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Evaluation of Koka Reservoir Operation under Sedimentation: Implications for Irrigation Water Demands in Upper Awash Valley, Awash River Basin

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Abstract

Water scarcity has been a major issue in the Awash River Basin of Ethiopia. The Koka Reservoir is the sole water storage source supporting extensive irrigation activities in the Upper Awash Valley, a key part of the basin. However, sedimentation has reduced the reservoir's active storage capacity, posing serious risks to its ability to meet irrigation demands in the valley. This study aims to evaluate the reservoir's operational performance by assessing irrigation water demand and analyzing the water supply-demand balance under recent sedimentation conditions. Key datasets include crops, census, digital elevation model, hydro-meteorological, and reservoir operation data. The primary software tools applied were CROPWAT, ArcMap, and HEC-ResSim. Water resource system performance evaluation criteria such as reliability, vulnerability, and resilience were employed. The annual estimated gross irrigation water requirement for the study region was 1,525 Mm^3. Reservoir operation has been simulated using three decades of daily inflow from 1985 to 2015 by considering different alternatives of the irrigation water demands. When the model was simulated for Alternative 1, the reservoir met full demand less than half the time (time reliability 42.7%), supplied most of the total demand volume despite shortages (volumetric reliability 73.7%), experienced severe deficits when failures occurred (mean vulnerability 25.4 m^3/s, maximum 80.0 m^3/s), and had limited ability to recover (resilience 27.7%); even in Alternative 2, reliability and resilience improved and vulnerability was moderate, but full demand was still not consistently met. The results indicate that the reservoir capacity under recent sedimentation conditions is insufficient to store high inflows and meet high demand during rainy and dry seasons, respectively. This study does not account for the potential impacts of land use/land cover and climate change, which could influence the hydrological balance and reservoir performance.

Keywords: Awash River; CROPWAT; HEC-ResSim; Performance Evaluation; Reservoir Operation; Water Scarcity.

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1. INTRODUCTION

1.1. Background

According to the (World Economic Forum, 2019), water scarcity has been considered as one of the largest global risks in terms of potential impact over the next decade. (FAO, 2012) distinguishes two major forms of water scarcity: physical and economic. Physical scarcity occurs when water is insufficient to meet all demands, including environmental flows, while economic scarcity results from lack of investment or capacity to supply water and it characterizes most of Sub-Saharan Africa. Water scarcity affects every continent, leading to unmet demand, competition over water quantity or quality, user conflicts, irreversible groundwater depletion, and environmental damage.

Ethiopia is one of the Sub-Saharan African countries where water availability varies widely both temporally and spatially across river basins (Berhanu et al., 2013). According to MoWR(1999), Ethiopia has a surface water potential of 122 BCM and groundwater potential between 2.6 and 6.5 BCM. Nevertheless, water availability is uneven and erratic due to limited infrastructure, causing economic water scarcity in different river basin of the country. Awulachew (2010) estimates the irrigable land potential at 5.3 Mha, including 1.6 Mha from rainwater harvesting and groundwater. (Berhanu et al., 2013) estimate 124.4 BCM river water, 70 BCM lake water, and 30 BCM groundwater, with potential for 3.8 Mha irrigation and 45,000 MW hydro-power. A review by Ayalew (2018) highlights challenges such as transboundary sharing, topography, and financial constraints but notes the country's promising water resource availability for the development opportunities.

Awash River basin is the most developed river basin in the country and water scarcity is a critical issue in the basin. Within the basin, there are many irrigation systems that face competition from other sectors for water(Hemel et al., 2013). The study by (Adeba et al., 2015) estimates that the average annual demand for water in the Awash River basin was about 4.67BCM, as compared to an annual average surface water availability from 1980 to 2012 of about 4.64BCM. This shows that, on annual average, the demand exceeds the availability by 0.03BCM during the study period. Seasonal and spatial water deficits are even more serious.

A storage reservoir is a vital component of the water resources system, creating necessary storage for flow regulation and providing hydraulic head for flow diversion by gravity and increased power generation (Karamouz et al., 2003) , and typically consisting of three main zones such as flood control, active, and dead storage(Doyle et al., 2019). Accordingly, the Koka Reservoir, commissioned in 1960 with a maximum capacity of 1,850 Mm^3 at MFL and a full supply capacity of 1,650 Mm^3, was built for hydro-power but also regulates the Awash River flow at downstream for irrigation, domestic use and flood control downstream of the reservoir (HALCROW, 1989) and (EEPC, 2004). Following the commencement of Koka Reservoir operation, irrigation development in the Upper Awash Valley has steadily expanded, relying almost entirely on releases from the reservoir. Currently, large areas in the valley are irrigated, including the Wonji and Metehara Sugar Plantations ESC (2019), Boset Fentalle, Nura Era, Bofa, Golgota and Tibila irrigation projects, Girma et al. (2007), OWWDSE (2007) and OWWDSE (2009).

However, the high rate of sedimentation in the Koka reservoir has significantly reduced its active storage capacity, posing a serious challenge to sustaining the existing irrigated area and limiting the potential for future irrigation expansion in the study area. Since the reservoir's original storage area elevation survey in 1959, several sedimentation studies have been conducted. The ministry of water resources of Ethiopia in 1999, estimated a capacity of 1,186 Mm^3, indicating 470 Mm^3 of total sedimentation and an average annual deposition of 12.2 Mm^3 (Ministry of Water Resources, 1999). Earlier surveys reported 10 Mm^3/year in 1973 by State Rivers and Water Supply Commission as cited in (Ministry of Water Resources, 1999) and 16.8 Mm^3/year in 1988 by (HALCROW, 1989). This study used forecasted 2015 storage area elevation data of the reservoir from the Awash River Basin Authority, based on the 1999 Ministry of Water Resources survey. The data indicated a 41% loss of active storage capacity due to sedimentation. The Koka Reservoir is a critical water source for irrigation and other uses in the Upper Awash Valley. Evaluating the Koka Reservoir's operation under current sedimentation conditions is essential to accurately assess the existing balance between irrigation water supply and demand. This provides critical insights for guiding sustainable reservoir water management.

A number of reservoir system analysis techniques are available for solving various problems associated with reservoir operation, with simulation and optimization being the most common. Simulation reproduces the behavior of an existing or proposed system by designing a model and conducting experiments to understand its functioning or evaluate management strategies, whereas optimization addresses "what should be" questions. One of the most efficient ways to evaluate water resources systems is through simulation models, which use physical relationships and operational rules to replicate phenomena and system behavior as closely as possible to reality under a specified policy(Simonovic, 1992) & (Loucks et al., 2005).

Models for simulating reservoir operations are essential tools for sizing storage, defining policies, supporting real-time decisions, and evaluating operational changes (Wurbs, 1993). Key components include inputs, physical relationships, constraints, operating rules, and outputs. These models simulate hydrological and sometimes economic performance using mass balance methods to track water flow through reservoir systems (U.S. Army Corps of Engineers, 1991). Common generalized reservoir/river system models used worldwide are described by Wurbs (Wurbs, 2005). HEC-ResSim is reservoir operation simulation models developed by the hydrological engineering center of the U. S. Army Corps of Engineers as the successor to the well-known HEC5(Joan D. Klipsch et al., 2002) and has been one of widely applied in water resources system analysis both globally and within Ethiopia. For example, Belay et al. (2019) used it to analyze reservoir operations for the Rib Reservoir in the Blue Nile Basin, while T. Seyoum et al. (2014) applied it to model cascaded dam operations for hydro-power generation along the Omo Gibe River Basin. Goshime (2011) evaluated the impact of climate change on Blue Nile cascade reservoirs using the model, and Tesfaye (2014) simulated the Grand Ethiopian Renaissance Dam operations and its downstream hydro-power effects. Additionally, Woldeyohanis (2010) and Wondye (2009)used HEC-ResSim for Tendaho Reservoir and Abbay Basin water allocation modeling, respectively. In this study, HEC-ResSim was employed to evaluate Koka Reservoir’s operation performance considering upper Awash Valley irrigation water demand and recent sedimentation condition. This simulation model was selected because it is free, well-documented, user-friendly with graphical interfaces, offers flexible reservoir operation options, and is widely accepted.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

2.1.1. Location

The Koka Reservoir, located in the upper part of Awash River Basin, is the most important reservoir in the basin, with an original storage capacity of 1,850 Mm^3. It was constructed on the Awash River, which drains a catchment of approximately 10,000 km^2 at the reservoir site and its location is shown in Figure 1. The major cascaded irrigation schemes in the Upper

Awash Valley that rely on Koka reservoir releases are located downstream of it along the Awash River.

