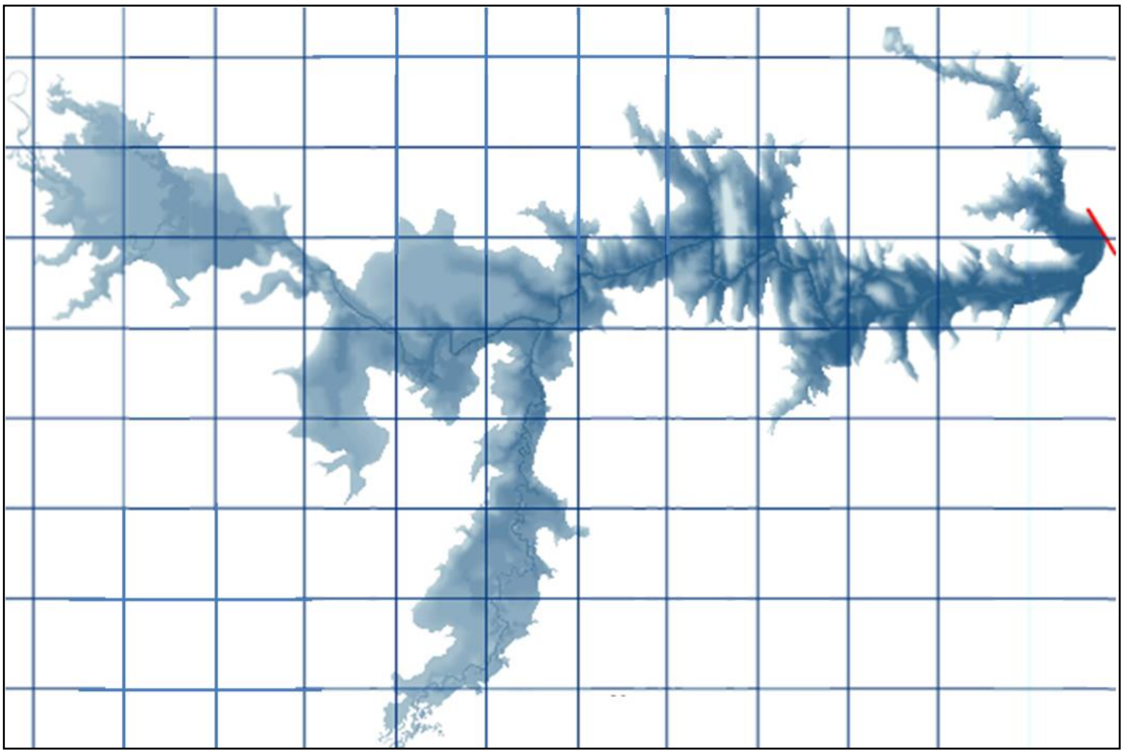
HYDROLOGY REPORT UPDATE

KIDUNDA RESERVOIR INUNDATION PATTERN



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ABSTRACT

This report presents the findings of the hydrological study aimed at providing insights of the frequency and duration of partial inundation of Selous Game Reserve (SGR) due to presence of the Kidunda reservoir. The study established daily time series of water balance inflow and outflow components that were used in water balance computations to obtain daily variations of reservoir water surface elevation that were linked to inundation of SGR.

The results indicate that reservoir fluctuations are mainly related to surface inflows and outflows through spillway, bottom gates and power intakes regardless of starting condition of the reservoir whether empty, half-full or full. Owing to small areal extent of the reservoir, reservoir rainfall and evaporative losses are insignificantly small.

The analyses have indicated that SGR will be inundated in various periods and for variable lengths in different years defined by the combinations of wetness and dryness of main seasons (Oct-Dec, Jan-Feb and MAM) of the wet period. In completely dry years, SGR will be inundated in small patches mostly between April and June/July. In wet years, continuous inundation will be observed between November and June/July although in similar patches with total area within SGR of less than 0.8 km^2 as for dry years.

Dam operations related to opening and closing of the 8 flap gates of the spillway will have significant on the inundation extents of Kidunda reservoir within SGR. Full closure of all gates to wait for releases when reservoir water level exceeds 84.5 m will result in large extent of inundation within SGR (areal extent: 5.646 km^2 corresponding to highest elevation of 85.5 m), which can significantly be lowered by opening of at least 4 gates on fulltime basis.

Inundations of SGR following implementation of the Kidunda dam project and its operations might have little impacts on surface organisms due to low inundation speeds of the order 32-52 cm a minute that can allow small organisms to flee the area being inundated. However, long inundation durations (3-8 months) that will be related to full closure of spillway gates might significantly affect vegetation that intolerable to long periods of being in or under water and which cannot flee the area. Moreover, with full closure of gates, high releases are anticipated in wet years to rapidly lower reservoir water elevation to prevent overtopping the flap gates. The release of the order of 3,000 m^3/s or more are expected that will be highly outside the range of observations and they might significantly affect downstream ecosystem well-being. This impact can be reduced by operating the reservoir up to the highest water surface altitude of 82 m or with at least 4 flap gates fully opened.

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ACRONYMS AND ABBREVIATIONS

AM	Arithmetic Mean
AR	AutoRegressive
ARMA	AutoRegressive Moving Average
DAWASA	Dar es Salaam Water Supply and Sewerage Authority
DWSSP	Dar es Salaam Water Supply and Sewerage Project
EIA	Environmental Impacts Assessment
EIS	Environmental Impacts Statement
FAO	Food and Agriculture Organisation
FDC	Flow Duration Curve
GEV	Generalised Extreme Value
GFFS	Galway Flood Forecasting System
GPA	Generalised Pareto
HBV	Hydrologiska Byråns Vattenbalansavdelning
IUCN	International Union for Conservation of Nature
LPM	Linear Pertubation Model
LP3	Log-Pearson Type III
MA	Moving Average
MAP	Mean Annual Precipitation
MoWI	Ministry of Water and Irrigation
NEMC	National Environ Management Council
NRI	Normalised Runoff Index
pdf	Probability Density Function
PWM	Probability Weighted Moments
P3	Pearson Type III
SGR	Selous Game Reserve
SLM	Simple Linear Model
SPI	Standardised Precipitation Index
WMA	Wildlife Management Area
WRED	Water Resources Engineering Department
WREP	Water Resources Engineering Programme

1 INTRODUCTION

1.1 BACKGROUND

Currently, the city of Dar es Salaam and the surrounding areas up to the mouth of River Ruvu derive most of their domestic water supply for an approximately population of 5 million inhabitants, together with the industrial water demand, from two intake weirs on the lower reaches of R Ruvu. Water supply to these intakes is at present unregulated and subject to seasonal shortages caused mainly by climatic variations and upstream abstraction including to cater for irrigation. The situation becomes worse during the dry season when flows of R Ruvu decreases to the extent that very little water can be drawn to meet the present Dar es Salaam water requirements. This problem is further enhamced by catchment land use and uncontrolled deforestation, changing run-off rates and seasonal flow patterns. As a result, the City has therefore been experiencing frequent water shortages.

In response to this shortage, the Ministry of Water and Irrigation (MoWI) has through DAWASA conducted a survey on the development of future water sources resulting in the Master Plan under the Dar es Salaam Water Supply and Sewerage Project (DWSSP), which included the analysis of 26 options of surface and groundwater development to meet the future water needs for Dar es Salaam City. During the development of the Master Plan, the Kidunda Dam and reservoir option was among the two most promising and complementary options. However, studies have suggested the need for a nominal water storage facility of at least 150 Mm^3 along the R Ruvu at Kidunda to satisfy the daily water demand of about 2 Mm^3 during the critical 4-5 months with R Ruvu flows below this demand for the next 30 years. The Kidunda Dam will be built on R Ruvu to therefore provide an impoundment storing water for a reliable water supply to Dar es Salaam to eliminate water shortage. The project comprises of water treatment plants and pumping stations in order to pump the water to Dar es Salaam as well as a small-scale energy generation component in the region of 35 MW.

1.2 RATIONALE

Whilst attempting to provide a solution for water shortage in the city of Dar es Salaam, the proposed Kidunda dam project might result in some impacts on the physical, biological and socio-economic environments within the Kidunda reservoir catchment as well as downstream to the Indian Ocean. It was therefore important to quantify impacts on these environments that could result from its implementation. This is also a requirement stipulated in the guidelines and procedures for environmental impacts assessment (EIA) that any reservoir project must undergo a full EIA as indicated in the EIA mandatory list (Sec 3.1: # 13).

The preliminary EIA report was prepared by NORCONSULT and disclosed internally after the stakeholders' workshop in 2007. This was for a larger dam than what was later considered by a multi-sectoral stakeholders' oversight committee with the modified primary objective of supplying drinking water to the city instead of the originally planned larger multipurpose dam. The new smaller dam site was also moved 12 km downstream to reduce the potential inundated area and to minimize the upstream environmental and social impacts. Consequently, a new EIA was eminent and was commissioned to Studio Ing. G. Pietrangeli s.r.l. (SP) from Italy.

An Environmental Impacts Statement (EIS) has not yet been approved by National Environment Management Council (NEMC), as it is pending finalisation and stakeholder consultation, which includes the World Heritage Centre and IUCN. The project design has reportedly been finalised and is expected to take between 4 and 5 years to reach full supply level, which will flood a total surface area of 55 km^2. Modelling estimates the maximum surface area to be inundated within the Selous Game Reserve (SGR) of about 4.5 km^2. The area that will be affected by this project is considered to affect wildlife movement to the Gonabis Wetlands and the migration corridor between SGR and Wami-Mbiki wildlife management area (WMA) to the north. In order to mitigate impacts, the State Party is in the process of preparing an alternative corridor of 2 km width, downstream of the dam wall, which would reportedly reconnect SGR with the rest of the wildlife corridor on the other side of the reservoir. The State Party has compensated communities that were relocated and that could be affected downstream, reportedly following the World Bank resettlement policy including stakeholder consultation processes. With respect to the OUV of the property, the mission considers that there are two key factors that need to be considered in the Environmental Impact Assessment (EIA)

i) the frequency of partial flooding or inundation
ii) the duration of flooding before water levels drop beyond the boundaries of the property

They current appear not to have been investigated or determined to date. This area within SGR that will be inundated is mostly wooded grassland and grassland vegetation types and therefore these habitats would be lost to inundation caused by the dam as well as impacting on ground-dwelling animals which will either be displaced or drowned should the dam be filled to its full supply level. These data are therefore important for determining the future operational management of the dam in order to avoid, minimise, or reduce the negative impacts of inundation by flooding on biodiversity in the property, in particular woody plant habitats.

1.3 OBJECTIVES

This studies is generally intends to investigate and quantify inundation patterns (frequency and durations) of Kidunda reservoir into SGR. More specifically, the study will involve

i) establishing continuous inflow (discharge) records and outflow (releases and evaporation) records from Kidunda reservoir
ii) categorising historical years into dry/drought, normal and wet years
iii) carrying out reservoir water balance to establish periodic changes of reservoir water surface elevation

1.4 REPORT ORGANISATION

Chapter 1 provides background information to the Kidunda dam and reservoir project, the EIA carried out and stating objectives of the this study to providing additional information for issues that were not provided in the current EIS submitted to NEMC for approval. **Chapter 2** presents rainfall data and their analyses required to characterise historical normal, drought and flooding years and seasons that are important in understanding behaviour the response of the proposed reservoirs if it were there and if the sequences repeat in the future. Similarly, **Chapter 3** presents river discharge data, their quality and reconstructions to provide a continuous daily inflow discharge series that is used to characterise hydrological normal, drought and flood years and seasons as well as in reservoir water balance analysis. **Chapter 4** presents estimations of time series of inflows and outflows for the reservoir and results of water balance analyses providing daily variations of reservoir volumes, area and water surface elevations, which are used to study inundation patterns of SGR. Conclusions are provided in **Chapter 5** followed by a list of **References** cited in the report.

2 RAINFALL ANALYSES

2.1 GENERAL

Rainfall is a fundamental variable in hydrology as it drive time-space variations of hydrological variables. In this study, rainfall is useful in relating time variations of streamflows within the Kidunda catchment that are related to seasonality of inundation of the proposed Kidunda reservoir and consequently on the impacts of inundation seasonality on the ecosystem of Selous Game Reserve (SGR). This section therefore presents inventories of rainfall stations within and closest to Kidunda catchment, collection and processing of rainfall data as well as analyses that categorises historical years according to their dryness and wetness using several relevant rainfall indices and analysis methodologies.

2.2 DATA AVAILABILITY AND PROCESSING

2.2.1 Data availability

Several data are required to effect the specific objectives of this study. Wetness and dryness of years is mainly related to rainfall abundance or deficit and therefore characterisation of years into dry, normal or wet will involve the use of rainfall data. Several studies have used seasonal and annual rainfall amounts while others (e.g. Valimba, 2012) have also include monthly rainfall amounts to characterise dryness and wetness of years. Therefore, monthly rainfall data are required at several stations within the Kidunda reservoir catchment to identify historical dry, normal and wet years. Moreover, gaps do exist in most streamflow records that usually requires filling by hydrological models, which require input of rainfall and other climatic variables. HBV hydrological model operating at the daily time step is used and consequently daily rainfall and climate data are needed.

