in each HU are combined into one WEAP object, this prevents these two demands from taking additional water, preventing other demands from using that water. Under these assumptions, all demands are met in every month in the historical period, except in some dry years when livestock experiences shortages because there is not enough water in the pans in the model to meet these demands every month. Additional data would be helpful to better understand how the livestock demands are met that are consistent with available supplies.

3. MODEL CALIBRATION AND VALIDATION

Before using the model to evaluate the performance of water supply reliability for various water users in the MRB, it was necessary to first calibrate and validate the hydrological routines to ensure that it can adequately estimate flow within the river.

3.1. CALIBRATION DATA

The first step in calibrating any model is to select a historical period of record that includes concurrent input and observation data that cover a period long enough to capture the range of conditions (wet and dry) within a basin. In this case, the main input data for the WEAP model include climate data and the observation data are gaged streamflow.

3.1.1. CLIMATE

Within the Mara River basin, the Kenyan Meteorological Department and the Tanzanian Meteorological Agency are responsible for operating and maintaining a network of meteorological stations. Monthly precipitation data was collected from these stations for a historical period dating back to around 1960 and extending to 2010. These data are summarized in Table 8 below.

Table 8. Meteorological stations within the Mara River Basin.

Station Number	Station Name	Beginning Date	End Date	Total Number of Records	Percent Missing
9035228	KIPTUNGA FOREST STATION ELBURGON	Feb-61	Jul-09	546	6%
9035265	BOMET WATER SUPPLY	Feb-67	Jul-09	449	12%
9035284	MULOT	Nov-73	Dec-98	291	4%
9135013	KEEKOROK HYDROMET STATION NAROK	Feb-65	Jan-97	352	8%
9135019	LEMEK MAASAI FARM	Jul-66	Oct-93	233	29%
9135026	GOVERNORS CAMP	Mar-73	May-04	254	32%
9035031	DANSON K NGUGI SAW MILL	Feb-61	Jan-88	230	29%
9035079	TENWEK MISSION SOTIK	Feb-61	Mar-02	453	8%
9035085	OLENGURUONE	Feb-61	Jan-05	418	21%
9035227	DISTRICT OFFICE BOMET	Feb-61	Nov-92	354	7%
9035236	CHEPALUNGU FOREST STATION SOTIK	Feb-70	Jan-93	276	0%
9035241	BARAGET FOREST STATION	Aug-61	Jan-98	428	2%
9035260	KOIWA ESTATE KERICHO	Feb-70	Jan-93	276	0%
9035302	NYANGORES FOREST STATION	Sep-79	Jul-09	336	6%
9133000	MUSOMA METEO STATION	Feb-70	Jan-93	276	0%
9134008	NYABASSI	Feb-70	Jan-93	276	0%
9134019	KISII NTIMARU AGRIC HOUSE	Feb-70	Jan-93	276	0%
9134027	LOLGORIEN WS	Feb-70	Jan-93	276	0%
9134033	MUGUMU	Feb-70	Jan-93	276	0%
9135001	NAROK METEOROLOGICAL STATION	Feb-61	Jul-09	578	1%
9135008	KABOSON GOSPEL MISSION SOTIK	Feb-61	Aug-85	280	5%
9135010	AITONG HYDROMET STATION SOTIK	Feb-61	Apr-89	200	41%
9135022	AFRICA GOSPEL CHURCH NAIKARA	Feb-69	Jun-88	207	11%
9135025	ILKERIN INTEGRAL DEVELOPMENT PROJECT	May-73	Dec-99	268	16%
9135035	KICHWA TEMBO CAMP	Feb-88	Jan-03	122	32%

While the basin is generally well-equipped with a network of rainfall and evaporation stations, a lack of adequate resources to operate and maintain the stations has resulted in inconsistent and occasionally sparse data collection. For this reason, we chose the 20-year period between 1971-1990 as the period for which we would calibrate and validate the model, because it contains the highest concentration of climate data over the 50-year period of record (Figure 6 and Table 9).