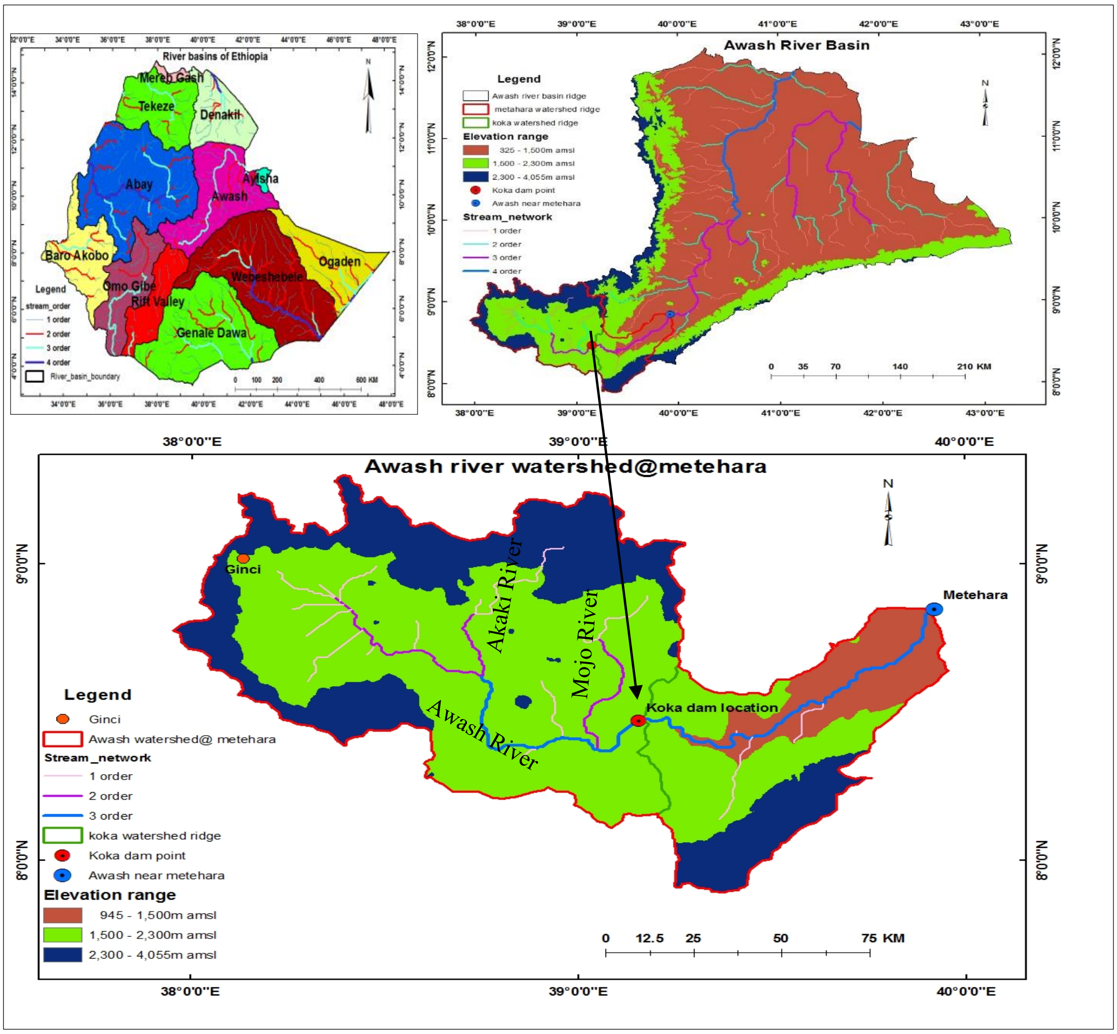

Figure 1. Location map of the study area

2.1.2. Topographic Characteristics

Based on the 30x30 m resolution Digital Elevation Model (DEM), the topographic characteristics of the study area were analyzed using the hypsometric curve and catchment slope. The elevation ranges of the study area lie between 945 m to 4055 m above mean sea level(amsl). Around 56.74% of the area lies in range of 1800 m and 4055 m, while the remaining 43.26% falls between 945 m and 1800 m elevation. The catchment features a predominantly flat to gentle slope in the central area, while steeper slopes are concentrated near the watershed boundaries. Overall, approximately 77.5% of the study area has a slope of less than 15%, and the remaining 22.5% exceeds 15%.

2.1.3. Rainfall

Monthly areal rainfall for the Upper Awash Sub-basin (upstream of Koka Dam) and the Upper Awash Valley (between Koka Dam and Metehara) was analyzed using the Thiessen polygon as shown in Figure 2(a). Using long-term rainfall data from 1990 to 2016, results indicate that the upper Awash sub-basin receives higher monthly aerial average rainfall than the Upper Awash Valley as graphically shown in Figure 2(b). In August, the maximum monthly average areal rainfall reaches 207.3 mm in the Upper Awash Sub-basin and 148.5 mm in the Upper Awash Valley, while the minimum occurs in December, with 21.4 mm and 15.57 mm, respectively.

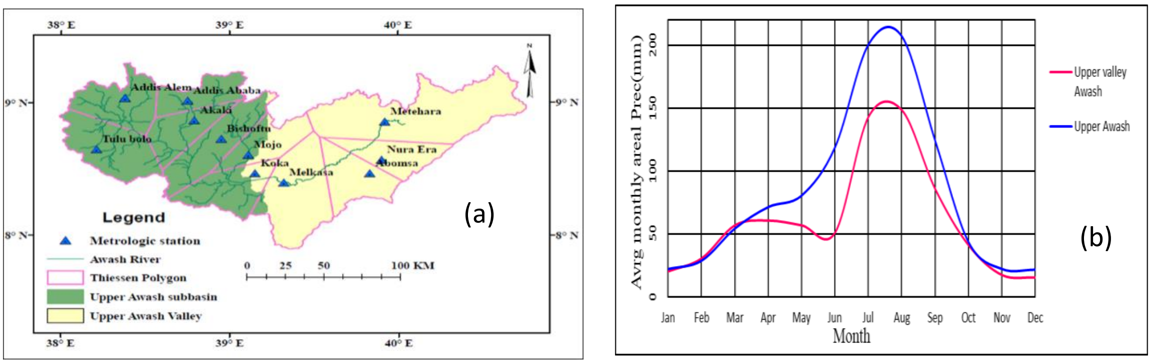

Figure 2. Aerial Rainfall; (a). Theisen polygon (b). Average monthly areal precipitation (1990-2016)

2.2. Conceptual Framework of the Study

The main procedures and methods employed in this study to achieve the stated objectives are outlined in the conceptual framework presented in Figure 3.

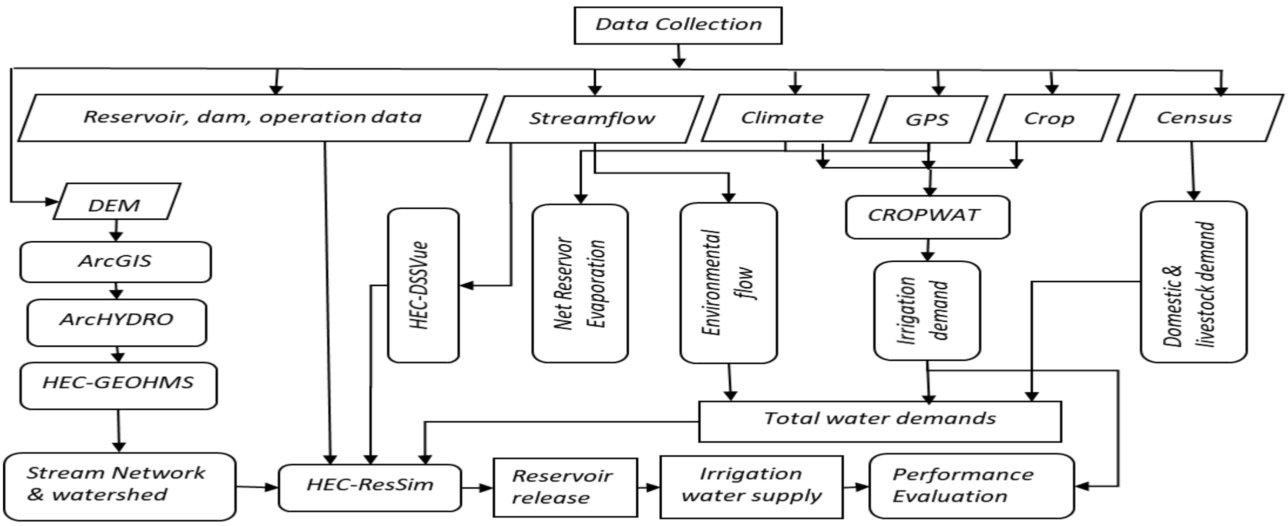

Figure 3. Conceptual framework of the study

2.3. Data Collection and Quality Analysis

Relevant data collected are shown in Table 1, and some of the standard methods applied for data analysis are illustrated in Table 2.

Table 1. Description of the data types and sources collected

Data	Sources	Year	Description
Census	CSAE	2019	Population and livestock
Streamflow	MoWIE	1986-2016	Daily stream flow
Meteorological	NMA	1986-2016	Daily T, P, RH, SH, U
Koka dam	EEP, MoWIE, ARBA		Dam, Reservoir, operation
Irrigation	ECO, ESC	2020	Command Area, Crop data
DEM	https://earthexplorer.usgs.gov/		30X30m Cell size resolution
GPS	NMA, MoWIE, ECO, ESC		X, Y, Z (Coordinate point)

Table 2. Various decision support tools adopted in this study and their purposes

Tools	Sources	Purpose
XLSTAT	https://www.xlstat.com/en/	Homogeneity test
FDC	https://hydrooffice.org/	Flow duration curve
XRealStats	https://www.real-statistics.com/	Regression analysis
HEC DSSVUE	https://www.hec.usace.army.mil/	Time series data storage system
HEC ResSim	https://www.hec.usace.army.mil/	Simulation of reservoir operation
CROPWAT	http://www.fao.org/	Irrigation water requirement

2.3.1. Meteorological Data Processing

To ensure reliable analysis, meteorological data must be complete, consistent, and free from errors including missing values, outliers, and inhomogeneities. Table 3 presents meteorological stations in the study area.

In this study, missing data were interpolated using the inverse distance weighted (IDW) method due to its efficiency and consideration of station proximity. Homogeneity of annual rainfall data was assessed using the Pettitt test, which identified a significant change point at one station (Mojo station) as shown in Figure 4, leading to its exclusion from further analysis. Additional consistency checks were performed using double mass curve analysis, which confirmed that rainfall records for the remaining stations were consistent as illustrated in Figure 5(a) and Figure 5(b) for upper awash valley and upper awash sub-basin, respectively.

Table 3. Location and variables of selected meteorological stations in the study area

Stations	y (°)	X (°)	Z (m asl)	climate variables
Bishoftu	8.73	38.95	1900	T, U, RH, P, sun hrs
Addis Ababa	9.02	38.75	2386	T, U, RH, P, sun hrs
Mojo	8.61	39.11	1763	T, U, P
Koka	8.47	39.15	1618	T, P
Akaki	8.87	38.79	2057	T, P
Addis Alem	9.04	38.38	1645	T, P
Tulu bolo	8.65	38.21	2190	T, P
Melkasa	8.40	39.32	1540	T, U, RH, P, Sun hrs
Abomsa	8.47	39.83	1630	T, U, RH, P, Sun hrs
Nura Era	8.57	39.90	1140	T, U, RH, P, Sun hrs
Metehara	8.86	39.92	944	T, U, RH, P, Sun hrs

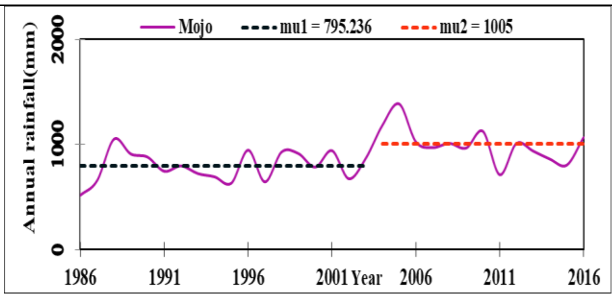

Figure 4. Detected inhomogeneity of annual rainfall time series of Mojo station

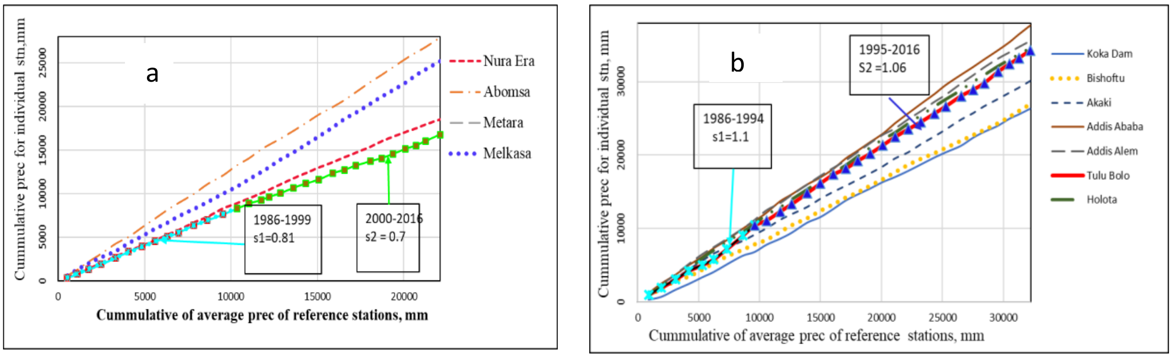

Figure 5. Double mass curve: Upper Awash valley (a); Upper Awash sub-basin (b)

2.3.2. Stream Flow Data Processing

In this study, missing streamflow data for selected stations were interpolated using multiple linear regression with reference stations exhibiting high correlation, as summarized in Table 4. Since no gauging station exists at the Koka Reservoir, located at the confluence of the Awash and Mojo Rivers, reservoir inflow was transferred from nearby Hombole and Mojo stations using the area ratio method, assuming comparable watershed characteristics (Ries Iii et al., 2000).