Inventory of rainfall stations that ever operated in the catchment of Kidunda reservoir indicates 37 were operated between March 1899 (Kisaki) and now although 12 were closed between July 1939 and February 1974 leaving only 25 non-closed stations (**Figure 2.1**, **Table 2.1**). Data for monthly rainfall amounts for all 25 non-closed stations were obtained from the database at the Department of Water Resources Engineering (WRED) of the University of Dar es Salaam. The records have not been updated ending mostly in the mid to late 1980s (**Table 2.1**). Moreover, daily rainfall records for different periods were available at 14 stations, which essentially updated some monthly records to late 1990s and 2000s. Some were obtained from WRED while others were provided by the Ministry of Water and Irrigation (MoWI).

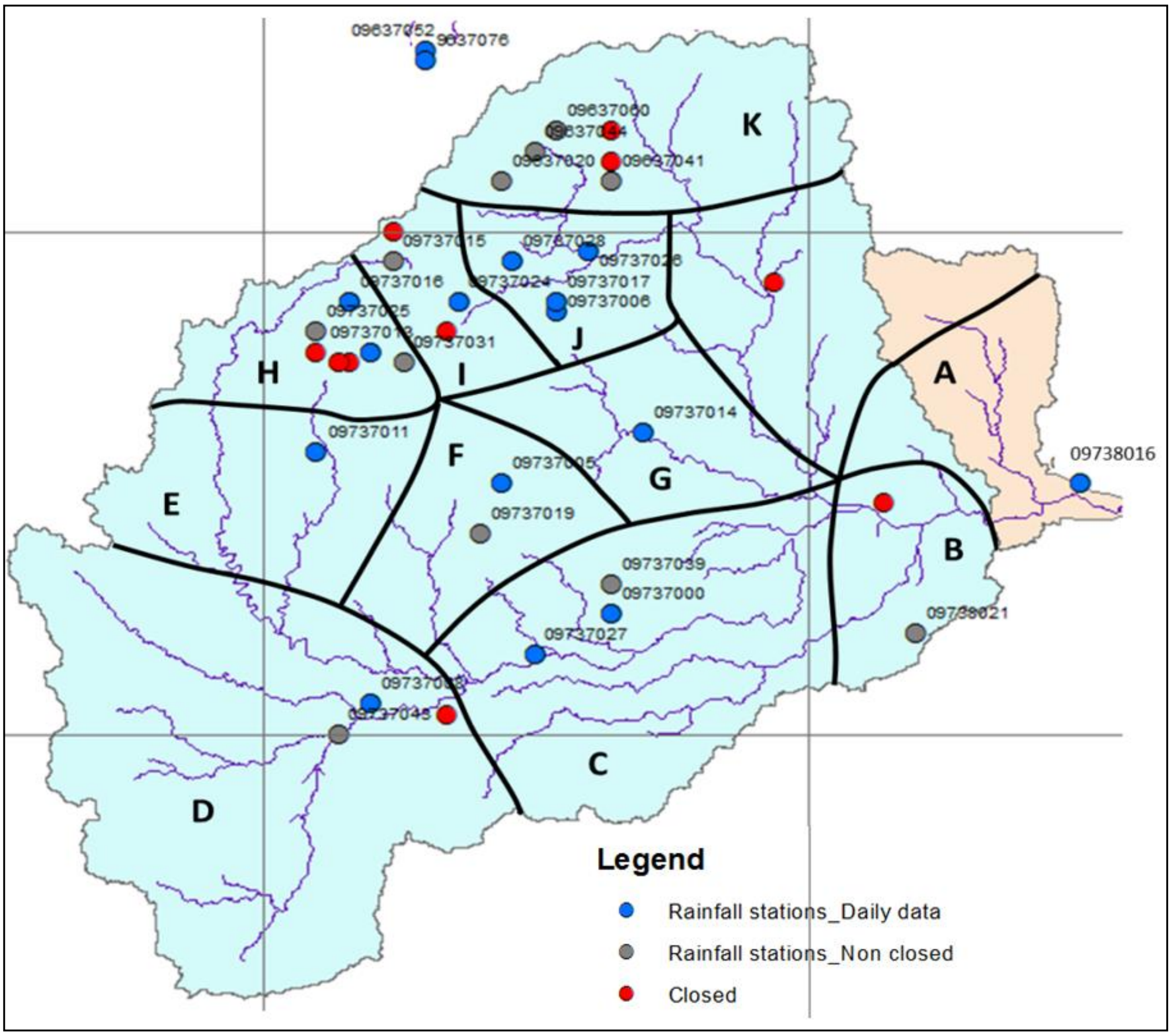

Figure 2.1: Spatial distribution of rainfall stations within Kidunda catchment.

Table 2.1: Inventory and availability of rainfall data in Kidunda catchment.

Sno.	Code	Name	Location			Status	Data Availability	
			Lat	Long	Alt (m)	Established	Monthly	Daily
1	09637020	TEGETERO MISSION	-6.95	37.72	991	1938-10-	Oct 1938 - Aug 1984	
2	09637041	MKUYUNI PRIMARY SCHOOL	-6.95	37.82	365	1952-06-	Jan 1961 - Dec 1988	
3	09637044	BIGWA MIDDLE SCHOOL	-6.92	37.75	610	1952-08-	Jan 1963 - Sep 1964	
4	09637060	KINOLE PRIMARY SCHOOL	-6.90	37.77	304	1962-11-	Nov 1962 - Dec 1975	
5	09737000	DUTHUMI ESTATE	-7.38	37.82	91	1931-01-	Jan 1949 - Sep 1979	1 Jan 1930 - 31 Jul 1986
6	09737005	SINGIZA MISSION	-7.25	37.72	457	1935-02-	Feb 1935 - Dec 1990	1 Dec 1955 - 31 Aug 1998
7	09737006	MATOMBO PRIMARY SCHOOL	-7.08	37.77	388	1938-06-	Jun 1938 - Dec 1990	1 Jan 1941 - 30 Sep 2010
8	09737008	KISAKI	-7.47	37.60	183	1899-03-	Jun 1938 - Dec 1976	1 Jul 1938 - 31 Mar 1980
9	09737011	KIKEO MISSION	-7.22	37.55	610	1941-01-	Feb 1941 - Oct 1976	1 Jan 1941 - 30 Jun 1982
10	09737013	CHENZEMA MISSION	-7.12	37.60	1676	1946-06-	Jan 1961 - Feb 1980	1 Jun 1946 - 29 Feb 1980
11	09737014	MVUHA	-7.20	37.85	131	1950-02-	Jan 1961 - Nov 1978	1 Jan 1951 - 31 Jan 1962
12	09737015	BUNDUKI	-7.03	37.62	1281	1907-01-	Jan 1961 - Apr 1989	
13	09737016	MIZUNGU MGETA	-7.07	37.58	1097	1951-08-	Jan 1961 - Mar 1986	1 Jan 1951 - 31 Oct 1986
14	09737017	MTAMBA	-7.07	37.77	320	1951-08-	Aug 1974 - Jun 1985	1 Aug 1974 - 30 Jun 1985
15	09737019	BWAKIRA JUU	-7.30	37.70	335	1952-10-	Jan 1961 - Feb 1981	
16	09737024	KIBUNGO MISSION	-7.07	37.68	975	1957-08-	Jan 1961 - Apr 1989	1 Jan 1973 - 30 Jun 1991
17	09737025	KIBUKO COFFEE	-7.10	37.55		1959-10-	Jan 1962 - Nov 1977	
18	09737026	KIBUNGO MAJI	-7.02	37.80	274	1956-01-	Jan 1961 - Apr 1989	1 Jan 1971 - 28 Feb 2010
19	09737027	BWAKIRA ESTATE	-7.42	37.75	152	1956-01-	Jan 1961 - Mar 1974	1 Jan 1961 - 31 Mar 1974
20	09737028	TAWA HEALTH CENTRE	-7.03	37.73	457	1963-01-	Jan 1963 - Apr 1989	1 Sep 1974 - 30 Jun 1999
21	09737031	MKATA SETTLEMENT	-7.13	37.63	579	1969-01-	Jan 1969 - Jan 1977	
22	09737039	DUTHUMI TCA FARM	-7.35	37.82		1978-06-	Aug 1978 - Dec 1985	
23	09737043	KISAKI TAZARA RAILWAYS	-7.50	37.57	178	1985-07-	Feb 1986 - Mar 1989	
24	09738016	MIKULA (MAGOGONI)	-7.25	38.25		1970-01-	Jan 1971 - Apr 1989	1 Jan 1976 - 31 Oct 2009
25	09738021	KINYANGURU RAILWAY STN.	-7.40	38.10	142	1985-07-	Oct - Dec 1985	
26	*09637052*	*MOROGORO HYDROMET (MAJI)*	*-6.82*	*37.65*	*512*	*1956-01-*		*1 Jan 1956 - 30 Nov 2010*
27	*9637076*	*MOROGORO MET. STN*	*-6.83*	*37.65*	*526*	*1970-09-*		*1 Jan 1971 - 30 Sep 2014*

2.2.2 Data processing

Data values

Visual analysis of values within individual records indicated data points were of good quality. The verification was also supplemented by plots of time series of daily and monthly aiming at identifying erroneous high daily or monthly amounts with the records. The results of such a procedure further indicated good quality data points.

Missing data gaps

Monthly records

Time series of monthly rainfall amounts were established using a combination of available daily and monthly records at each station (**Table 2.1**). With interest in the 1951-1989 period when quality flow records exist, availability of data in this period was assessed. A few records (2: 09737005 and 09737006) are most continuous in the 1951-1989 period while several others have most continuous records either between the early 1960s through 1989 or early 1950s through late 1970s/early 1980s (**Figure 2.2**). However, most of the stations have records starting before or in 1961/62. Percentage and length of gaps of missing data varies between records.

Daily records

Despite highly varying periods of data availability at individual stations, there is at least one record representing each spatial group. The gaps within available daily record periods are mostly short (**Figure 2.3**).

Selection

Categorisation of years

Owing to variability of record period, lengths/distribution of missing monthly data among the available records as well as closeness of some stations that can lead to similar variability patterns, 11 spatial groups were identified from closeness of stations and labelled A-K (**Figure 2.2**). These groups contain 1 – 4 stations with variable record periods, lengths and gaps of missing data. A single representative record with longest and most continuous data in the 1949/50-1988/89 period was selected for each group (bolded stations, **Figure 2.2**).

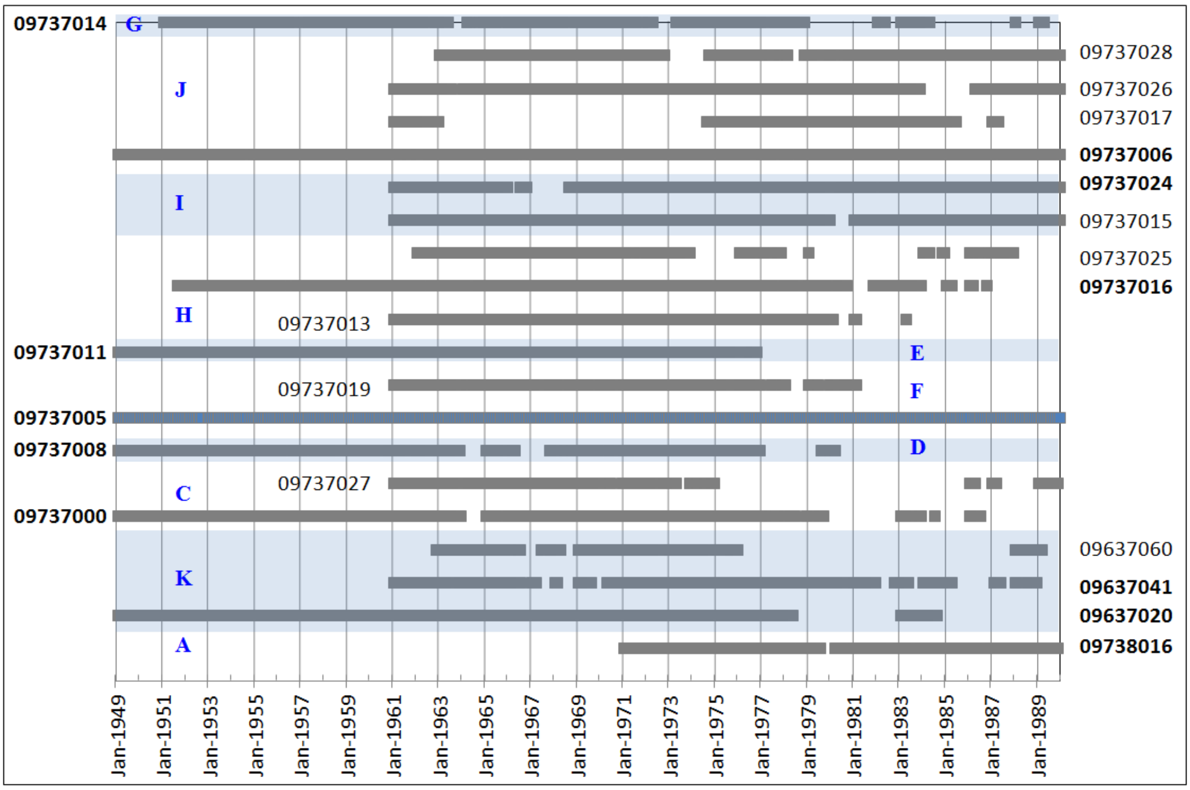

Figure 2.2: Availability of monthly rainfall data within Kidunda catchment.