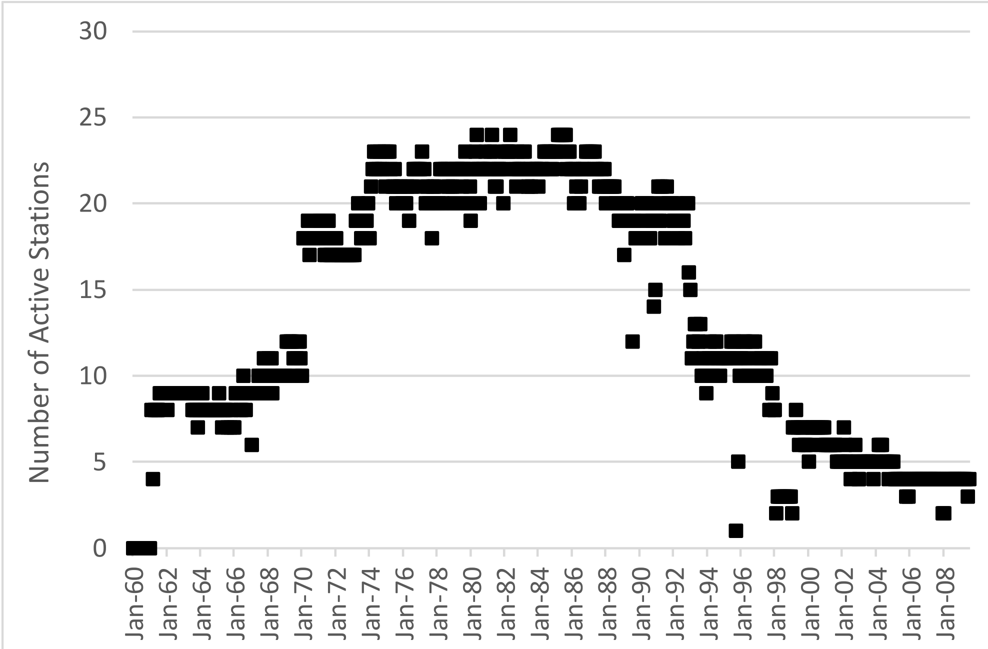


Figure 6. Number of active meteorological stations, 1960-2010.

Table 9. Percent coverage of each meteorological station for calibration and validation periods.

Station Name	Percent Coverage 1971-1980	Percent Coverage 1981-1990
KIPTUNGA FOREST STATION ELBURGON	98%	98%
BOMET WATER SUPPLY	79%	99%
MULOT	66%	99%
KEEKOROK HYDROMET STATION NAROK	99%	98%
LEMEK MAASAI FARM	65%	68%
GOVERNORS CAMP	63%	63%
DANSON K NGUGI SAW MILL	71%	71%
TENWEK MISSION SOTIK	98%	98%
OLENGURUONE	94%	65%
DISTRICT OFFICE BOMET	90%	98%
CHEPALUNGU FOREST STATION SOTIK	100%	100%
BARAGET FOREST STATION	98%	97%
KOIWA ESTATE KERICHO	100%	100%
NYANGORES FOREST STATION	13%	98%
MUSOMA METEO STATION	100%	100%
NYABASSI	100%	100%
KISII NTIMARU AGRIC HOUSE	100%	100%
LOLGORIEN WS	100%	100%
MUGUMU	100%	100%
NAROK METEOROLOGICAL STATION	100%	98%
KABOSON GOSPEL MISSION SOTIK	89%	45%
AITONG HYDROMET STATION SOTIK	45%	72%
AFRICA GOSPEL CHURCH NAIKARA	93%	61%
ILKERIN INTEGRAL DEVELOPMENT PROJECT	75%	83%
KICHWA TEMBO CAMP	0%	13%

3.1.2. STREAMFLOW

The 20-year period between 1971 and 1990 also coincides with the period of most reliable data collection for the main streamflow gages in the basin. These include stations on the Nyangores River at Bomet Bridge, the Amala River at Kapkimolwa, and the lower Mara River at Mara Mines (Table 10 and Figure 7).