Table 4. Multiple linear regression of selected stations (2007-2015)

Stations	Multiple linear regression	R^2
Hombole	= 5.920 + 0.1920*(Akaki) + 1.043*(Melka Kunture)	0.96
Akaki	= -0.4+0.178*(Melka Kunture) +0.0126*(Hombole)	0.92
Melka Kunture	= -2.16+1.61*(Akaki)+ 0.615*(Hombole)	0.97
Mojo	= 0.76+0.0907*(Melka Kunture) + 0.0863 * (Akaki)	0.7

Hence, equation 1 was used to transfer flow from gauged site to reservoir inlet.

$$\text{Reservoir inflow}=1.07*\text{Hombole gauged} + 1.18*\text{Mojo gauged} \qquad 2.1$$

2.3.3. Irrigation and census data

Currently, several medium (200–3000 ha) and large scale (>3000 ha) irrigation schemes exist and some are under construction in the upper awash valley part of the basin. Existing and proposed medium and large irrigation schemes relying on Koka releases are listed in Table 5 for irrigation demand analysis.

Table 5. Medium and large-scale irrigation schemes in the upper Awash valley

Schemes	@Headwork		Command Area(ha)	Source
	Long (°)	Lat (°)		
Wonji Shoa	39.23	8.46	16000	(ESC, 2019)
Metahara	39.88	8.76	10230	(ESC, 2019)
Tibila	39.52	8.47	7000	(OWWDSE, 2009)
Golgota	39.75	8.65	600	(Dejen, 2015)
Boset Fentalle	39.85	8.72	19271	(OWWDSE 2007)
Nura Era	39.81	8.66	7187	(Girma et al., 2007)
Bofa(proposed)	39.42	8.42	4050	(ECO, 2020)

Figure 6 illustrates the spatial distribution of woredas and major irrigation schemes at periphery of awash river below Koka dam in upper awash valley part of the basin. Human and livestock populations are key water-demand sectors, and their size and distribution are critical for estimating demand; projected 2019 figures for both, obtained from Ethiopia's central statistical agency (CSA), were used for the woredas.

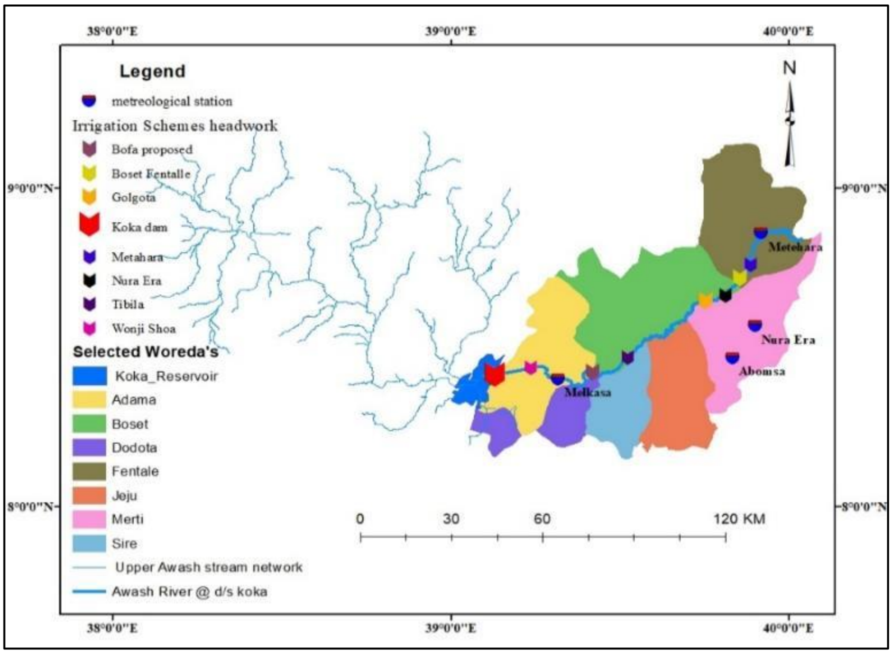

Figure 6. Schemes, nearest meteorological stations and woredas in the Upper Awash valley

2.3.4. Koka Reservoir data

Koka hydro-power Characteristics

The general physical characteristics of the reservoir, dam, outlets, and hydro-power components are summarized in Table 6.

Table 6. Physical Characteristics of Koka hydro-power Reservoir

Items	Unit	Value
Hydro power characteristics		
Power house location		Ground surface
Type of turbine		Francis, vertical
No of unit		3
Installed Capacity	MW	3x14.4MW= 43.2MW
Firm capacity	MW	34.5MW
Power Intake		
Type		gated
Number		1
Length	m	6.1
Height	m	5.15

Storage Area Elevation Curve

Reservoir simulation requires the elevation area capacity curve. For Koka Reservoir, the curve adjusted for sedimentation predicted by the Awash Authority as of 2015 was used, as shown in Figure 7.

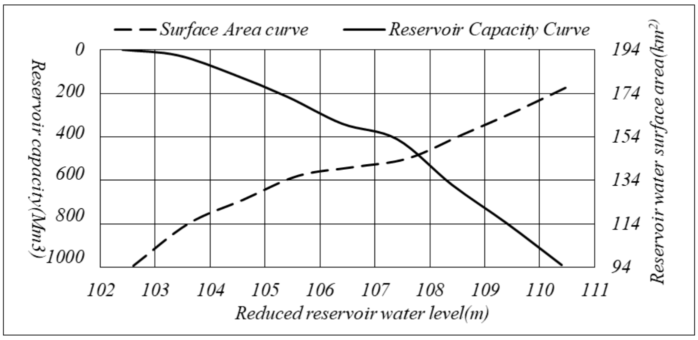

Figure.7. Forecasted Storage-Area Elevation Curve to 2015 from Sedimentation Surveys

Spillway Discharge Capacity

Koka Dam, a concrete gravity structure, features an ogee spillway controlled by four radial gates. Accurate calculation of spillway discharge at various water levels and gate openings is essential for reservoir operation simulation. These calculations are based on Equation 2 and spillway discharge capacity for different opening size were presented in Figure 8.

$$Q = \frac{2bC\sqrt{2g}\ (H^{3/2} - H1^{3/2})}{3} \qquad 2$$

where, Q is discharge through spillway gate opening (m^3/s), b is effective crest length of spillway (m), C is coefficient of discharge, which is a function of ratio of gate opening and reservoir water level (d/H1), H is head of water above the crest (m), H1 is head of water above bottom edge level of the gate (m) and g is acceleration due to gravity (m/s^2).

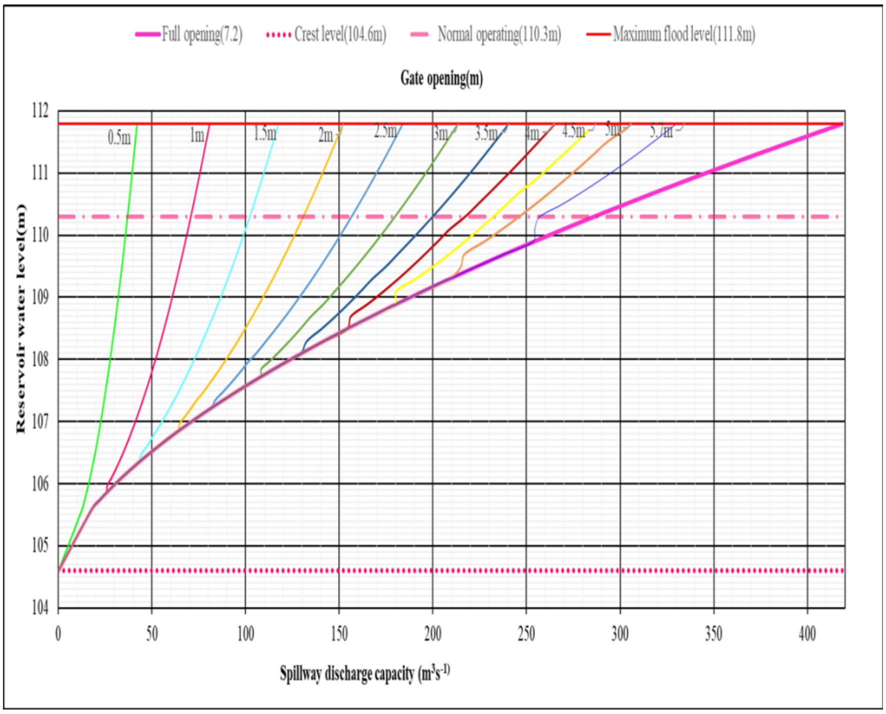

Figure 8. Spillway discharge capacity for different gate opening size

Power Intake Discharge Capacity

For both the power intake and bottom outlet, Equation 3 was used to estimate discharge capacity at various reservoir water levels and outlet dimensions.

$$Q = CA\sqrt{2gHa} \qquad 3$$

where, Q is Discharge through orifice flow of gate controlled (m^3/s), C is coefficient of discharge of 0.65 for radial gate controlled, A is opening area (m^2), g is acceleration due to gravity (m/s^2) and Ha is the hydraulic head above the orifice opening center-line elevation (m).

Bottom Outlet Discharge Capacity

Bottom outlets, located near the dam foundation, allow water release to the downstream river and help lower reservoir levels. Depending on outflow and tail water conditions, they may operate under pressurized or free-flow conditions. Besides emergency draw down, they serve for downstream flow regulation and sediment flushing to extend dam life.