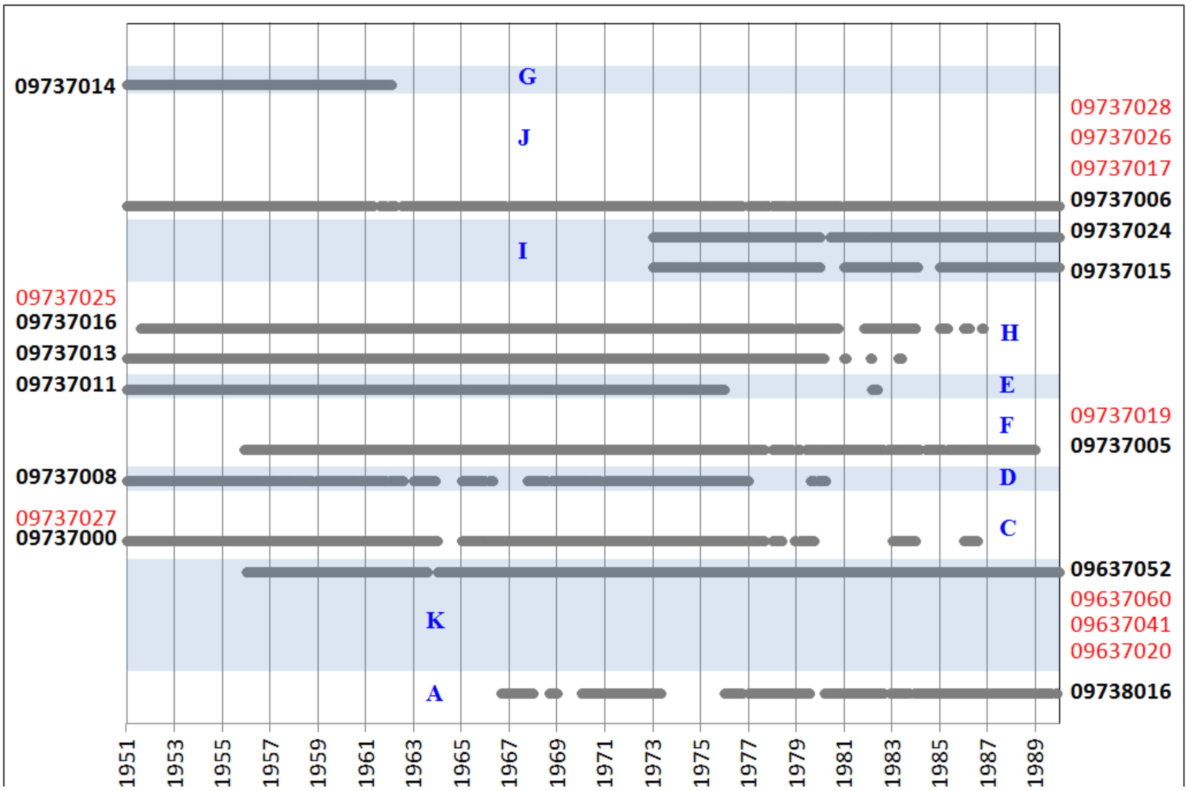

Figure 2.3: Availability of daily rainfall data within Kidunda catchment.

Hydrological modelling

Daily rainfall records of variable length were available at some stations (**Table 2.1**). These records are used in the reconstruction of daily discharge records for selected years that are used to assess impacts on SGR. The selection process is therefore delayed until years and/or seasons are categorised.

2.3 METHODOLOGY

Defining rainfall seasonality and hydrological years

Rainfall seasonality is defined from long-term averages of monthly rainfall amounts at individual ground stations. The procedure involves

i) establishing monthly rainfall amounts from daily rainfall amounts simply as accumulation of daily rainfall amounts for complete months (where no day misses a record)

ii) for each of the 12 months in a year, compute the monthly average from non-missing values of rainfall amounts in this particular month over the years in the record (long-term monthly averages)

iii) divide the 12-month period into seasons as follows:

   a. a wet season: monthly rainfall amounts with contribution to mean annual amount exceeding 5%

   b. dry season: monthly rainfall amounts with contribution to mean annual amount are less than 5%

iv) define rainy and dry seasons, which may be more than one (≥ 1)

v) define a hydrological year: this is the one comprising all rainy seasons within the 12-months period

Categorising years

Standard Precipitation Index (SPI) is used in categorisation of dryness and wetness of years in this updating study. The review of suitability of SPI for categorisation of wetness and dryness of years is adopted from Valimba (2012) and its application procedure is outlined as follows.

- Generating time series of monthly, seasonal and annual rainfall amounts
- Fitting a frequency distribution to the established time series by estimating parameters to produce a probability density function (pdf), f(x). In this case, P3 is fitted to data

$$f(x) = \frac{|\beta|}{\Gamma(\alpha)} \left(\beta (x - \xi)\right)^{\alpha - 1} e - \beta^{(x-\xi)} \tag{1}$$

where α, β and ξ are shape, scale and location parameters respectively.

The parameters are estimated from data as

$$\mu = \xi + \frac{\alpha}{\beta}, \quad \sigma^2 = \frac{\alpha}{\beta^2}, \quad \gamma = \frac{2\beta}{|\beta|\alpha^{1/2}} \tag{2}$$

where μ, σ^2 and γ are mean, variance and skewness estimators for population values.

- Establish time series of equivalent normal variate, $z_{p_i}(x)$, of elements x_{p_i} of a P3 distributed time series from

$$x_{p_i} = \mu + \sigma K_{p_i} \tag{3}$$

and

$$K_{p_i} = \frac{2}{\gamma}\left[1 + \frac{\gamma z_{p_i}}{6} - \frac{\gamma^2}{36}\right]^3 - \frac{2}{\gamma} \tag{4}$$

where

K_{p_i} is the P3 variate
z_{p_i} is the normal variate
x_{p_i} is an element of a time series
$p_i = F(x)$

Re-arranging for K_{p_i} in eqn (3) gives

$$K_{p_i} = \frac{(x_{p_i} - \mu)}{\sigma} \tag{5}$$

Substituting eqn (5) into eqn (4) and solving for z_{p_i} gives

$$z_{p_i} = \frac{6}{\gamma}\left\{\left[\frac{\gamma(x_{p_i} - \mu)}{2\sigma} + 1\right]^{1/3} + \frac{\gamma^2}{36} - 1\right\} \tag{6}$$

- Estimating cumulative frequency, F(x), from z_{p_i} using the following equations

$$z_{p_i} = W - \left[\frac{2.515517 + 0.802853W + 0.010328W^2}{1 + 1.432788W + 0.189269W^2 + 0.001308W^3}\right] \tag{7}$$

where

$$W = \sqrt{ln\left(\frac{1}{p_i^2}\right)} \tag{8a}$$

$$p_i = F(x) \tag{8b}$$

For F(x) < 0.5, z_{p_i} is negative.

Or from the MS Excel (spreadsheet) function

NORMSDIST(z_{p_i})

- Estimating modified cumulative frequency, H(x) to account for zero values in the series

$$H(x) = q + (1 - q)F(x) \quad (9)$$

where

q is the fraction of zero events in the series obtained from $q = \frac{n}{N}$ where *n* denotes total number of zero events in the *N* available data points in the series respectively.

- Recomputing z_{p_i} from equation (7) replacing p_i by H(x)
- Comparing estimated time series of z_{p_i} to standard SPI values to define floods and droughts levels

Table 2.2: Description of SPI classes (McKee *et al.*, 1993).

SPI value	Category
≥ 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤ -2	Extremely dry

- Identifying dry/drought, normal and wet years, seasons and months

2.4 RESULTS

2.4.1 Rainfall seasonality

Long-term average monthly rainfall amounts indicate a wet period extending between October and May while a dry period is prevails in June-July-August-September (JJAS) period (**Table 2.3**). Plots of these monthly amounts (**Figure 2.4**) further suggest organisation of the wet period into two peaks, a minor peak in November and a major peak in April corresponding to the short “Vuli” rains in October-November-December (OND) and long “Masika” rains in March-April-May (MAM) period respectively. The period January-February (JF) received slightly reduced amounts visible in eastern parts (**Figure 2.4**) with monthly contributions to mean annual rainfall (MAP) exceeding 5% and it is referred to as a transition season between the two main rainy seasons. As a summary, the year is therefore organised into 3 rainy seasons and a single 4-month dry season and a water or hydrological year is defined as a 12-month period starting in October of the first year to end in September of the following year (October-September). Owing to variable amounts received in these four seasons, MAM receives the largest amounts contributing, on average, 46% (Range: 31-62%) of MAP, OND contributes about 25% (Range: 14-39%), JF contribution is 20% (Range: 15-25%) while the dry JJAS season contributes about 9% (Range: 4-17%). The two main rainy seasons, MAM and OND contribute a total of 71% (Range: 66 -77%) indicating that they are responsible for water flow changes in a year. Consequently, the filling and draining of the proposed Kidunda reservoir will be affected by changes of rainfall amounts in either of or both the seasons. High amounts in either or both seasons in wetter seasons can be responsible for rapid filling probably to full reservoir level and spillage while low amounts in drier/drought seasons can be associated with partial and slow filling of the reservoir.

Table 2.3: Long term averages of monthly rainfall amounts for stations in the Kidunda catchment.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
09738016	9.0%	7.0%	16.5%	24.6%	9.0%	2.0%	0.9%	1.3%	2.7%	3.3%	9.2%	14.3%
09637020	*7.6%*	*7.2%*	*13.1%*	*20.6%*	*11.5%*	*4.7%*	*3.8%*	*3.4%*	*4.6%*	*6.2%*	*8.5%*	*8.8%*
09637041	*11.1%*	*9.6%*	*13.6%*	*17.8%*	*7.8%*	*2.7%*	*3.1%*	*2.0%*	*3.3%*	*5.7%*	*10.0%*	*13.2%*
09637060	*11.4%*	*8.0%*	*14.0%*	*21.1%*	*6.6%*	*3.6%*	*3.2%*	*3.2%*	*3.3%*	*3.1%*	*8.7%*	*13.7%*
09737000	11.2%	10.5%	17.7%	24.1%	10.5%	2.6%	1.2%	0.9%	2.0%	3.1%	7.8%	8.5%
09737027	10.5%	7.4%	14.6%	22.3%	11.2%	3.6%	2.9%	1.3%	2.2%	4.1%	11.5%	8.5%
09737008	*10.9%*	*8.5%*	*17.8%*	*27.5%*	*16.3%*	*2.3%*	*0.6%*	*0.6%*	*1.9%*	*2.6%*	*4.6%*	*6.4%*
09737005	9.4%	10.0%	16.7%	26.4%	11.4%	2.3%	1.7%	1.0%	2.2%	3.1%	7.3%	8.5%
09737019	7.1%	11.3%	17.0%	25.7%	8.4%	2.4%	1.8%	1.9%	2.3%	3.7%	8.5%	9.9%
09737011	*12.2%*	*12.4%*	*18.6%*	*25.0%*	*9.1%*	*2.1%*	*0.8%*	*0.7%*	*0.9%*	*2.0%*	*6.3%*	*9.9%*
09737013	12.3%	11.8%	15.1%	23.9%	7.8%	2.1%	1.4%	0.5%	1.9%	3.0%	9.0%	11.0%
09737016	11.2%	13.2%	16.1%	23.9%	5.9%	0.8%	0.8%	0.6%	2.1%	4.5%	8.7%	12.1%
09737025	14.2%	10.6%	16.2%	22.7%	10.6%	1.4%	0.8%	0.4%	2.3%	2.2%	7.8%	10.7%
09737015	*9.1%*	*7.9%*	*12.8%*	*16.8%*	*6.9%*	*1.8%*	*1.4%*	*2.1%*	*4.4%*	*8.3%*	*15.2%*	*13.4%*
09737024	*10.5%*	*7.3%*	*11.8%*	*13.9%*	*5.6%*	*1.5%*	*2.4%*	*3.0%*	*5.2%*	*9.4%*	*13.6%*	*15.6%*
09737006	10.1%	9.8%	15.2%	16.5%	8.3%	3.1%	3.4%	3.3%	3.6%	5.3%	9.2%	12.4%