Table 10. Percent of period with monthly streamflow observations.

	Bomet Bridge	Kapkimolwa	Mara Mines
Calibration (1971-1980)	75%	87%	55%
Validation (1981-1990)	87%	86%	65%

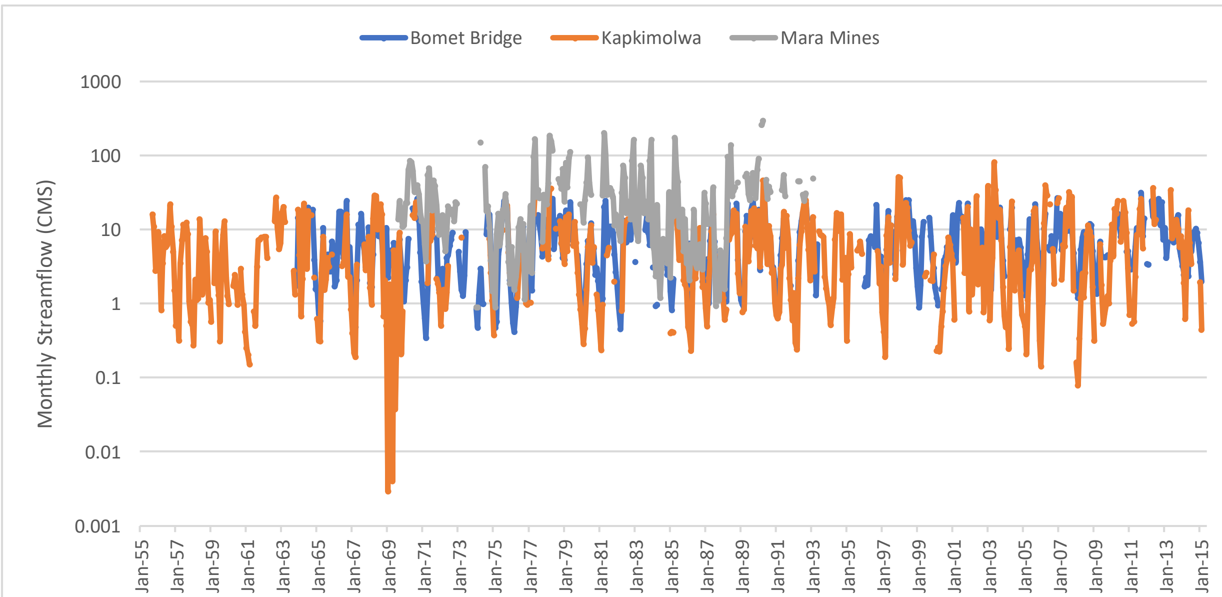


Figure 7. Historical streamflow observations for the three main gages in the MRB.

3.2. RESULTS

The Mara River WEAP model was calibrated to historical streamflows using a combination of manual methods and the optimization tool PEST (Doherty, 2002). PEST is an advanced software tool used for model calibration, parameter estimation, and predictive uncertainty analysis. Model simulations are most sensitive to soil water content (Rd_j) and root zone hydraulic conductivity (k_z). Thus, initial calibrations focused on these two parameters. Further refinements to the shape and timing of the resulting hydrographs were accomplished by adjusting the runoff resistance factor (*RRF*) and crop/plant coefficients (k_c).

The calibration process assumed that model parameters are unique for each land class and that land-class characteristics are uniform across the basin. For example, grasses may respond differently than forests, but grasses in the upper basin will respond the same as grasses in the lower basin.