2.4. Methods for Data Analysis

2.4.1. Potential Evaporation

Potential evaporation is defined as the amount of water evaporated per unit area and time from an idealized, extensive free water surface under existing atmospheric conditions. The two main factors influencing evaporation from open water are the energy supply for latent heat and the ability to transport vapor away from the surface. Solar radiation is the main heat source. Vapor transport depends on wind speed and the humidity gradient above the surface (Chow, 1988).

Different methods for estimating open water evaporation include the pan method, water balance method, energy budget models, mass transfer models, combination methods (energy and mass transfer), and other empirical approaches(J W Finch et al., 2001), (McMahon et al., 2016). However, the selection of a given method mainly depends on the availability of meteorological data, model simplicity and applicability across regions, and its accuracy. The Koka reservoir site has reliable data on rainfall and temperature, while the nearby Adama station provides relative humidity, wind speed, and sunshine hours. Therefore, the Penman-48 combined method, a widely used and globally accepted standard, was used to estimate the potential evaporation rate for the Koka reservoir. The Penman-48 model established an analytical solution for the energy balance and mass transfer equations, and generating a unique Equation 4 as followed for the estimation of potential evaporation (Eo) (Penman, 1948).

$$E_o = \frac{\Delta}{\Delta+\gamma}E_r + \frac{\gamma}{\Delta+\gamma}E_a \qquad 4$$

where E_r and Ea are evaporation estimate (mm/day) based on energy balance method and aerodynamic method respectively; Δ is the gradient of the saturated vapour pressure curve at air temperature (kpa°c^{-1}); γ psychrometric constant (kpa°c^{-1}).

2.4.2. Reference Evapotranspiration

Reference evapotranspiration is the rate of evaporation and transpiration from an idealized, well-watered grass surface that completely shades the ground, with a height of 0.12 m, an albedo of 0.23, and a surface resistance of 70 s/m. It is also influenced by the same two factors affecting open water evaporation energy supply and vapor transport. Estimation can be made using the same method as for open water evaporation, with adjustments for vegetation and soil conditions, as described by Van Bavel (1966) and Monteith (1980), cited in (Chow, 1988).

The method selection depends on available meteorological data and required accuracy. The FAO Penman-Monteith method, recommended and most widely applied for estimating ETo from temperature, humidity, sunshine, and wind speed, was used in this study to assess irrigation demand. Estimation was done using the CROPWAT 8 model, which applies the FAO Penman-Monteith Equation 5 as shown below.

$$ETo = \frac{0.408\Delta(Rn-G) + \gamma\left(\frac{900}{T+273}\right)U2(es-ea)}{\Delta+\gamma(1+0.34U2)} \qquad 5$$

where ETo is the grass reference evapotranspiration(mmday^{-1}), Rn is the net radiation at the crop surface (MJm^{-2} day^{-1}), G is soil heat flux density (MJm^{-2} day^{-1}), T is mean daily air temperature measured at 2m height (°C), U_2 is wind speed at 2m height (ms^{-1}), es is saturation vapour pressure(kpa), ea is actual vapour pressure(kpa), Δ is slope of vapour pressure curve(kpa°C^{-1}), γ is psychometric constant (kpa°C^{-1}).

2.4.3. Water Demands in Upper Awash Valley

Water demand in study area considered includes in-stream uses (hydro-power, environmental flow) and out-stream or consumptive uses (irrigation, livestock, domestic, industrial, etc.). Their estimations are described as follows.

Irrigation Water requirement

Irrigation water requirement analysis needs estimated reference evapotranspiration (ETo), crop coefficient, and effective rainfall. Accordingly, four meteorological stations shown in Table 7 were selected based on their proximity to the irrigation site to estimate reference evapotranspiration (ETo) and subsequently irrigation water requirements.

Table 7. Existing irrigation schemes and nearest meteorological station

Irrigation Schemes	Coordinate		Proximity station	Coordinate		
	X (°)	Y (°)		X (°)	Y (°)	Z
Wonji Shoa	39.23	8.46	Melkasa	39.32	8.40	1540
Bofa	39.42	8.42	Melkasa	39.32	8.40	1540
Metahara	39.89	8.76	Metehara	39.92	8.86	944
Tibila	39.52	8.47	Abomsa	39.83	8.47	1630
Golgota	39.75	8.65	Abomsa	39.83	8.47	1630
Boset Fentalle	39.83	8.73	Nura Era	39.90	8.57	1140
Nura Era	39.90	8.57	Nura era	39.90	8.57	1140

Reference Evapotranspiration (ETo)

Reference evapotranspiration was calculated for each station using climatic data (temperature, humidity, wind speed, sunshine) through FAO Penman-Monteith method in CROPWAT 8.

Crop Water Requirement (CWR)

Crop water requirement (CWR) is the water needed (mm) for optimal crop growth under ideal conditions. CWR for each crop was determined using ETo and crop data in CROPWAT 8 (Eq. 6). Crop parameters like crop coefficient (kc) were sourced from local studies and FAO 24.

$$CWR=KC^* \, ETo \qquad 6$$

Effective Rainfall

Estimating dependable rainfall is preferred over mean rainfall for irrigation planning. Monthly dependable rainfall was derived from probability curves (75% probability exceedence). Since not all dependable rainfall is effective, effective rainfall was estimated using the USDA SCS method in CROPWAT 8 using equations 7 and 8.

$$P_{eff} = \frac{p(125-0.2p)}{125} \quad \text{for} \quad p<=250mm \qquad 7$$

$$P_{eff} = 125+0.1p \quad \text{for} \quad p>250mm \qquad 8$$

Net Irrigation Requirement

Finally, the net irrigation water requirement, NIWR (mm), was estimated based on crop water requirements and effective rainfall available at each site as indicated in the equation 9.

$$NIWR = CWR - Peff \qquad (9)$$

Gross Irrigation Water Requirement (GIWR)

To account for losses, irrigation efficiency was applied as of 70% for sprinkler as good irrigation efficiency and 50% for surface systems as fairly good Irrigation efficiency (FAO, 1989) , in estimating gross irrigation water requirements as equation 10..

$$GIWR = \frac{NIWR}{Eff} \qquad (10)$$

where GIWR is gross irrigation water requirement(mm), NIWR is net irrigation water requirement(mm) and Eff is overall irrigation schemes efficiency.

Domestic Water Demand

Domestic water demand was estimated using GTP2 standards (MoWIE, 2015) as of 25 l/c/day for rural areas, and 40 – 100 l/c/day for urban areas based on town population size.

Commercial and Institutional Water Demand (CIWD)

Commercial and institutional water demand (CIWD) was estimated as 10% of domestic demand for large towns (>50,000 people) and 5% for medium (10,000–50,000) and small (2,000–10,000) towns, based on MoWR guidelines(MoWR, 2002).

Industrial water demand (IWD)

Industrial water demand (IWD) was estimated as 30% of domestic demand in large and medium towns, and 10% in small towns, based on MoWR's 2002–2016 program.

System losses

System losses were considered as 25% of total urban demand (domestic, commercial, institutional, industrial) and 5% of rural domestic demand, based on MoWR's 2002–2016 program.

Livestock Water Demand

Livestock water demand was estimated using livestock numbers and species-specific needs, influenced by feed intake and temperature. Because the moisture available in the feed varies with the season, voluntary water use was set at 90% of TWR in the dry season and 25% in the wet season (Sileshi et al., 2003).

Environmental flow Analysis

Impoundments and abstractions (diversions) of the river flow using different hydraulic structures for different purposes impose modifications on the river flow at its downstream. These interventions have had significant impacts, reduced the total flow of rivers and affected both the seasonality of flows and the size and frequency of floods. These modifications have adversely affected the ecological and hydrological services provided by water ecosystems. Such modifications to the river flows need to be balanced with the maintenance of essential water-dependent ecological services (Richard Davis et al., 2005).

Even though various approaches to prescriptive and interactive methods are available for assessment of environmental flow, but difficult arise in its actual estimation due to the lack of both understanding and quantitative data on relationships between river flows and various components of river ecology(Lumbroso, 2003). In this study, the hydrological index methods, the flow duration curve (FDC) analysis technique were selected for environmental flow estimation. In flow duration curve analysis, naturalized or present-day historical flow records are analyzed over specific duration to produce curves displaying the relationship between the range of discharges and the percentage of time each of them is equaled or exceeded. he 100% probable flow, or average monthly minimum flow, was used because the river is perennial and monthly probable flow values are available, as shown in Figure 9.

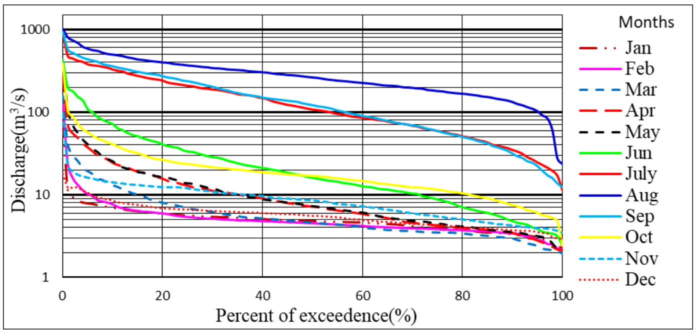

Figure 9. Monthly flow duration curve of Koka reservoir inflow (1986-2016)

2.4.4. Reservoir operation simulation Model

The operation of the Koka Reservoir was simulated using the HEC-ResSim model, which comprises three modules: Watershed Setup, Reservoir Network, and Simulation. The general HEC ResSim module concept is as shown in Figure 10.

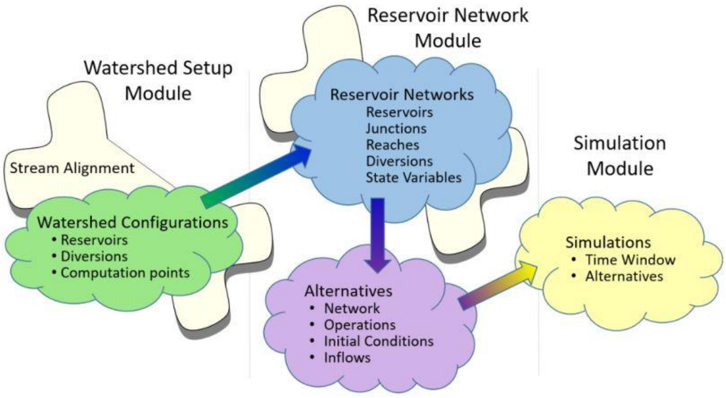

Figure 10. HEC ResSim module concepts

The Watershed Setup module defines the physical layout of the watershed by allowing users to import maps, draw stream alignments, and watershed configurations such as reservoirs, diversions and computational points. In the Reservoir Network module, watershed elements are connected via reaches to form a complete reservoir network, with junctions derived from computation points. This module enables input of both physical and operational data. Physical data includes reservoir pool characteristics (elevation-storage-area relationships), dam elements (outlets, leakage, tailwater elevation, spillways, power plant), and losses such as evaporation and seepage. Operational data are defined through an operation set composed of zones (inactive, conservation, and flood control) & operational rules. Zones segment the reservoir pool to apply specific constraints; rules govern release decisions and vary depending on their target (e.g., pool, dam, outlets, or power plant). Rule types include release functions, downstream controls, hydro-power requirements, and change rate limits. Alternatives are created by combining the reservoir network, operation sets, initial conditions (look back), and time series data mapped using DSS path names. These alternatives are simulated within the Simulation module, which runs scenarios over defined time windows based on user-specified look back, start, and end dates. The reservoir network system for Koka reservoir was sketched as in Figure 11. The simulation period allows the model to evaluate input data, make release decisions, and route flows through the system(US Army Corps of Engineers, 2021).