09737017	8.7%	9.2%	14.8%	15.6%	6.9%	2.5%	3.6%	1.8%	4.5%	8.0%	9.0%	15.4%
09737026	11.8%	9.1%	13.7%	17.8%	7.6%	3.2%	2.4%	2.1%	3.0%	6.2%	8.6%	14.5%
09737028	8.2%	8.0%	13.8%	18.8%	8.7%	3.4%	3.4%	4.3%	4.4%	6.7%	10.2%	10.3%
09737014	*11.8%*	*11.0%*	*17.9%*	*20.4%*	*8.1%*	*2.1%*	*1.6%*	*2.1%*	*2.9%*	*4.5%*	*7.8%*	*10.0%*

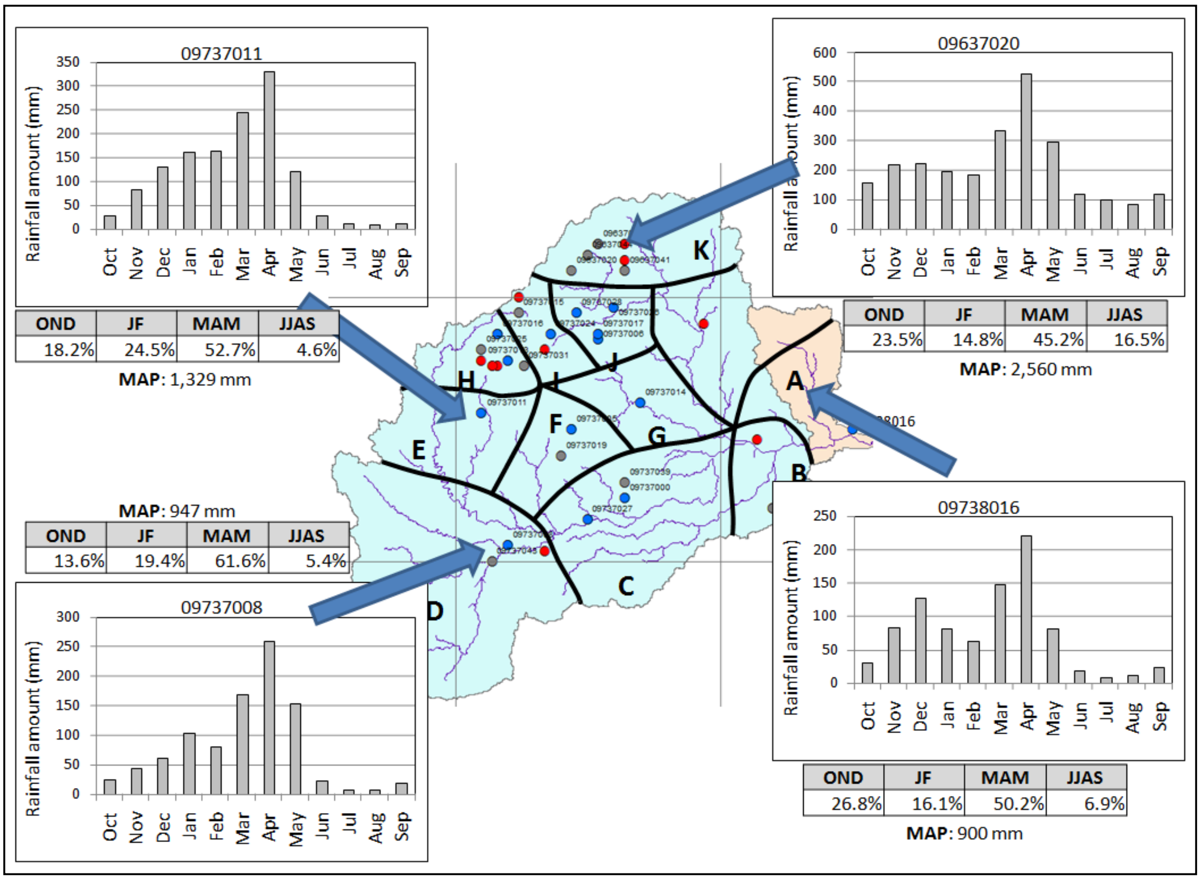

Figure 2.4: Seasonality of rainfall in Kidunda catchment.

2.4.2 Categorising wetness of years and seasons

Analysis results of selected 11 records indicate that year are seldom dry or wet (e.g. at 09737005, **Table 2.4**). A few different years were identified with different magnitudes of dryness and wetness while a close observation indicates that there are some years which are common to a number of stations (**Table 2.5**). Consequently, these common 11 years were considered either dry/drought (4) or wet (7) years and include

i) Drought years: 1953/54; 1964/65; 1974/75; 1976/77

ii) Wet years: 1951/52; 1961/62; 1962/63; 1965/66; 1967/68; 1972/73; 1978/79

The common dry years are spaced at about 10-11 years in the early 1950s and 1960s as well as the mid-a970s. However, four (4) of the 7 wet years occurred in the 1960s while two (2) were in the 1970s and one (1) in the early 1950s.

Table 2.4: Categorisation of seasons and years at 09737005.

Year	OND	JF	MAM	JJ	AS	Ann
1949	-0.089	0.102	0.653	0.366	-0.437	-0.413
1950	0.011	0.394	1.296	0.237	-0.198	0.777
1951	1.292	2.507	2.382	0.763	-1.144	2.383
1952		0.630	0.834	-1.027	0.406	1.033
1953	-0.499	-3.792	1.622	-1.027	0.101	0.240
1954	0.322	0.124	-0.297	-1.026		-0.921
1955	-0.485	1.345	0.531	1.091	-1.144	0.973
1956	-0.658	0.968	0.544	0.574	-0.764	0.447
1957	0.006	-0.189	1.220	-1.018	1.113	0.497
1958	-0.470	-0.497	0.498	0.836	-0.846	0.111
1959	-1.294	-2.948	-1.519	0.398	0.888	-4.584
1960	-1.757	0.767	0.081	1.071	-0.262	-0.122
1961	1.970	0.981	-1.014	1.338	0.526	-0.588
1962	-0.120	0.733	-0.247	-1.027	0.871	0.951
1963	1.136	0.414	-0.147	0.656	-1.144	-0.154
1964	-1.111	-3.271	-0.829	-1.027	-1.144	-0.500
1965	0.400	-0.811	-1.015	-1.027	0.250	-5.155
1966	-1.343	-3.360	-0.820	0.817	-0.365	-0.876
1967	0.623	-3.209	0.123	1.145	1.415	-0.544
1968	0.536	-0.084	0.187	0.466	-1.105	0.215
1969	-1.185	-0.630	0.021	-0.067	0.038	-0.051
1970	-0.528	1.189	-1.666	-1.008	0.785	-0.817
1971	-0.540	-0.107	-0.340	1.174	-1.121	-0.591
1972	0.859	0.021	0.717	-1.027	0.954	0.170
1973	-0.904	0.486	0.004	0.557	-0.117	0.455
1974	-1.388	-0.425	0.033	1.230	0.986	-0.297
1975	-0.742	-3.296	0.647	1.168	0.274	-0.372
1976	-1.483	0.518	-0.128	0.791	1.201	-0.050
1977	0.753	0.234	-1.474	0.107	1.767	-1.768
1978	1.952	0.333	-1.340	0.533	0.718	-0.132
1979	0.700	1.220	1.809	0.895	0.428	1.984
1980	-0.057	0.640	0.659	-0.312	-0.049	0.731
1981	0.147	0.320	-1.707	1.364	0.754	-0.501
1982	1.916	1.565	-0.269	1.162	2.535	1.211
1983	0.326	-0.413	0.333	2.607	1.170	1.500
1984	1.364	0.526	0.964	0.862	-1.144	0.785
1985	0.234	0.629	-0.248	0.432	-0.019	0.625
1986	0.822		0.002	-1.008	-0.108	-0.383
1987	-0.297	-0.007	-0.575	-1.023	0.701	-0.044
1988	-0.105	0.111	-1.403	0.584	0.786	-1.090
1989	-0.093	-0.186	0.935	0.686	0.104	0.447

Table 2.5: Identified wet and dry years in the Kidunda catchment.

Station	Dry			Wet			Missing years
	Extreme	Severe	Moderate	Moderate	Severe	Extreme	
09738016	1981/82		1982/83	1972/73, 1984/85	1977/78		1940/51-1970/71; 1976/77; 1979/80
09637020	1975/76	1976/77	1948/49, 1973/74	1965/66, 1966/67	1949/50, 1951/52, 1967/68		1977/78-1982/83; 1983/84-1988/89
09637041	1964/65			1962/63, 1972/73		1961/62	1950/51-1960/61; 1982/83-1988/89
09737000		1952/53	1953/54		1962/63	1961/62, 1967/68	1963/64; 1976/77-1988/89
09737008		1974/75	1952/53, 1955/56, 1956/57	1967/68, 1972/73	1971/72, 1973/74		1961/62; 1963/64-1966/67; 1976/77-1988/89
09737005	1964/65, 1958/59	1976/77	1987/88	1951/52, 1981/82	1978/79, 1982/83	1950/51	None
09737011		1964/65	1948/49, 1953/54, 1958/59, 1959/60	1962/63, 1967/68	1972/73	1961/62	1975/76-1988/89
09737016	1974/75		1953/54, 1965/66	1969/70, 1972/73, 1981/82, 1982/83	1951/52	1961/62	1950/51; 1980/81; 1983/84-1988/89
09737024	1983/84		1964/65, 1970/71, 1974/75	1982/83, 1984/85, 1988/89		1978/79	1950/51-1960/61; 1965/66-1967/68; 1979/80
09737006		1979/80	1981/82	1962/63, 1967/68, 1978/79	1964/65, 1965/66	1963/64	1961/62
09737014		1968/69, 1976/77		1958/59, 1961/62	1967/68	1965/66	1950/51; 1956/57; 1962/63; 1963/64; 1971/72; 1972/73; 1978/79-1988/89
Overall	**1953/54; 1964/65; 1974/75; 1976/77**			**1951/52; 1961/62; 1962/63; 1965/66; 1967/68; 1972/73; 1978/79**			

Further analyses indicate dryness and wetness are more frequent at the seasonal timescale than at the annual timescale (e.g. **Table 2.4**). As expected, the dry/drought and wet years identified earlier were rather contributed by similar conditions in the wet seasons (OND, JF & MAM) as any combinations of the three seasons e.g. OND & MAM (1976/77), OND, JF & MAM (1978/79), JF & MAM (1958/59). It is further observed some of categorised normal years were actually related to contrasting dryness and wetness levels in the underlying seasons. In some years, dry early rainy seasons (OND, JF) and wet late rainy season (MAM) were responsible for such normality of a year (e.g. 1966/67 at 09737005, **Table 2.4**). Further observations indicated rarity of complete wet or dry wet period in which all the three rainy seasons (OND, JF, MAM) are categorised as dry or wet. Owing to this, complete dry wet period (October-May) were identified to differ between locations but were mainly 1952/53, 1977/78 and 1983/84 depending on the location. Similarly, completely wet October-May period varied spatially but were either 1961/62 or 1978/79. Between these two extremes lie groups of years where wetness and dryness differed between seasons that will result in different levels of reservoir filling and inundation duration with different impacts levels in SGR.

Rapid reservoir filling and sustained high reservoir levels would occur from high river flows resulting from abundant rainfall sustained throughout the wet October – May period. However, rapid reservoir filling can also occur due to high flows in only one season although persistence of inundation will be affected by reduction of rainfall in the other seasons. Therefore, assessment of impacts of reservoir filling and inundation duration on SGR involves assessment of impacts in completely dry (1952/53 and 1983/84), wet (1961/62 and 1978/79) and all the 5 combinations of dryness between OND, JF and MAM seasons. The most prevailing years with different combinations are therefore

i) Dry/dry/dry (1952/53 or 1983/84)
ii) Dry/dry/wet (1974/75)
iii) Dry/wet/wet (1971/72)
iv) Wet/dry/dry (1977/78)
v) Wet/wet/dry (1972/73)
vi) Dry/wet/dry (1969/70)
vii) Wet/wet/wet (1961/62 or 1978/79)

3 STREAMFLOW ANALYSES

3.1 GENERAL

Reservoir inflows are mainly river discharges while outflows are dam releases and evaporation from open reservoir water surface. Understanding of reservoir inundation patterns into and from SGR requires knowledge of changes of water surface elevations as a result of net change in reservoir storage caused by differences between water inflows and outflows.

3.2 DATA AVAILABILITY AND PROCESSING

3.2.1 Stage data

3.2.1.1 Availability

Discharge data are required to determine the water inflows into the Kidunda reservoir. According to available information, the reservoir will receive water from the main River Ruvu and its two tributaries, River Mgeta and Mkulazi stream (**Figure 3.1**). Discharge of R Ruvu downstream of its confluence with R Mgeta is monitored by a river gauging station 1H10 (Ruvu @ Mikula). Mkulazi stream joins R Ruvu about 6.65 km downstream of 1H10 and the next gauging station, 1H3, monitoring discharge of R Ruvu is located at Kidunda, about 11.33 km from the Ruvu-Mkulazi confluence. The two gauging stations are therefore only 17.98 km apart with discharge difference between the two gauging sites attributed to flows of ungauged Mkulazi stream discharges.