While some of the objective function values presented in Table 11 are relatively poor, the overall results illustrated in Figure 8, Figure 9, and Figure 10 are generally acceptable. Where there are observed data available that can be considered reasonably representative of flow conditions, the WEAP model is certainly able to approximate the frequency characteristics. The sometimes-poor values for NSE and PBIAS are likely to be partly associated with inadequate rainfall data to accurately quantify individual monthly rainfall totals at the catchment scale, the effects of different spatial distributions of rainfall for the same monthly spatially-averaged depth, and the effects of different temporal distributions of rainfall for the same monthly depth (i.e. different daily distributions). None of these types of uncertainty can be resolved with a monthly time-step model applied in an area the size of the Mara River Basin, where many parts of the basin are inadequately gauged.

These issues of data uncertainty can be seen by looking at the percentage of precipitation that arrives at the three streamflow gages (Figure 11). The simulated values fall within the range of expected percentages and the month-to-month changes in these percentages are generally gradual, which is to be expected with a hydrological model that accounts for runoff attenuation and soil water storage. On the other hand, the observed values are much more erratic, do not exhibit a recognizable seasonal pattern, and occasionally reach unreasonable values. This suggests that there are inconsistencies between the precipitation and streamflow data. It should be the long-term goal to resolve these issues by conducting a thorough examination of the input and observation data. However, it is our contention that the calibration is sufficient for the purposes of using the model to conduct scenario analysis as a means of exploring potential management strategies for the basin.

Table 11. Calibration and validation metrics.

	NSE		PBIAS		SDR	
	1971-1980	1981-1990	1971-1980	1981-1990	1971-1980	1981-1990
Nyangores River at Bomet Bridge	0.55	0.64	-12%	-6%	0.70	0.93
Amala River at Kapkimolwa	0.76	0.51	-10%	9%	0.74	0.89
Mara River at Mara Mines	0.64	0.45	-22%	-11%	0.58	0.43