Supporting this modeling environment, the Hydrologic Engineering Center's Data Storage System (HEC-DSS) is used to store and retrieve sequential data such as time series, curves, and gridded datasets. HEC-DSSVue, the graphical interface for accessing HEC-DSS files, allows users to plot, tabulate, edit, and manipulate data using over 50 mathematical functions.

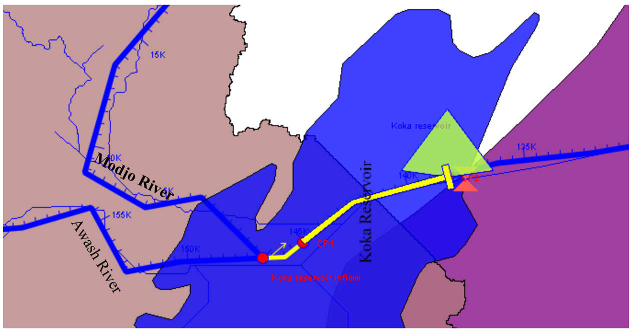

Figure 11. Koka reservoir network system

Each time series in a DSS file is identified by a six-part path name (A–F), which encodes project name, location, parameter, start date, interval, and user-defined descriptors. Data can be manually entered or imported from external sources like Excel. The HEC-DSS enables effective storage, retrieval, and management of the hydrologic data necessary for reservoir simulation(US Army Corps of Engineers, 2020).

Hydrologic Balance computations in the model are based on the principle of continuity equation 10.

$$S_i = S_{i-1} + I_i - Q_i - E_i \qquad 10$$

where S_i is reservoir storage volume at the end of the current period (based on mass balance), i, Si-l is reservoir storage volume at the end of the previous period, i-1, I_i is inflow volume during period, i, Qi is release volume during period i (based on release decision logic), and E_i is net evaporation volume during period i .

Power calculations are programmed in the model-based equation 11 as:

$$GE_i = \eta_i \gamma_w Q_i H_i t \qquad 11$$

where γ_w is unit weigth of water (9.81 KN/m^3), GE_i is energy in KWhrs generated during period i, Q_i is average flow in (m^3/s) through generating units during period i, H_i is average effective head in meters on the turbine during period i (calculated by subtracting tail water elevation and head loss from the reservoir surface elevation) and t is hours in the period i.

2.5. Performance Evaluation of a Water Resources System

Performance evaluation criteria are essential for assessing how effectively water resource systems operate under varying hydrologic conditions and demands, particularly during droughts, peak demand, or extreme events. Such measures guide decisions on system capacity, configuration, operating policies, and targets. (Hashimoto, 1982) identified three fundamental criteria reliability, resilience, and vulnerability which have since been expanded by other researchers (Loucks and Van Beek 2017), McMahon et al. (2006)) , as cited in (Priyank J. Sharma et al., 2014). Reliability measures how frequently the system meets its target demand, either in terms of time or volume. Resilience assesses the system's ability to recover promptly after a failure. Vulnerability quantifies the severity of deficits when failures occur. In this study, these three criteria form the basis for evaluating system performance.

Reliability

Time based reliability

It is defined as the ratio of time intervals during the simulation period in which the reservoir meets the target demand to the total number of intervals in the simulation period, and can be expressed as equation 12.

$$R_t = \frac{N_s}{N} \qquad 0 \leq R_t \leq 1 \qquad 12$$

where R_t is time-based reliability, $N_s$is number of intervals that the target demand was fully satisfied and N is the total number of intervals covering the historical or simulation analysis period.

Volumetric reliability

It is expressed as the ratio of volume of the total supply deficit that is released from the reservoir or water resource system during the simulation period to the total volume of water demand (D_t) as equation 13.

$$R_v = 1 - \frac{\sum_{t=1}^{T} d_t}{\sum_{t=1}^{T} D_t} \qquad 0 \leq R_v \leq 1 \qquad 13$$

where, Rv is volume-based reliability, d_t is water released deficit from the reservoir in time period t, D_t is total demand in time period t and T is total simulating time period.

Resilience

These metrics assess the probability that, following a deficit period, the system returns to a satisfactory state in the next period. In other words, they measure the likelihood of success after failure (Hashimoto, 1982), as shown in Equation 14. It indicates how quickly the system recovers from failure. Prolonged failures and slow recovery may have significant implications for the water system.

$$\text{Res} = \frac{\text{Number of times success follow time of failure}}{\text{Number of failure during simulation period}} \qquad 14$$

Vulnerability

These measures quantify the average magnitude of the deficit caused by the failure event. Even when the probability of failure is small, attention should be paid to the possible consequences of failure or level of deficit as show in equation 15 and equation 16. Vulnerability indicates how bad the consequences of failure are? (Hashimoto, 1982). Kjeldsen and Rosbjerg (2004) as cited in (Priyank J. Sharma et al., 2014), simplified vulnerability as the mean value of the deficit events.

$$\text{Vul}_{\text{mean}} = \frac{1}{M}\sum_{j=1}^{M} V_j \qquad 15$$

where V_j is deficit volume of the failure event. The maximum vulnerability is determined:

$$\text{Vul}_{\text{max}} = \text{Max}\ (V_j) \qquad 16$$

3. RESULTS AND DISCUSSION

3.1. Upper Awash Valley Water Demands

The Upper Awash Valley faces increasing water demand, particularly for irrigation. At the same time, regulated flow is declining due to sedimentation reducing the Koka Reservoir's capacity, making demand assessment vital for efficient resource use. Therefore, the current water demands in the upper Awash Valley for different water users were determined as one of the targets of this study. The study area has three main types of consumptive water demands (off stream flow requirements): domestic supply, irrigation, and livestock, and non-consumptive water uses (in-stream flow requirements), such as environmental flow requirements and hydro-power demand. Therefore, the estimated water requirements for each demand category are as follows:

Estimated Irrigation Water Demand

The regulated flow of the Awash River by the Koka reservoir has enabled the expansion of irrigation in the upper Awash Valley portion of the Awash River Basin, allowing cultivation of two or more crops annually, including perennial crop cycle. The cultivated area has been increasing in the past few years. Cultivated area in 1965 was only 6650 ha according to FAO (1965) as cited in(HALCROW, 1989), while the cropped area was 23300 ha in 1989 according to (HALCROW, 1989) and currently around 64338 ha of land is under irrigation. In the valley, water released from the Koka Reservoir is abstracted from the Awash River for irrigation via pick-up weirs or cascaded diversion structures (permanent or temporary), and pumping stations located at various points along the river. Only medium and large-scale irrigation schemes are considered in this irrigation demand assessment. In the upper Awash Valley, the total area under current medium and large-scale irrigation was estimated to 64,338 ha. Irrigation water demand for the study area was determined using CROPWAT 8.0 software. FAO Penman–Monteith method was applied to estimate ETo. The main input data for CROPWAT 8.0 included climate data (to estimate ETo), crop data such as Kc, the existing crop calendar, base period (to estimate crop water requirements), and rainfall data. Most irrigation sites in the area cultivate sugarcane and vegetable. The estimated monthly net irrigation water requirement and the command area of the selected scheme and for each scheme are presented in Tables 8 and 9, respectively.

Table 8. Monthly NIWR of irrigation schemes (Mm^3/month)

Schemes	Wonji Shoa		Bofa	Nura Era	Tibila	Golgota	Fentalle	Metahara	Total
System	Surface	Sprinkler	Surface	Surface	Surface	Surface	Surface	Surface	
Jan	6.8	8.7	3.5	7.8	6.2	0.5	18.7	9.5	61.7
Feb	10.2	13.0	1.8	6.3	2.8	0.2	7.4	13.7	55.5
Mar	13.6	17.4	1.7	5.5	2.7	0.2	9.6	19.4	70.4
Apr	12.2	15.6	3.5	5.1	5.3	0.5	15.4	19.0	76.5
May	14.2	18.2	6.5	9.0	9.9	0.9	28.6	20.8	108.1
Jun	10.9	14.0	4.1	9.8	7.3	0.6	27.1	21.5	95.3
Jul	4.9	6.3	0.7	2.7	1.2	0.1	7.4	16.1	39.4
Aug	3.7	4.7	0.1	1.4	0.3	0.0	3.8	12.2	26.4
Sep	7.4	9.4	0.0	1.9	0.0	0.0	1.1	15.9	35.7
Oct	11.6	14.8	3.0	5.9	3.6	0.3	13.6	17.1	69.9
Nov	9.9	12.7	5.2	7.5	7.7	0.7	23.3	14.4	81.4
Dec	8.8	11.3	6.2	8.8	9.0	0.8	27.0	12.3	84.2
Annual	114.3	146.1	36.3	71.7	56.1	4.8	183.2	191.8	**804.3**

Table 9. Irrigation schemes and major irrigation methods of study area

Schemes	Wonji Shoa		Bofa	N/ Era	Tibila	Golgota	Fentalle	Metahara
Area(ha)	7022.2	8977.85	4050	7187	7000	600	19271	10230
system	Surface	Sprinkler	Surface	Surface	Surface	Surface	Surface	Surface

The estimated monthly NIWR high during the dry season and low during the rainy season, mainly due to seasonal variability in effective rainfall and climatic conditions in the study area. The estimated annual net irrigation water demand in the valley is 804.35 Mm^3. The gross irrigation water requirement depends largely on the overall efficiency of the irrigation system, which is influenced by factors such as irrigation method, canal type, operational method, and availability of control structures. For the GIWR estimation, overall efficiencies of 50% for surface irrigation and 70% for pressurized irrigation were considered, resulting estimated annual irrigation water demand of approximately 1,525 Mm^3.