Inventory of available information for the two gauging stations (**Table 3.1**) indicates that 1H3 was established on 26th July 1951 while 1H10 on 23rd August 1966. However, assessment of data availability at these two river gauges indicates that 1H3 have river stage data in two periods, 26th Jul 1951 – 28th Aug 1969 and 2nd Nov 2006 – 30th Sep 2009. There is therefore a huge gap between 29th Aug 1969 and 1st Nov 2006 (**Figure 3.2**). 1H10, on the other hand, has data in the 22nd Dec 1966 – 30thSep 1988 and 1st Mar 2005 and 31st Oct 2008 periods (Table 1) and a huge gap of missing data in the 1stOct 1988 – 28th Feb2005 period (**Figure 3.2**).

3.2.1.2 Quality assessment

Data values

Stage data were available at 1H3 and 1H10 for periods indicated in **Table 3.1**. The old 1H3 record had stage data in imperial units (ft) and was entirely converted to metric units (m), which are used in rating curves. The 1H10 record had metric units since 16th January 1971 and imperial units before this date (**Figure 3.3a**), which were converted to metric units to harmonise the two parts into a metric record (**Figure 3.3b**). Apart from missing values, individual stage values were of good quality for processing into river discharges.

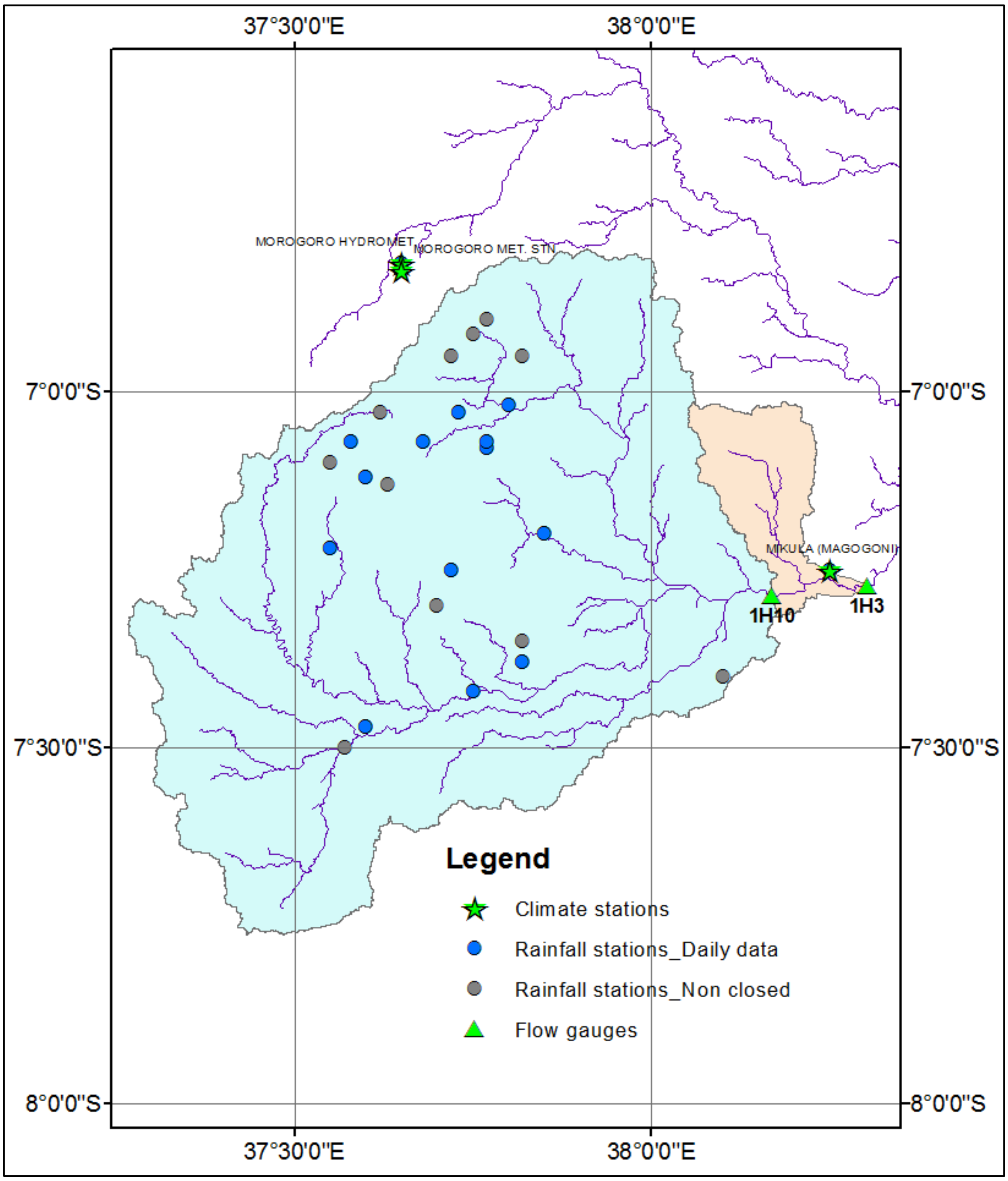

Figure 3.1: **Location of river gauging, rainfall and climate stations within Kidunda catchment.**

Table 3.1: Inventory of gauging stations and stage data availability for Kidunda inflow sites.

Sno	No.	Name	River	Location	Established	Water Level
1	28	1H3	Ruvu	Kidunda	26/07/1951	26/7/1951 – 31/8/1969; 2/11/2006 – 30/9/2009
2	63	1H10	Ruvu	Mikula	23/08/1966	23/8/1966– 30/9/1988; 1/3/2005 – 31/10/2008

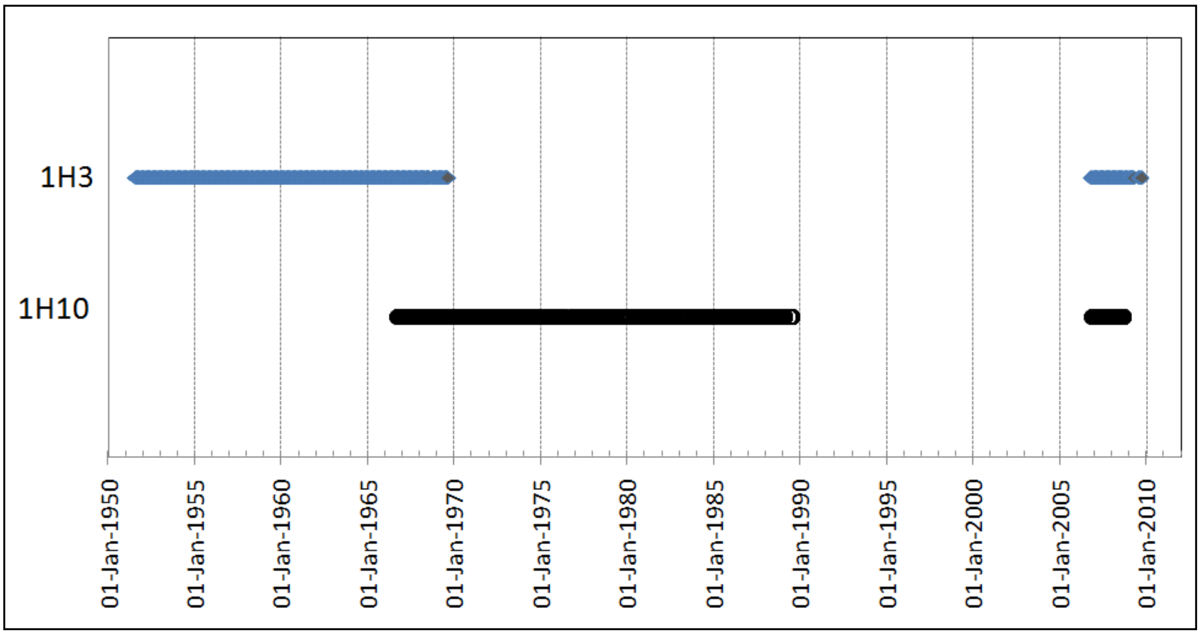

Figure 3.2: **Availability of daily river stage / discharge data at 1H3 and 1H10.**

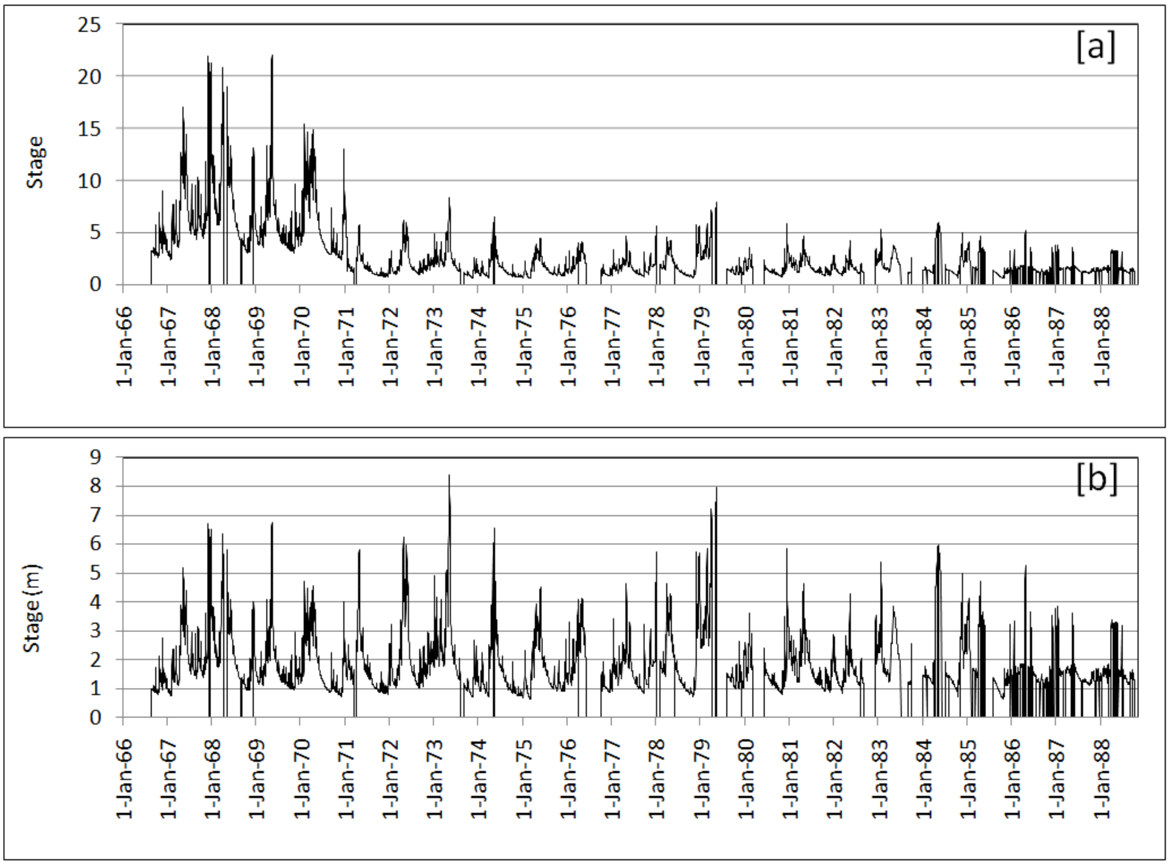

Figure 3.3: **a) Raw and b) corrected daily stage data at 1H10.**

Missing data

Except for a few missing observations in July 1951 (25), August (23) and September (5) 1968 and June 1969 (13), the 1H3 record is mostly continuous (**Table 3.2**). The 1H10 records, on the other hand, has a lot of missing values from gaps of few consecutive days (≥ 1 day) to several consecutive months (≤ 14) with different number of missing observations within individual months (e.g. December 1985 – January 1987, **Table 3.3**). For the first common period of the two record (23rd August 1966 – 31st August 1969), the two records have 41 (1H3) and 40 (1H10) days with missing observations with only August 1968 being missed in both stations (1H3: 23 days; 1H10: 10 days). Within this common period, the largest number of missing observations was in 1968 with 28 days missing in August (23) and September (5) 1968 at 1H3 and 36 observations missing in April (24), May (1), August (10) and December (1) 1968 at 1H10. The other longest missing gaps of observations were in June 1969 (13) at 1H3. Moreover, the 1H10 record is mostly continuous with a few missing days of observations until May 1976 after which the longest continuous 122 days gap of missing observation prevails from 1st June to 30th September 1976 (**Table 3.3**). Other three longest gaps also exists in the record, the 1st March-31st May 1980 (92 Days), 1st September-30th November 1982 (91 days), 9th May-3rd August 1979 (87 days), 1st July-31st August 1983 (62 days) and 1st June-31st July 1985) gaps.