NYANGORES RIVER at BOMET BRIDGE

CALIBRATION | VALIDATION

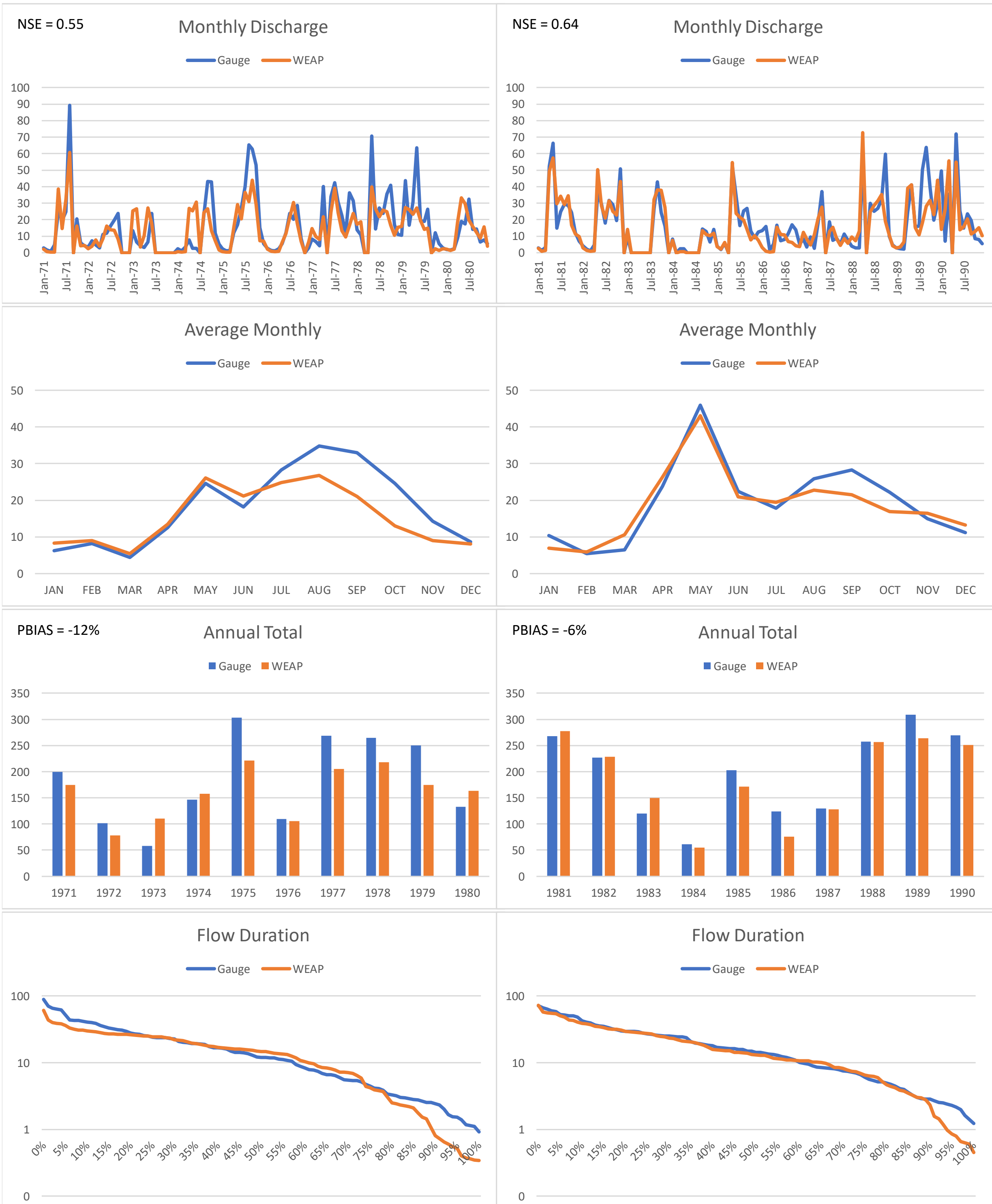


Figure 8. Calibration and validation results for Nyangores River at Bomet Bridge.