Domestic Water Demand

The domestic water demand in the rural and urban areas of the study area which includes industrial, commercial, institutional, and residential was estimated according to the Growth and Transformation Plan II (GTP2) minimum water supply coverage standard, or the minimum per capita demand set by the Ministry of Water, Irrigation, and Energy(MoWIE, 2015). Based on this, the total annual domestic water demand for the selected woredas in the study area is estimated to 34.3 Mm^3, and the monthly estimated demand for each selected woreda is presented in Table 10.

Table 10. Monthly domestic water demand (Mm^3) of selected woreda of study area

Woreda	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Fentalle	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1.9
Boset	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	2.9
Adama	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.2	0.3	3.0
A s/zone	1.7	1.5	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	20.2
Merti	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.7
Jeju	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.2	1.8
Dodota	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6
Sire	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
Total	2.9	2.6	2.9	2.8	2.9	2.8	2.9	2.9	2.9	2.9	2.8	2.9	34.3

Livestock Water Demand

Water is essential for the survival of livestock, fulfilling their needs through direct consumption or indirectly through the feed they ingest. Generally, the amount of water consumed by livestock depends on factors such as weather, diet, livestock management, and species type. Therefore, in this study, the estimated water requirements for livestock are based on the species' average dry matter intake (feed) per head and the average air temperature of the area. The results of the daily water demand per head are presented in Table 11. The voluntary water requirement of livestock varies seasonally due to the moisture content in their feed, accounting for approximately 25% of the total water requirement during the wet season and 90% during the dry season.

Table 11. Daily voluntary water requirement of livestock per head (L/head/day)

Livestock	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cattle	21.2	21.2	21.2	21.2	21.2	5.9	5.9	5.9	5.9	21.2	21.2	18.5
Sheep	4.7	4.7	4.7	4.7	4.7	1.2	1.2	1.2	1.2	4.2	4.2	3.7
Goat	4.7	4.7	4.7	4.7	4.7	1.2	1.2	1.2	1.2	4.2	4.2	3.7
Donkey	12.7	12.7	12.7	12.7	12.7	3.5	3.5	3.5	3.5	12.7	11.1	11.1
Horse	12.7	12.7	12.7	12.7	12.7	3.5	3.5	3.5	3.5	12.7	11.1	11.1
Mule	12.7	12.7	12.7	12.7	12.7	3.5	3.5	3.5	3.5	12.7	11.1	11.1

The estimated amount of water used by livestock in the selected woredas of the study area is minimal compared to other sectors. The annual total and voluntary livestock water demands are estimated at 8 Mm^3 and 5.34 Mm^3, respectively. The seasonal estimates are presented in Table 12.

Table 12. Monthly total and voluntary livestock water requirement

Demand	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total (Mm^3)	0.74	0.67	0.74	0.72	0.74	0.72	0.74	0.74	0.72	0.74	0.72	0.65
Voluntary (Mm^3)	0.68	0.61	0.68	0.66	0.68	0.18	0.19	0.19	0.18	0.67	0.64	0.58
Voluntary (m^3/sec)	0.25	0.25	0.25	0.25	0.25	0.07	0.07	0.07	0.07	0.25	0.25	0.22

Environmental Water Demand

The water demand for the environment could increase rapidly as awareness of water-related environmental issues grows. The monthly environmental flow for the study area was determined using the flow duration curve of reservoir inflow for each month, corresponding to the 100% exceedence flow. This flow is necessary to satisfy the downstream ecological water requirements of the river course. Consequently, the annual environmental demand is estimated to 182.5 Mm^3, and the monthly demand is illustrated in Figure 12. Around 9.6% of the total annual reservoir inflow volume has been allocated as environmental flow.

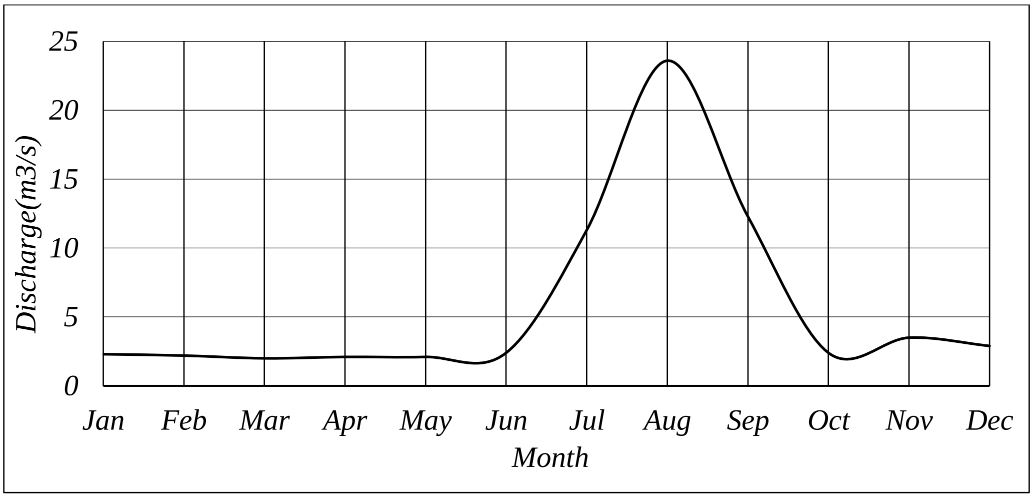

Figure 12. Monthly flow for environmental demand (m^3/s)

Total water demand of the study area

The estimated total annual water demand for all considered sectors is approximately 1,747 Mm^3. A comparison of monthly sectoral water demands is clearly presented in Table 13.

Table 13. Upper awash valley part of Awash River basin water demands (m^3/s)

Demand type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Environment	2.3	2.2	2.0	2.1	2.1	2.4	11.3	23.6	12.3	2.4	3.5	2.9
Domestic	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Livestock	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.2
GIWR	44.2	42.5	48.8	55.6	76.9	70.4	28.1	18.7	25.5	49.0	60.0	60.5
Total	47.9	46	52.2	59	80.3	74	40.5	43.4	38.9	52.8	64.9	64.7

A comparison of current annual demands among these sectors clearly shows the dominance of irrigation water requirements over domestic and livestock demands. The irrigated agriculture sector is the largest user and consumer of water in the study area, accounting for more than 87%of the total water demand. Analysis of long-term streamflow data at the reservoir site indicates that the long-term mean annual inflow volume to the Koka reservoir is 1,898 Mm^3. The current annual water use for irrigation in the study region is estimated to be 80% of the average annual inflow to the reservoir. Environmental demand, estimated based on the 100%

exceedence flow (minimum flow), is slightly higher than the demands of other sectors such as livestock and domestic use. The proportion of annual water demand by sector is as follows: irrigation 87%, domestic 2%, voluntary livestock water 0.3%, and environmental demand 10.45% of the total annual water demand considered in the study area. According to these findings, livestock is the sector with the lowest water consumption in the study area. Within the study area, the current total annual consumptive water demand is estimated to be 1,564.64 Mm^3. In estimating the water demand for the study area, neither the reuse of water nor the return flow as drainage water was considered. Therefore, the annual water withdrawal in the valley accounts for approximately 82.4% of the total annual inflow available to the Koka reservoir.

3.2. Net Evaporation Loss from Koka Reservoir

When conducting a reservoir simulation or water balance analysis, it is essential to calculate evaporation from the reservoir's water surface. In most cases, evaporation losses from reservoirs or lakes are not measured directly but are instead estimated indirectly using techniques such as the water balance method, energy budget method, mass transfer (aerodynamic) method, or other approaches. In this study, the monthly evaporation rate from the Koka Reservoir was calculated using the Penman method (Penman, 1948), based on long-term historical meteorological data from the Koka Dam station and other nearby stations. Although the total annual evaporation loss from a reservoir remains relatively constant from year to year, it varies seasonally according to the reservoir's surface area and prevailing climatic conditions. Therefore, it is sufficient to estimate mean monthly values and apply them consistently for each year in the reservoir simulation. The calculated monthly net evaporation values were used as input data in the HEC-ResSim reservoir simulation model. The results of the estimated evaporation losses are presented in Figure 13.

The analysis indicates that the average annual net and potential evaporation rates of the reservoir are 1,357.26 mm and 2,207.74 mm, respectively. Approximately 54.76% of the average annual net evaporation occurs during five months, specifically December, January, February, March, and April, while the remaining 45.24% occurs during the other seven months. In contrast, about 52.84% of the average annual potential evaporation occurs during March, April, May, June, July, and October, with the remaining 47.16% distributed across the other months. The highest potential evaporation (205.6 mm) was recorded in May, while the lowest (167.4 mm) occurred in September. For net evaporation, the maximum value (153.27 mm) was observed in January, and the minimum value (−0.17 mm), indicating a net gain from rainfall, was recorded in August.

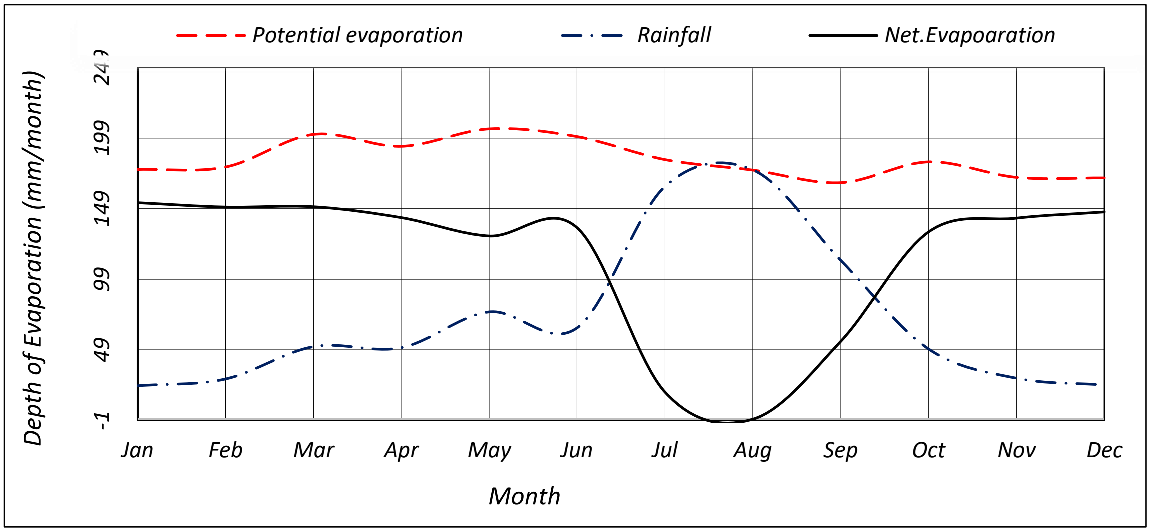

Figure 13. Net evaporation loss of Koka reservoir

3.3. Reservoir Operation Simulation Analysis

The HEC-ResSim reservoir simulation models were run on daily time steps for a total of 372 months, from January 1986 to December 2016, based on the given inputs of daily reservoir inflows, monthly evaporation losses, monthly water demands in the upper Awash Valley, reservoir storage capacity, physical dam characteristics, outlet structures, and hydro-power plant operation data. The total storage volume was divided into three zones: flood control, conservation, and dead storage. These zones were maintained at different elevations. In this study, conservation storage formed part of the active storage and was managed according to operational rules. All simulations were conducted within the given limitations of reservoir capacity, spillway capacity, and the release capacity of the power plant and bottom outlet to downstream areas. Since electricity generation is one of the purposes of the Koka Reservoir, releases for consumptive uses were routed through the turbines up to their generating capacity.