Table 3.2: Available daily data points at 1H3 in the Jan 1951 – Dec 1969.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1951							6	31	30	31	30	31
1952	31	29	31	30	31	30	31	31	30	31	30	31
1953	31	28	31	30	31	30	31	31	30	31	30	31
1954	31	28	31	30	31	30	31	31	30	31	30	31
1955	31	28	31	30	31	30	31	31	30	31	30	31
1956	31	29	31	30	31	30	31	31	30	31	30	31
1957	31	28	31	30	31	30	31	31	30	31	30	31
1958	31	28	31	30	31	30	31	31	30	31	30	31
1959	31	28	31	30	31	30	31	31	30	31	30	31
1960	31	29	31	30	31	30	31	31	30	31	30	31
1961	31	28	31	30	31	30	31	31	30	31	30	31
1962	31	28	31	30	31	30	31	31	30	31	30	31
1963	31	28	31	30	31	30	31	31	30	31	30	31
1964	31	29	31	30	31	30	31	31	30	31	30	31
1965	31	28	31	30	31	30	31	31	30	31	30	31
1966	31	28	31	30	31	30	31	31	30	31	30	31
1967	31	28	31	30	31	30	31	31	30	31	30	31
1968	31	29	31	30	31	30	31	8	25	31	30	31
1969	31	28	31	30	31	17	31	31				

The data availability and record continuity of River Ruvu at Kidunda (1H3, **Table 2.3**) indicate availability of complete years for analysing impacts of Kidunda reservoir filling and inundation patterns for the hydrological (1st October-30th September) years 1952/53 and 1961/62. For the other 6 years (1969/70, 1971/72, 1972/73, 1974/75, 1977/78 and 1983/84), there is no observation record at 1H3. Therefore, an upstream gauge 1H10 (Ruvu at Mikula) is used to estimate discharges at 1H3 in these 6 years. 1H10 record indicates complete hydrological years 1969/70, 1971/72 and1974/75, complete wet period in 1972/73, partly missing wet period in 1977/78 (Dec: 1 day; Jan: 31 days; May: 1 day) and largely missing 1983/84 (**Table 3.3**).

Table 3.3: Available daily data points at 1H10 in the Jan 1966 – Dec 1989 period.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1966								9	30	31	30	31
1967	31	28	31	30	31	30	31	31	30	31	30	27
1968	31	29	31	6	30	30	31	21	30	31	30	30
1969	31	28	31	30	31	30	31	31	30	31	30	31
1970	31	28	31	30	31	30	31	31	30	31	30	31
1971	31	28	15	30	31	30	31	31	30	31	30	31
1972	31	29	31	30	31	30	31	31	30	31	30	31
1973	31	28	31	30	31	30	31	0	30	31	30	31
1974	31	28	31	30	25	30	31	31	30	31	30	31
1975	31	28	31	30	31	30	31	31	30	31	30	31
1976	31	29	30	30	31	0	0	0	0	31	30	31
1977	31	28	31	30	31	30	31	31	30	31	30	30
1978	0	28	31	30	30	30	31	31	30	31	30	31
1979	31	28	29	1	5	0	0	28	30	31	29	31
1980	31	29	0	0	0	30	31	31	30	31	30	31
1981	31	28	31	30	31	30	31	31	30	31	30	31
1982	31	28	31	30	31	30	30	31	0	0	0	31
1983	31	28	31	30	31	30	0	0	30	0	0	0
1984	30	29	28	19	23	0	30	31	30	30	30	31
1985	27	13	21	23	17	0	0	31	30	31	30	27
1986	15	18	21	19	13	18	29	25	22	23	18	11
1987	20	28	16	30	22	30	20	31	30	31	23	26
1988	28	28	29	23	23	21	31	29	27			

3.2.1.3 Reconstruction of 1H3 record

3.2.1.3.1 Selection of study period

The selected analysis period should lie between 26th July 1951 and 30th September 1988 of availability of reliable streamflow records and should also consider hydrological years in the analysis. Consequently, the period 1st October 1951 – 30th September 1988 was selected. Hydroclimatologically, this period encompasses several hydrological and climatological extreme. With emphasis of the study on simulation of reservoir filling and depletion following seasonality of inflows and outflows in understanding inundation patterns into Selous Game Reserve, this period is considered sufficient to provide required sequences of dry, normal and wet seasons and years useful in the simulation.

3.2.1.3.2 Gap filling of 1H10 record

Continuous records at 1H3 were required for the years 1972/73, 1977/78 and 1983/84, which required estimation from 1H10 record. However, 1H10 record contains gaps of missed observations in these years with different patterns (**Figure 3.4**) that needed filling. The following methods were used to fill gaps in the 1H10 record:

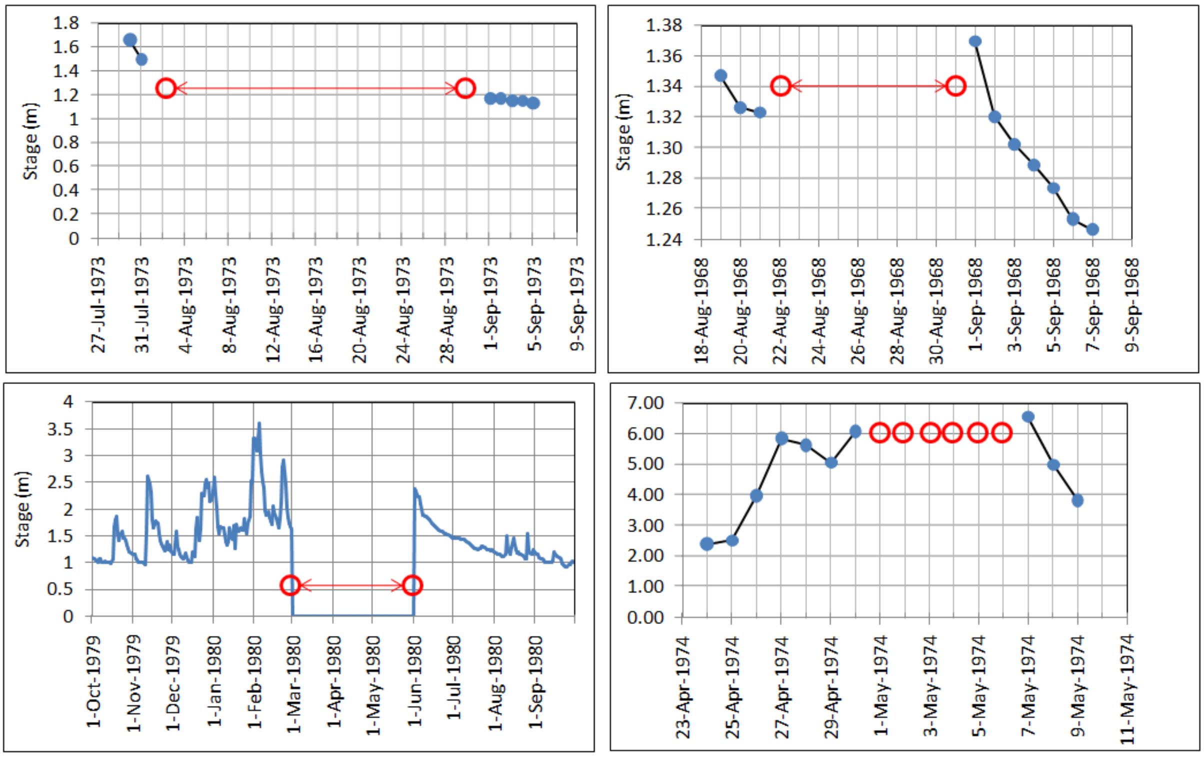

Figure 3.4: Nature of gaps in 1H10 record.

1-4 missing daily data

These gaps were filled by linear interpolation regardless of the seasonal (dry or wet season) of occurrence. This method filled the 1 day missing in May 1978.

5-14 missing daily data

Such moderately long gaps that occurred during the dry season (and where values before the gap were higher than those after the gap) were efficiently filled by recession curve model given as

$$Q_t = Q_o e^{-t/k}$$

Where Q_t is the estimated discharge, Q_o is the initial discharge, *t* is the time (days) from initial date with discharge Q_o and *k* is the recession constant.

This recession model was used to fill the missing daily August 1972 stage data as well as August (1966, 1968, 1973, 1976, 1983), September 1976, June (1976, 1984, 1985), July (1976, 1983, 1985) and October (1982, 1983) before start of the October rains. Otherwise, for dry season gaps in which values before gaps show recession and also values after the gap recessing from a value higher than that before the gap (e.g. 1968 & 1974, **Figure 3.4**), the gaps were filled by polynomial models of 4-6 orders depending on the model fit.

Several rainfall-runoff (R-R) systems models available in the Galway Flood Forecasting System (GFFS) including Simple Linear Model (SLM), Linear Pertubation Model (LPM), A daily system rainfall-runoff (R-R) simple linear model (SLM) was used to fill long gaps occurring during the rainy season (November-May) in the 1H10 record. The model is represented by

$$Q_i = \sum_{j=1}^{m} R_{i-j+1} h'_j + e_i$$

$$= \quad G \sum_{j=1}^{m} R_{i-j+1} B_j \quad \text{where} \quad \sum_{j=1}^{m} B_j = 1$$

where Q_i and R_i are the discharge and rainfall respectively at the *i*-th time-step, h'_j is the *j-th* discrete pulse response ordinate or weight, *m* is the memory length of the system and *G* is the gain factor.

Model inputs

Rainfall

SLM model uses a single input of series of rainfall that represents catchment rainfall. This was determined by arithmetic mean (AM) and Thiessen methods. The AM method assigns equal weights to all stations regardless of influential areas and therefore catchment rainfall is determined a simple average of daily rainfall amounts at each station. With the Thiessen method, weights (w_i) are assigned to stations as the fraction of influential area over total catchment area.

According to availability of daily rainfall data (**Figure 3.1**) and spatial proximity of stations, 5 stations within the Kidunda catchment and 1 (Morogoro Maji, 09637052) were selected that represent the most uniform and spatially distant spacing of stations (**Figure 3.5**). Lack of rainfall stations and data in the southwestern and eastern parts of the catchment resulted in large influential areas of stations 09737008 and 09737014 (**Figure 3.5**) representing about 51.8% of the catchment. Owing to availability of many records close to 09737016, missing daily rainfall at this station were estimated as averages of daily amounts at the other stations (09737013, 09737015, 09737024, 09737025) for a particular missing day. Similarly, the daily 09737000 rainfall record was filling by available daily record at its closest station, 09737005.

AM method was used to compute catchment rainfall for each day simply as averages from the six (6) stations and provided a continuous daily record in the 1st January 1966 – 31st December 1989 period. Thiessen polygon method, however, produced a gapped daily series with missing values resulting from unavailability of data at any of the six stations. A comparison of AM and Thiessen method catchment rainfalls for non-missing periods indicated closely matching daily rainfall amounts whenever the highly contributing stations (09737014, 09737008, 09337000 and 09737016; total contribution = 82.2%) had observations and also AM and Thiessen series were comparable for non-missing periods. Therefore, final catchment daily rainfall record was taken from AM series with non-missing data at 09737014, 09737008, 09337000 and 09737016. This approach provided a continuous catchment rainfall record in the 1st January 1966 – 30th September 1985 period.