AMALA RIVER at KAPKIMOLWA

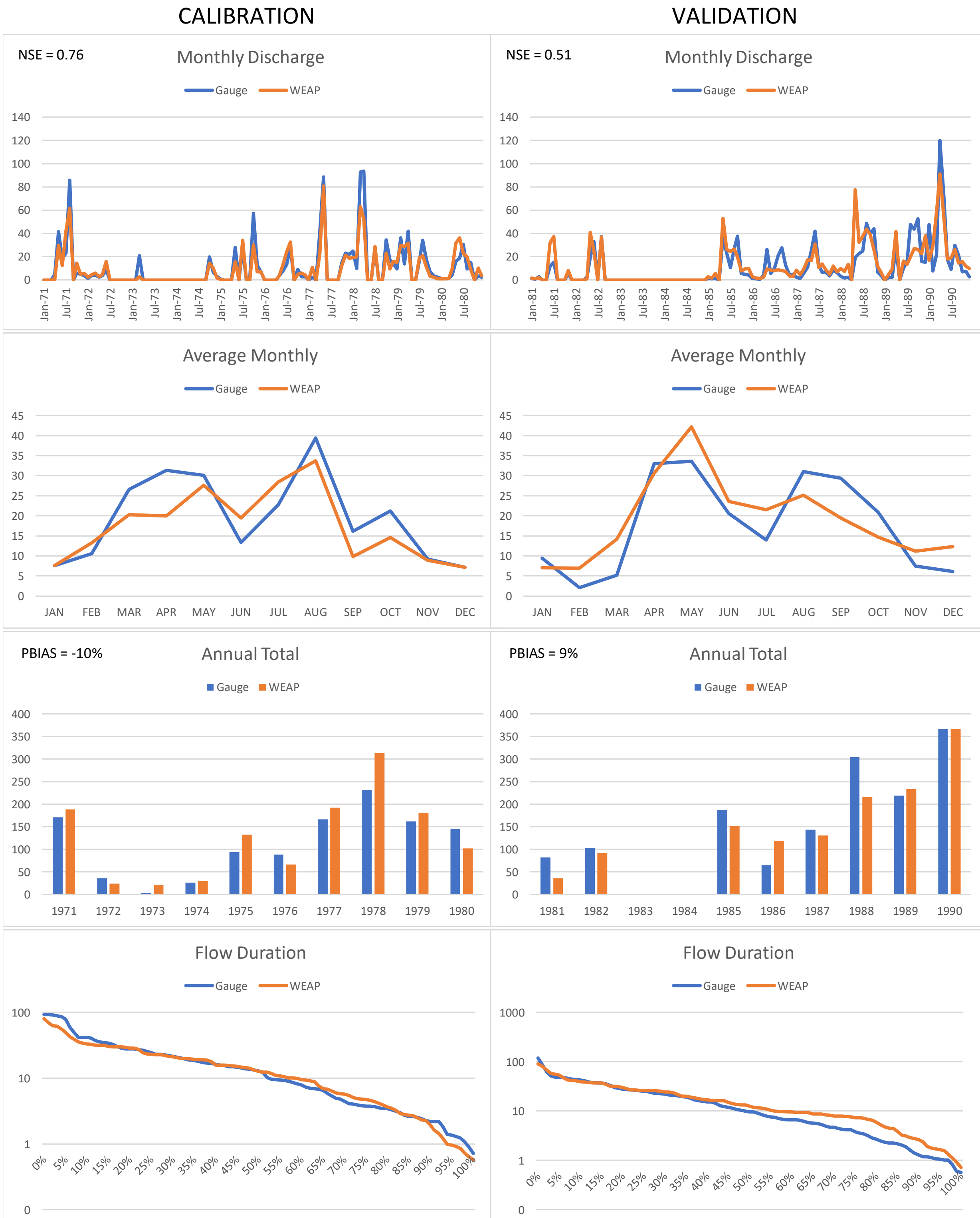


Figure 9. Calibration and validation results for Amala River at Kapkimolwa.