Three alternatives, representing 100%, 50%, and 25% of the monthly irrigation water demand, were defined for the Koka Reservoir operation simulations to assess reservoir performance indices, as illustrated in Table 14. The simulations also considered 31 years of daily inflow data, monthly evaporation losses, reservoir capacity, and other physical and operational data for the dam. The performance of reservoir operations was assessed by calculating various performance indices for each irrigation water demand alternative, as presented in Table 15.

Table 14. Alternative considered for reservoir simulation

Month	Other demands(m^3/s)	Irrigation demand(m^3/s)		
		Alt-1(100%)	Alt-2(50%)	Alt-3(25%)
Jan	3.638	44.238	22.1	11.1
Feb	3.538	42.479	21.2	10.6
Mar	3.338	48.812	24.4	12.2
Apr	3.438	55.563	27.8	13.9
May	3.438	76.852	38.4	19.2
Jun	3.554	70.422	35.2	17.6
Jul	12.454	28.054	14.0	7.0
Aug	24.754	18.667	9.3	4.7
Sep	13.454	25.473	12.7	6.4
Oct	3.735	49.021	24.5	12.3
Nov	4.831	60.021	30.0	15.0
Dec	4.203	60.458	30.2	15.1

Alternative 1

In this alternative, the HEC-ResSim model was run with 100% of the irrigation demand. The simulation result indicates that the annual water supply was insufficient to meet the monthly irrigation water demand. As shown in Figure 14, the reservoir water level declines and frequently reaches the minimum operating level. The reservoir's performance in meeting the target demand over the 31-year period is very low as shown in Table 15. Figures 14 and 15 present the reservoir water level and power generation, respectively, for the entire simulation period. Monthly outflow and total water demand were plotted and compared in Figure 16.

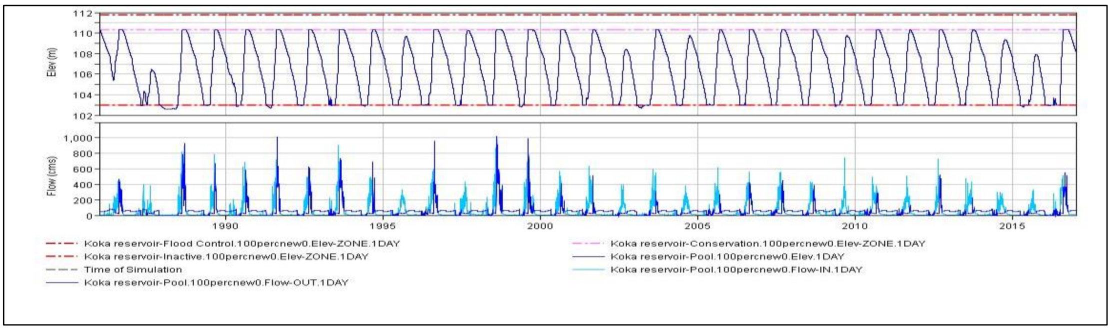

Figure 14. Reservoir water level simulated for alternative 1 irrigation water demand

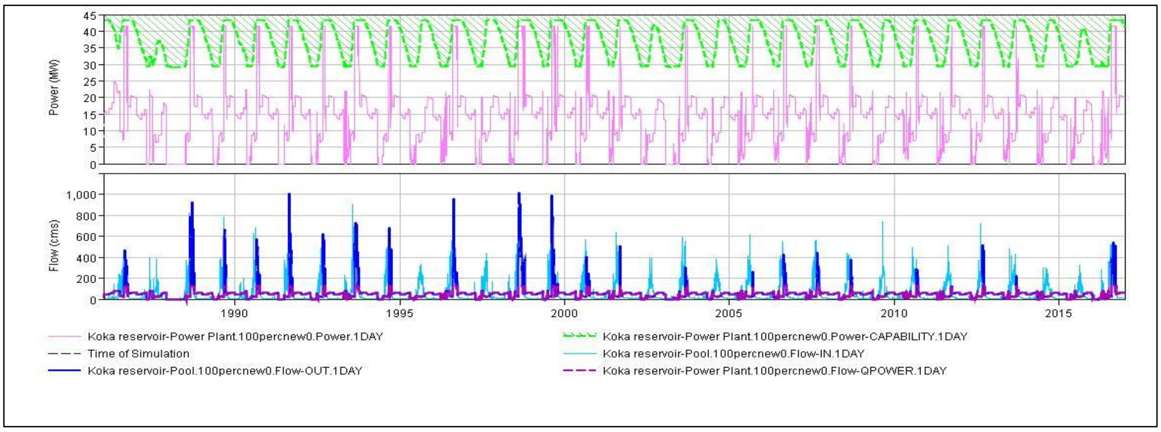

Figure 15. Power generated simulated for alternative 1 irrigation demand

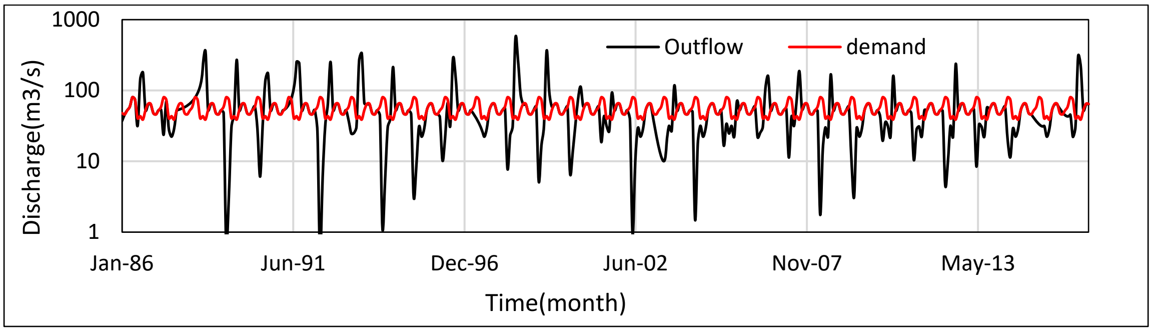

Figure 16. Outflow and monthly irrigation water demand for alternative 1

Alternative 2

In this alternative, 50% of the irrigation water demand was considered. The simulation result shows that reservoir storage was insufficient to meet the reduced irrigation demand as shown in Table 15. Conversely, the volume of excess water discharged through the spillway was greater than in Alternative 1. Reservoir performance improved because of the 50% reduction in irrigation demand. Figure 17 presents the reservoir elevation over the simulation period, while Figure 18 depicts the power generated during the same period. Monthly outflow and the demand considered were plotted and compared in Figure 18.

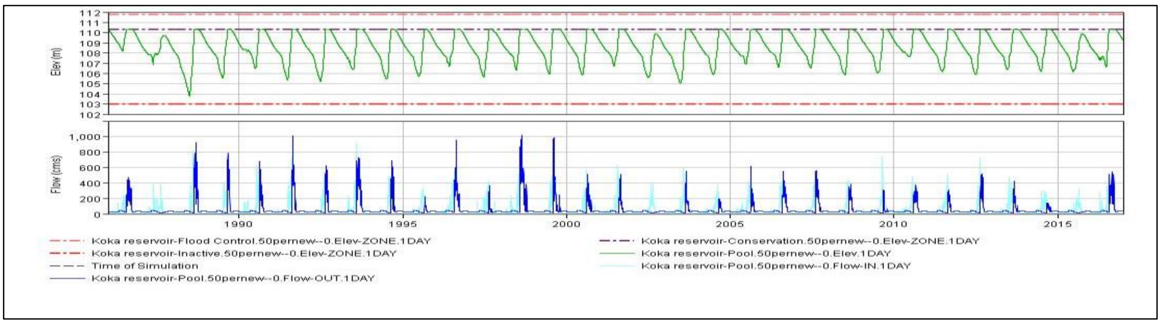

Figure 17. Reservoir water level of simulated for alternative 2

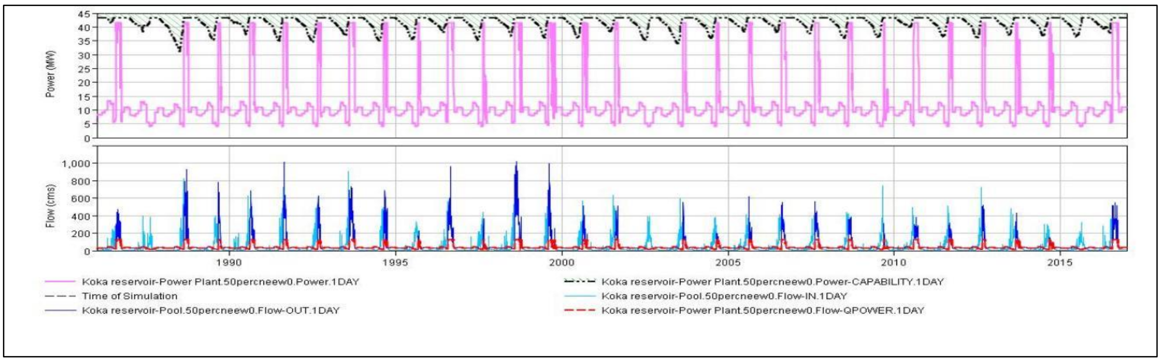

Figure 18. Power generated for reservoir simulated for alternative 2

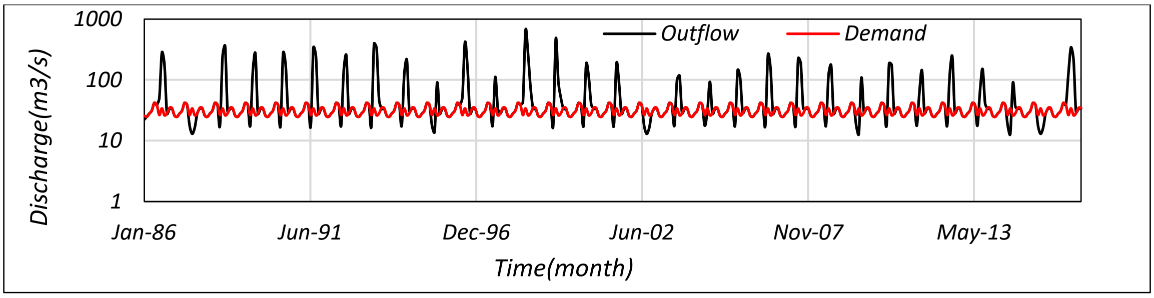

Figure 19. Reservoir outflow and monthly irrigation water demand for alternative 2

Alternative 3

In this alternative, the simulation was conducted by considering 25% of the irrigation water demand. Annual outflow and demand analysis indicate that, out of the 31 years of inflow data, some years were unable to meet the reduced irrigation water demand. Conversely, the volume of excess water discharged through the spillway was greater than in the previous two alternatives. Reservoir performance in meeting the target demand improved as a result of the reduced irrigation demand, as shown in Table 15. The reservoir water level, power generation, and monthly release and demand over the simulation period are presented in Figures 20, Figure 21, and Figure 22, respectively.