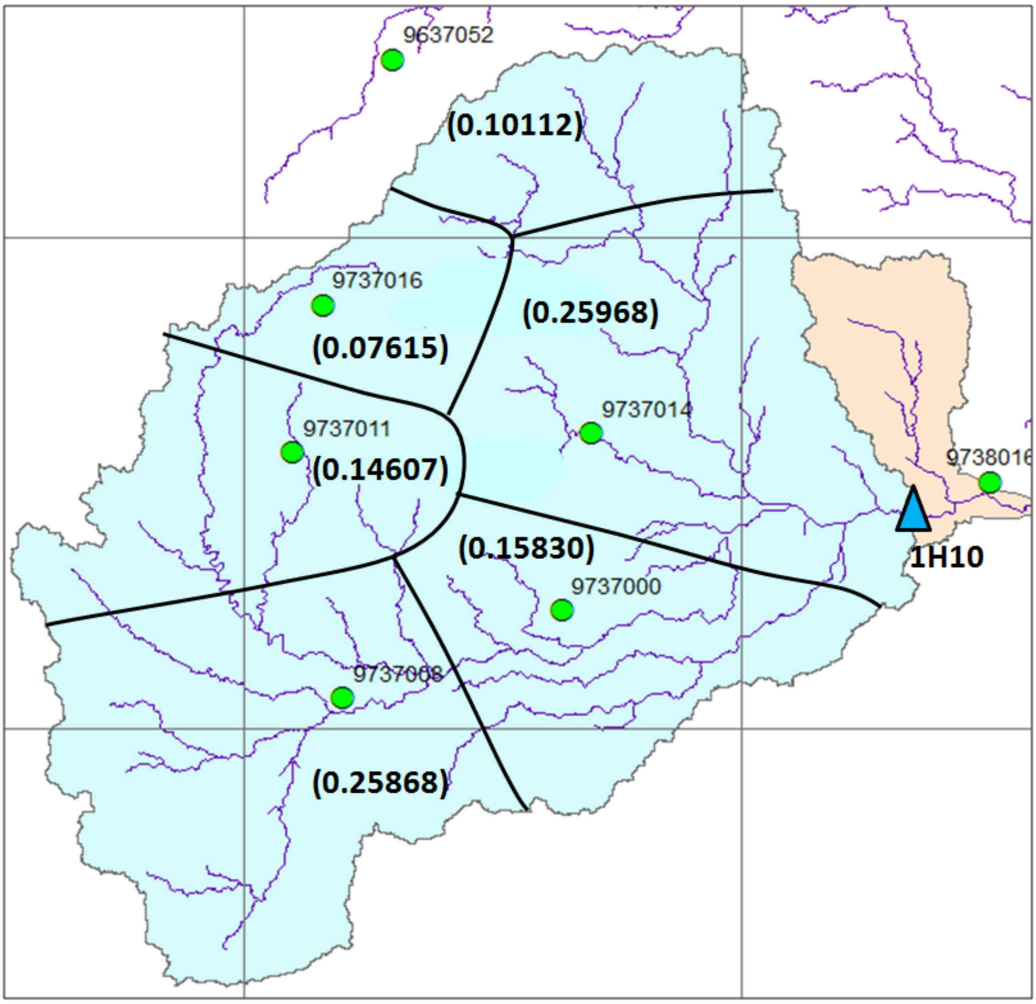

Figure 3.5: Spatial distribution of stations used in estimating Kidunda catchment rainfall.

Discharge

Daily discharge time series was generated from quality river stage data for the August 1966 – September 1988 period and rating curves. 1H10 has rating data in the Aug 1966 – Apr 1989 period. The rating curve (**Table 3.4**) was established by the Ministry of Water under the assistance of the then Water Resources Engineering Programme (WREP) of the University of Dar es Salaam. It is reliable for the discharge range 0.43 – 7.62 m (**Figure 3.6**).This rating curve was therefore considered applicable in the first record periods and specified validity range of river stages while its usefulness in the recent (2006 – 2008/09) period has not been assessed and consequently is not used to compute average daily river discharges. Furthermore, extreme recorded daily stages are somehow outside the rated ranges. The recorded extreme high stages are far above the highest recorded stages while extreme low stages are within the rated range (**Table 3.5**). Consequently, discharges estimated using the curves at these gauging stations for extremes beyond rated ranges are of low confidence. The resulting discharge series was formatted into the GFFS input format for the SLM to read.

Table 3.4: Inventory of flow gauging stations and data availability for Kidunda inflow sites.

Sno	No	Name	Data availability	Validity	Equations	Source
1	28	1H3	Oct 1951-Aug 1966	-0.34 – 10.0	$Q = 14.6534(h + 0.34)^{1.7448}$	WREP (Oct 1993)
2	63	1H10	Aug 1966-Apr 1989	0.43 – 7.62	$Q = 11.4482(h)^{1.896}$	WREP (Mar 1993)

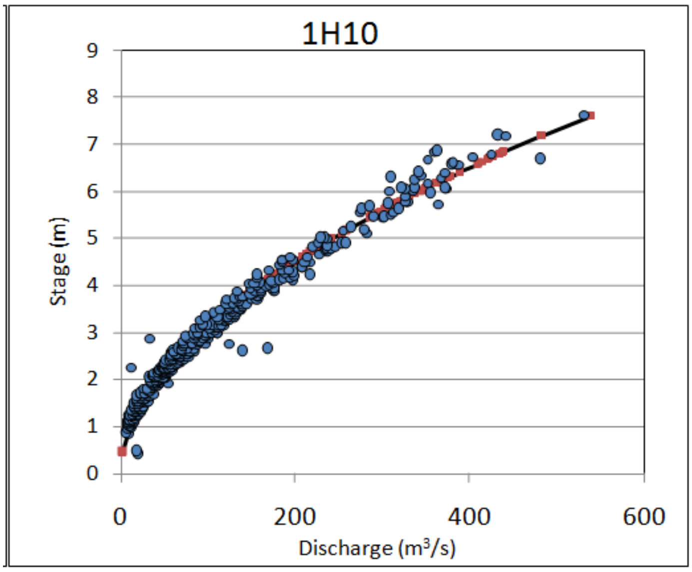

Figure 3.6: Quality of rating curves at 1H3 and 1H10.

Table 3.5: Comparison of rated (measured) and recorded extremes at selected gauging sites.

Station	Period (data points)	Rating curve data				Observation data			
		Min		Max		Min		Max	
		WL (m)	Q (m^3/s)	WL (m)	Q (m^3/s)	WL (m)	Q (m^3/s)	WL (m)	Q (m^3/s)
1H3	1951-1966 (52); 1993 (2)	0.037	0.301	1.585	29.02	0.021	0.317	6.843	555.83
1H10	1966-1981(448); 1981(1); 1989(1)	0.43	6.73	7.62	530.5	0.66	5.207	8.393	646.42

Model calibration

The model was calibrated for the continuous 1st October 1968 – 28th February 1971 (29 months) and verified in the 1st April 1971 – 31st July 1973 (28 months). Calibration of this model involved a trial-and-error estimation of the memory length m and estimation of orders p and q of the ARMA model for residues e_i series. The memory length was established by a procedure where a length was varied between 5 and 45 days, model fitted in a non-updating mode (without ARMA) and fit efficiency of estimated to observed discharges computed each time. The optimum m = 30 was selected corresponding to that length after which no significant change of efficiency occurred. The fitted SLM gave calibration and verification efficiencies of 65.4% and 59.8% respectively. Despite moderately high efficiencies, the model could not capture several parts of the observed discharges including highest peak and several medium and low flows (**Figure 3.7a**).

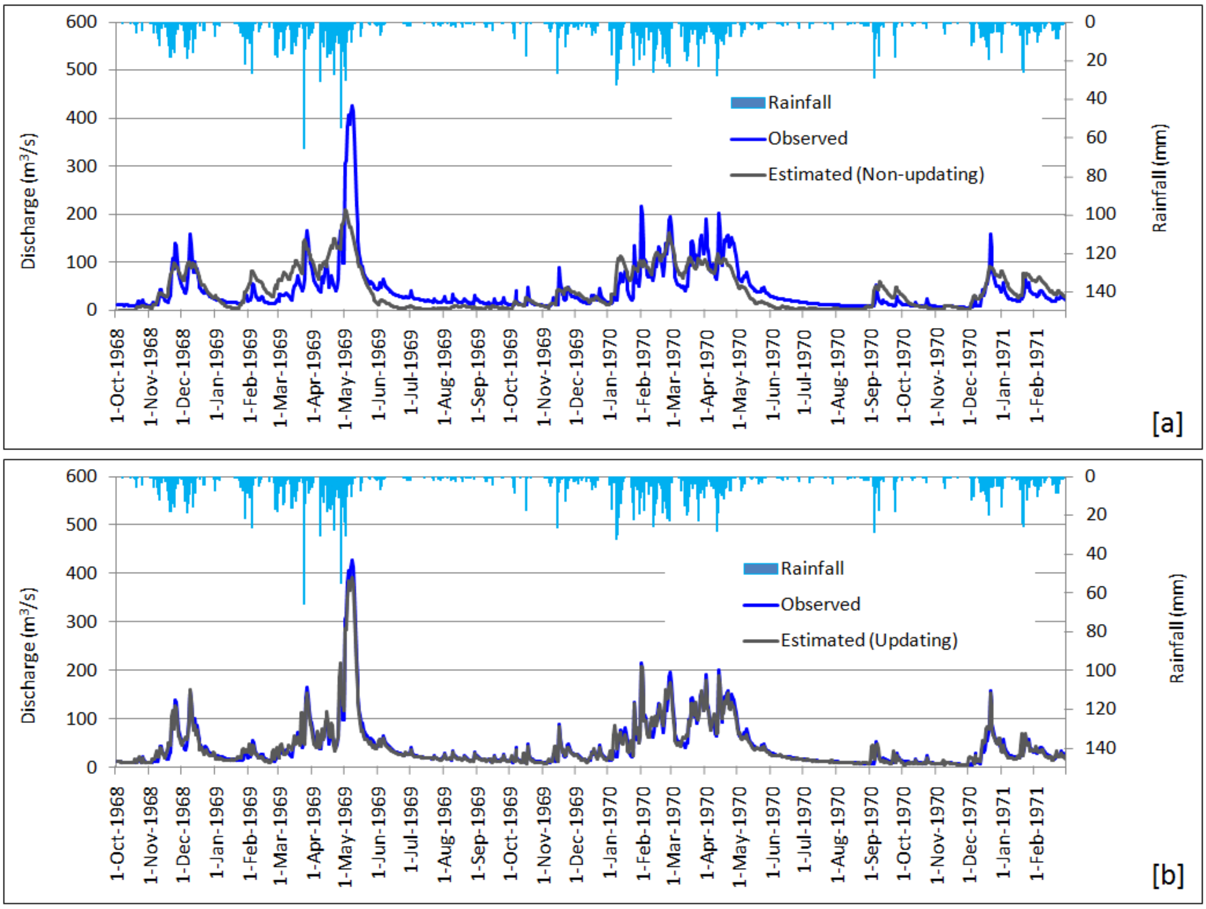

Figure 3.7: Observed and SLM estimated daily discharges at 1H10 a) non-updating and b) updating modes.

Residuals plot (**Figure 3.8**) show consistency indicating correlations with observed discharges. An autoregressive moving average model of orders p and q (ARMA(p,q)) was fitted to residuals to remove the correlations. The order p for the autoregressive (AR) model and q of the moving average model (MA) were determined to be 1 from autocorrelogram and partial autocorrelogram respectively. The establish ARMA(1,1) model for residuals is given as

$$e_i = 0.9295e_{i-1} + 0.9492(e_{i-1,obs} - e_{i-1,est})$$

This component was added to SLM as an updating component and significantly reduced the magnitude of residual and consistency (**Figure 3.8**). This SLM in updating mode was therefore used to estimate daily discharges during calibration and verification periods. The updating model fitted well the observed discharge series (**Figure 3.7b**) while giving high calibration and verification efficiencies of 91.6% and 96.5% respectively. The model was therefore adequate used to fill gaps of missing daily discharge data (**Figure 3.9**).

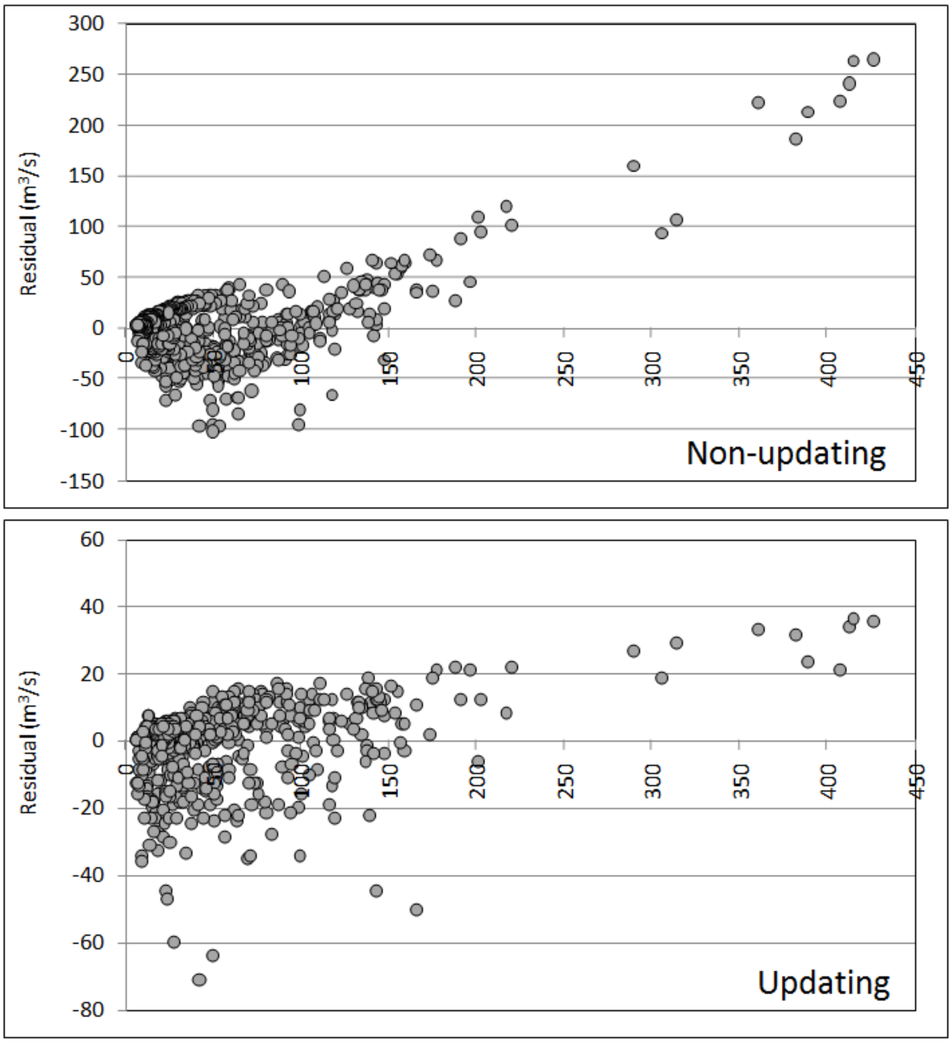

Figure 3.8: Plot of residuals against observed discharges at 1H10.