MARA RIVER at MARA MINES

CALIBRATION VALIDATION

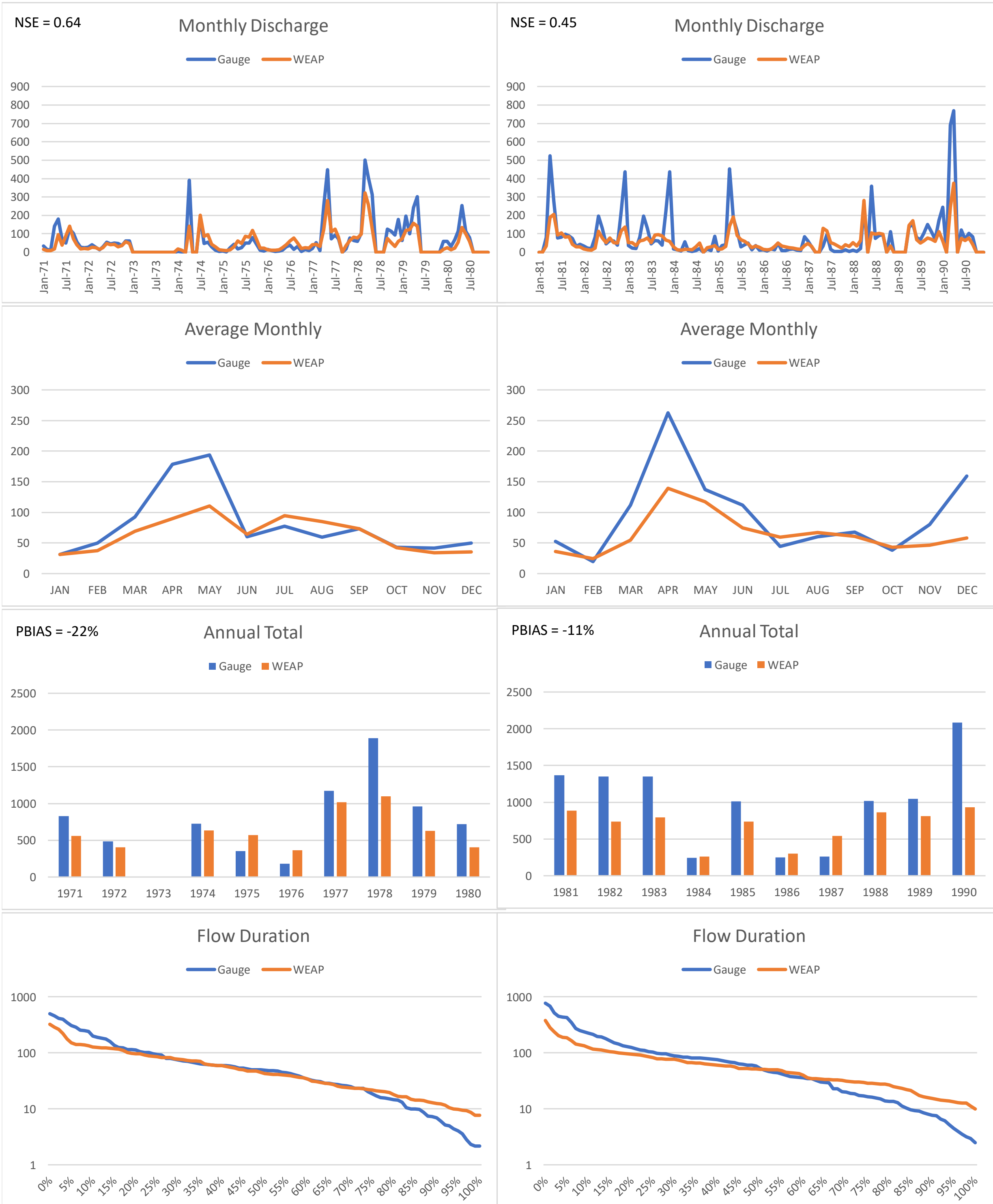
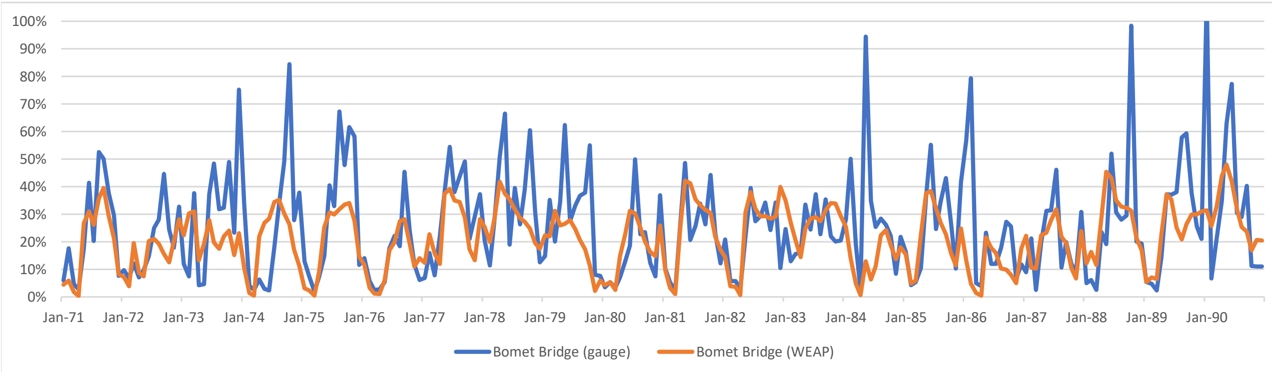
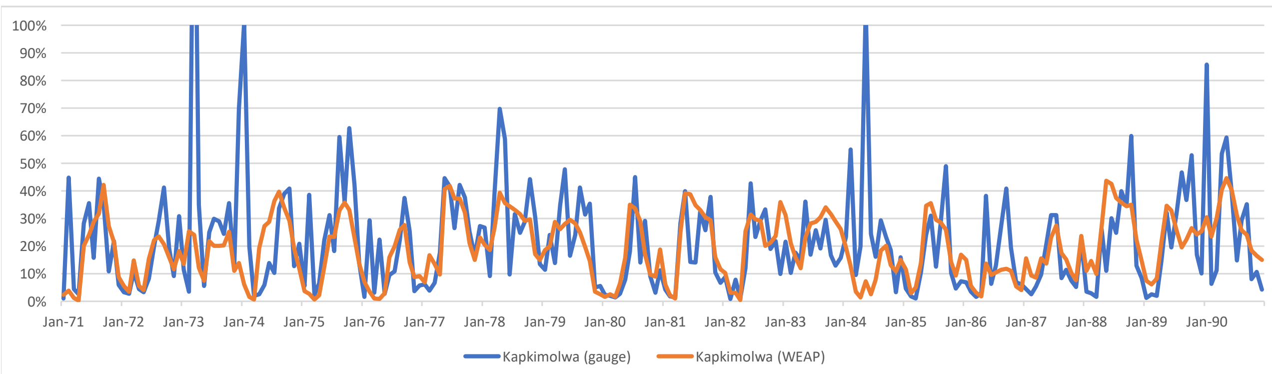