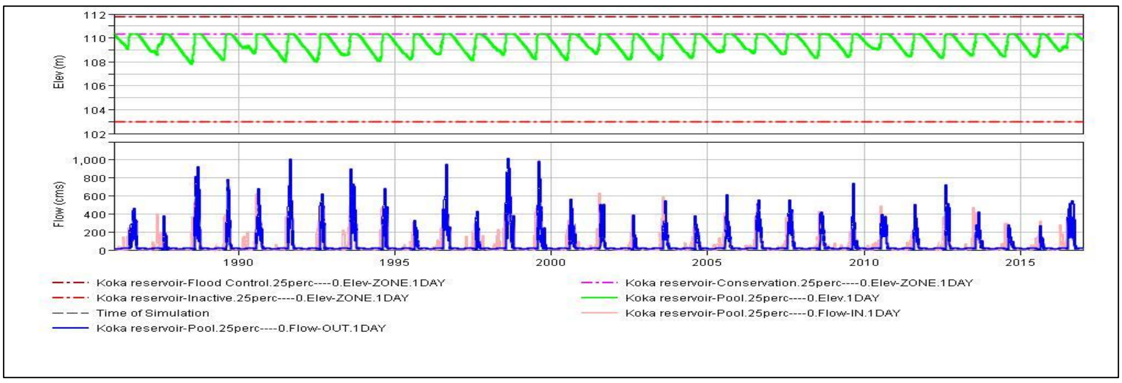

Figure 20. Reservoir water level for simulation of alternative 3 water demand

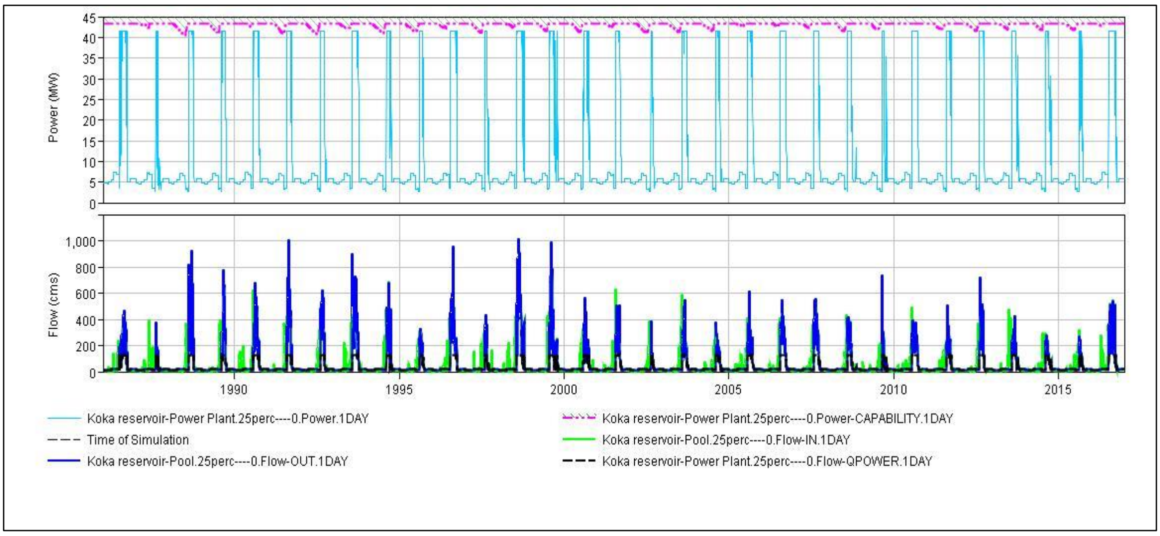

Figure 21. Power generated for simulation of alternative 3 water demand

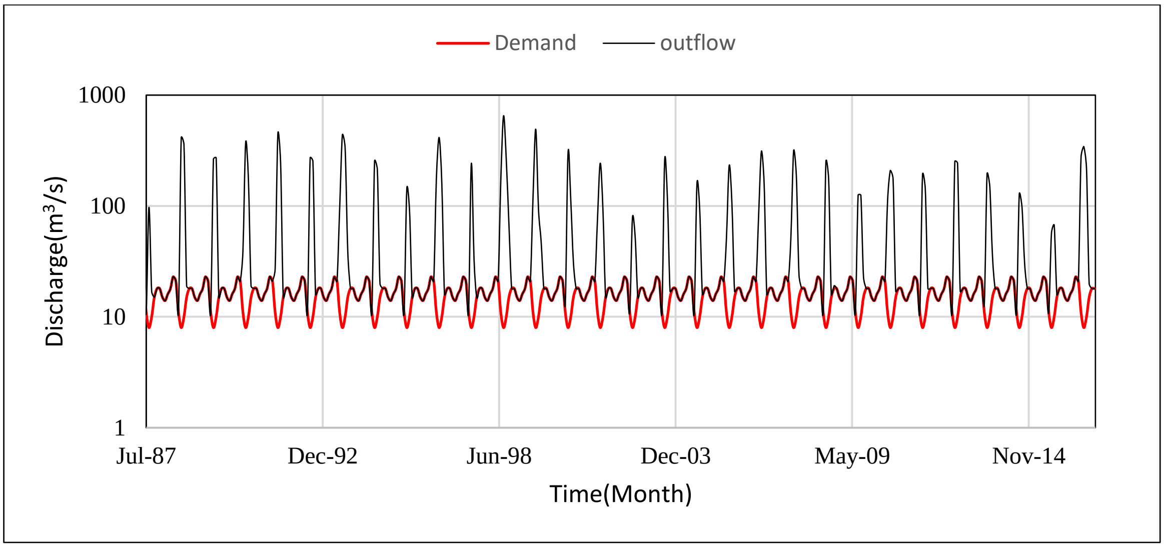

Figure 22. Monthly water demand and outflow for alternative 3 water demand

Based on the simulation results for all three alternatives, the reservoir system demonstrates low performance for alternative 1 and does not guarantee sufficient water supply for irrigation and other demands in the valley during the analysis period.

Table 15. Performance indices based on monthly time scale (1986-2015)

Indices	Reliability (%)		Vulnerability(m^3/s)		Resilience (%)
	Time	Volumetric	Vul_{mean}	Vmax	
Alt-1	42.74	73.73	25.43	80.00	27.70
Alt-2	81.45	96.47	5.93	21.00	85.51
Alt-3	100	100	0	0	NA

NA: Not applicable since there is no failure

To meet the full irrigation demand (Alternative 1), the reservoir satisfied the demand less than half of the time, with a time reliability of 42.7%. Despite this, it still supplied most of the total required volume, achieving a volumetric reliability of 73.7%. When shortages occurred, they were substantial, with an average deficit of 25.4 m^3/s and a maximum of 80.0 m^3/s. The system's low resilience of 27.7% indicated a limited capacity to recover quickly from failures. Even in Alternative 2, where reliability (81.5%) and resilience (85.5%) improved considerably and mean vulnerability (5.9 m^3/s) was moderate, full reliability was still not achieved. The findings indicate that the reservoir was unable to store enough water every year to meet the total irrigation and other demands considered.

4. CONCLUSIONS

Irrigation development aims to enhance agricultural output, thereby improving the community's economic, social, and environmental well-being and contributing to overall national living standards. This study evaluates Koka Reservoir operation under sedimentation and its implications for irrigation water demands in the Upper Awash Valley, Awash River Basin that were not considered in previous studies for the study area. By applying reliability, vulnerability, and resilience metrics over three decades of daily inflow data, the study provides a comprehensive assessment of reservoir performance under sedimentation conditions. The irrigation water requirements were estimated using climate data, crop types, and cropping patterns for the available command area, applying the CROPWAT-8 model. The study results show that the current annual irrigation water demand and total considered water demands in the Upper Awash Valley, part of the Awash River Basin, are approximately 1,525 Mm^3 and 1,747 Mm^3, respectively. This demonstrates that irrigation development consumes a substantial proportion of available water resources. Reservoir inflow analysis indicated that the mean annual inflow is slightly greater than the total annual water demand; however, significant seasonal variability exists.

The HEC-ResSim model was applied to simulate reservoir operation over 31 years of daily streamflow data under recent sedimentation conditions. The results for the full irrigation demand (Alternative 1), the reservoir met full demand less than half the time (time reliability 42.7%) while still supplying most of the total required volume (volumetric reliability 73.7%). Shortages were substantial when they occurred, with an average deficit of 25.4 m^3/s and a maximum of 80.0 m^3/s, and the system's low resilience (27.7%) indicates limited capacity to recover quickly from failures. Even under reduced irrigation demands (Alternatives 2), the reservoir capacity under recent sedimentation was insufficient to retain high rainy-season inflows. To improve the reservoir's long-term performance, different options like capacity enhancement measures such as dam heightening or supplementary storage to reduce wet-season spill and improve dry-season supply; upgrade existing surface gravity irrigation systems to more efficient methods to minimize losses and reduce overall irrigation water demand; implement sediment control and removal strategies; periodic reservoir capacity surveys to keep operation guide curves updated; and investigate conjunctive use of groundwater resources with surface water to boost water supply in the Upper Awash Valley can be considered.

These findings quantify the severity and frequency of supply deficits and highlight the reservoir's limited recovery capacity, providing a benchmark for future studies on reservoir operation and water resources planning. Future research should assess the impacts of land use/land cover and climate change on inflows and performance, explore alternative operation strategies, and evaluate long-term sedimentation and uncertainty to improve understanding of reservoir behavior under changing conditions.

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Conflicts of Interest

I declare that there is no conflict of interest related to this work. No financial, personal, or professional relationships influenced the research or the preparation of this manuscript. The study was conducted independently and objectively.

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