Figure 10. Calibration and validation results for Mara River at Mara Mines.

NYANGORES RIVER at BOMET BRIDGE



AMALA RIVER at KAPKIMOLWA



MARA RIVER at MARA MINES

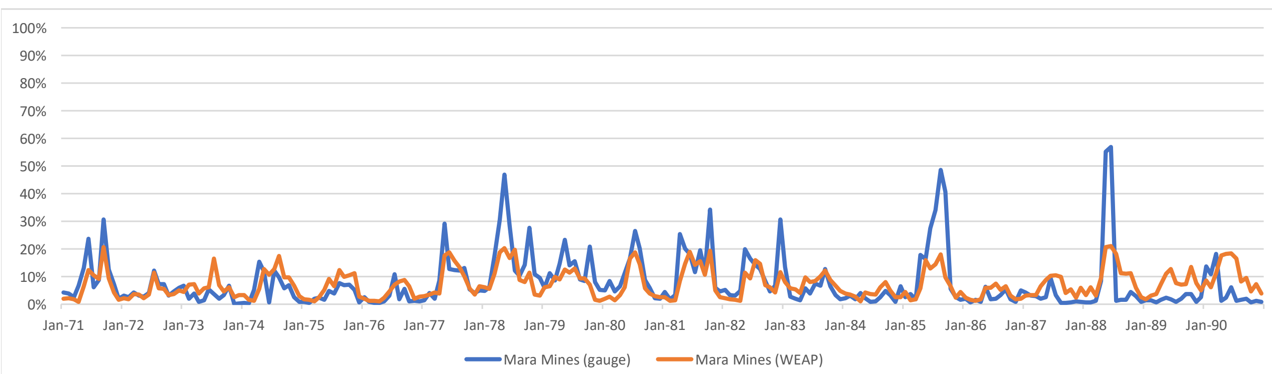


Figure 11. Simulated and observed monthly runoff as a percentage of precipitation.

4. SUMMARY

The Mara River WEAP model has been developed as a tool to assess water availability throughout the basin under current and possible future conditions. The model was developed to represent the main water supply and demand features of the Mara River Basin (MRB) at a spatial scale appropriate to simulate major hydrologic flows; to represent major demographic trends; and to evaluate the effects of water management responses to anticipated changes within the basin.

The major weakness of the model is the fact that it is based on a very limited data set, particularly around the tributaries. It is a useful model for planning, but it is critical that sensitivity analyses are conducted given the uncertainty around the calibration.