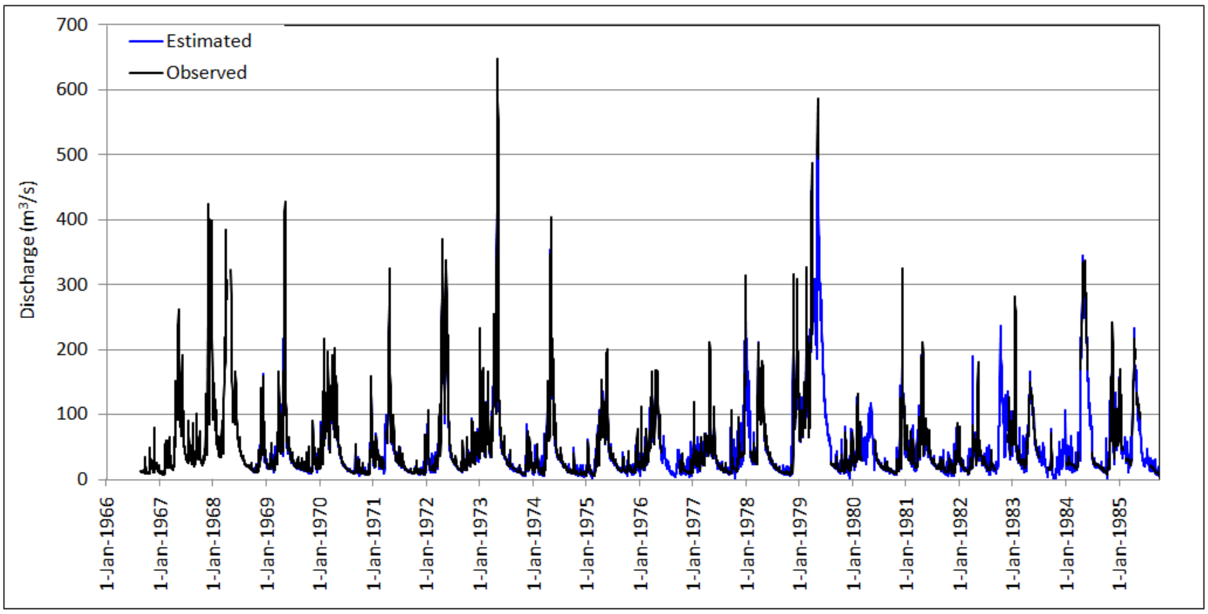

Figure 3.9: Reconstructed daily discharge record at 1H10.

3.2.1.3.2 1H3 record extension

Stage record at 1H3 and its rating curve were used to estimate 1H3 discharge in the period with observations. This location (1H3) has been rated in the Oct 1951 – Jul 1993.The rating curve at 1H3 was of good quality and was therefore considered suitable in the 1951-1969 periods and specified validity range of river stages (**Table 3.5**) while its usefulness in the recent (2006 – 2008/09) period has not been assessed and consequently is not used to compute average daily river discharges. Furthermore, extreme recorded daily stages at the two gauging stations are somehow outside the rated ranges. The recorded extreme high stages are far above the highest recorded stages while extreme low stages are only lower than rated range at 1H3 (**Table 3.5**).

Availability of discharge records at an upstream flow gauge (1H10) and a downstream gauge (1H3) makes the use of Muskingum routing procedure possible despite presence of a small seasonal Mkulazi stream between the two gauges. Therefore, Muskingum routing model coded in ForTran Program was calibrated for the most continuous 1st September 1966 – 31st March 1968 (19 months) period and verified in the 1st December 1968 – 31st May 1969 (6 months) period. The model is given by

$$Q_{1H3,i+1} = C_1\left(\frac{Q_{1H10,i}+Q_{1H10,i+1}}{2}\right) - C_2 Q_{1H3,i}$$

where Q_i and Q_{i+1} are discharges at time i and time $i+1$ and coefficients C_1 and C_2 are given by

$$C_1 = \frac{\Delta t}{2k+\Delta t} \qquad C_2 = \frac{2k-\Delta t}{2k+\Delta t}$$

where Δt is the routing interval (1 for daily series) and *k* is the storage coefficient.

The estimated 1H3 discharges in the calibration period using of a single value of parameter *k* of 0.527 (giving C_1 = 0.487 and C_2 = 0.026) somehow underestimated peaks (**Figure 3.10a**). It was therefore necessary to establish values of parameter k that describe different flow regime components (low, medium and high flows). A flow duration curve (FDC) was constructed at 1H10 and after trial-and-error process, Q30(1) and Q70(1), which are respectively 50.5 m^3/s and 17.74 m^3/s, were retained as thresholds separating high from medium and medium from lowflows respectively. Consequently, low flows are considered those below Q70(1), high flows as those exceeding Q30(1) and the rest as medium flows. The approach improved simulation of peaks as well as other flows (**Figure 3.10b**) and was therefore used to extend 1H3 daily discharge record to September 1985 (**Figure 3.11**) using the 1H10 daily discharge record.

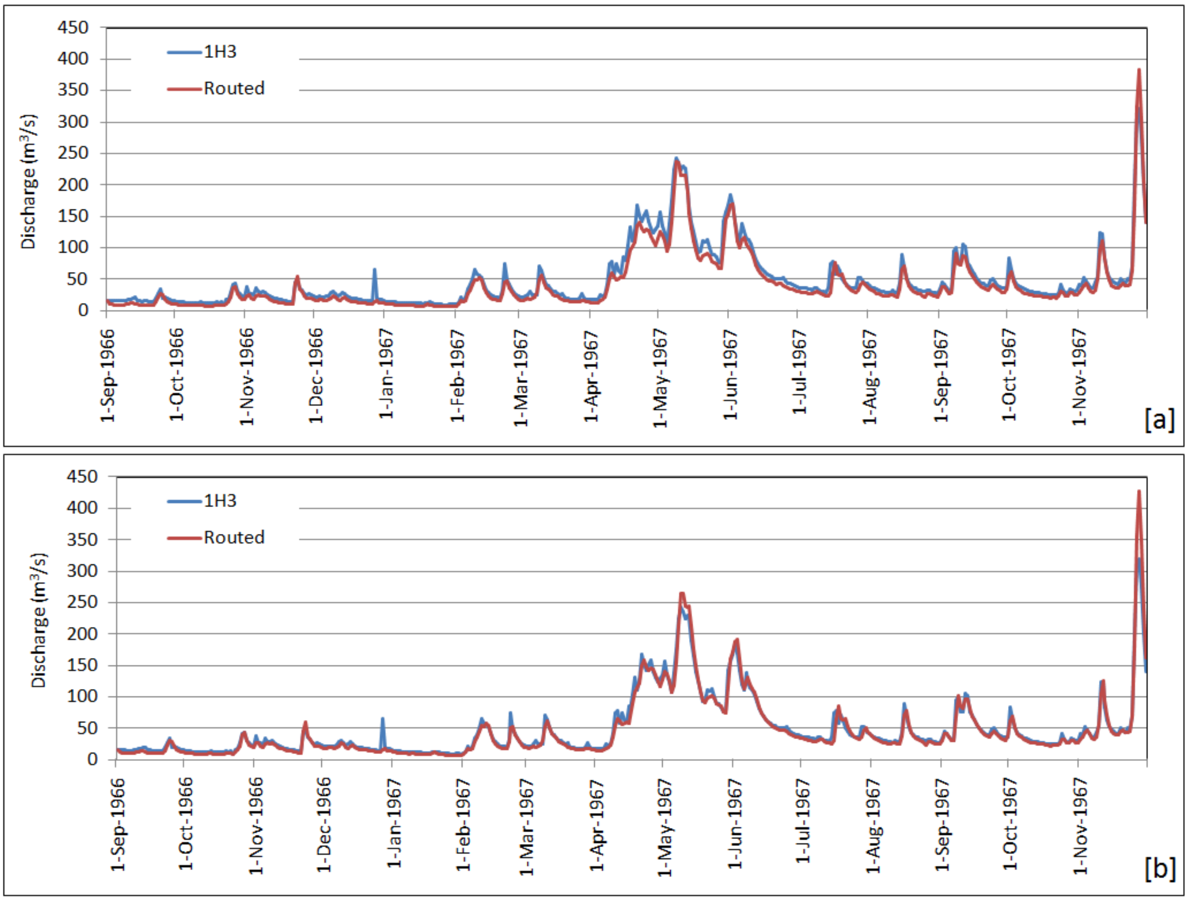

Figure 3.10: Observed and routed flows at 1H3.

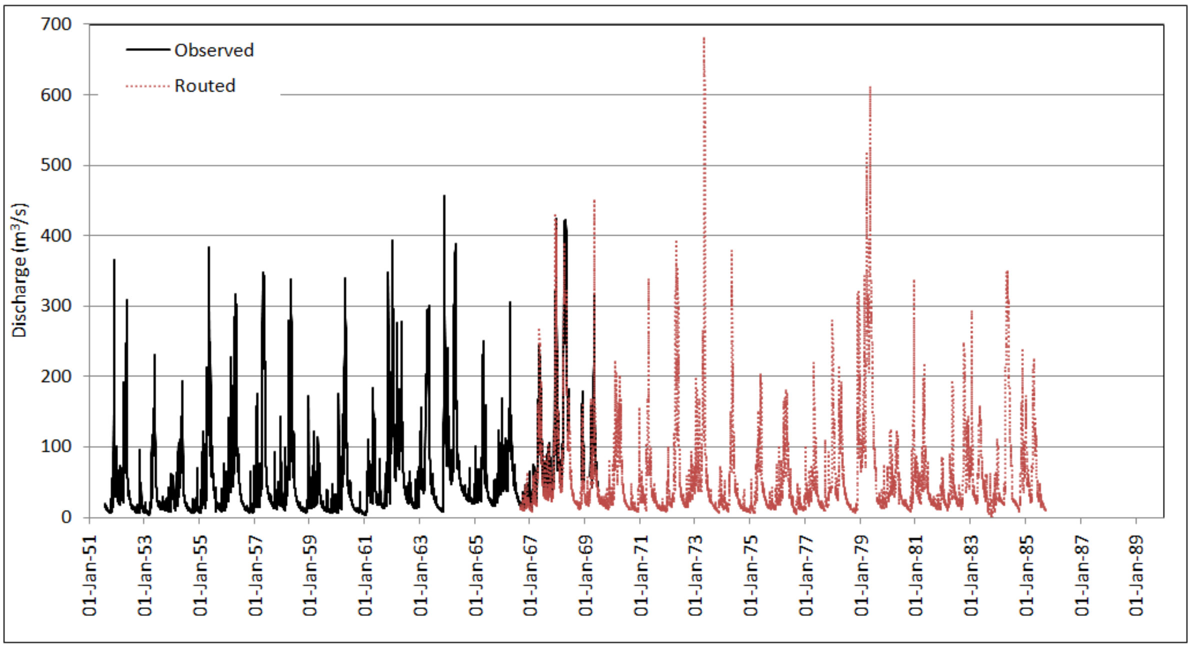

Figure 3.11: Reconstructed daily record at 1H3.

3.3 CATEGORISING YEARS

3.3.1 Methods

Normalised Runoff Index (NRI) as introduced by Valimba (2012) adopts a similar approach to SPI in which flow indices are fitted to a probability distribution. For distributions other than normal, transformation into a normal distribution is carried out. Similar to SPI, NRI are essentially standard deviations of a normally distributed streamflow series from its mean. According to Mkhandi (1997), the best fitting probability distributions to flows in Tanzania are Generalised Pareto (GPA), Pearson Type III (P3), Generalised Extreme Value (GEV) and Log-Pearson Type III (LP3) while Valimba (2012) obtained best fitting distribution for Mara Sub-basin to be GPA/L-Moments, LP3/ML and GEV/MoM. The procedure adopted uses GPA/L-Moments and GEV/L-Moments) are used to establish NRI as follows

- Generating time series of discharge for a required accumulation period
- Fitting a frequency distribution to the established time series by estimating parameters to produce a probability density function (pdf), f(x)

For GPA/L-moments

$$f_{(\xi,\mu,\sigma)}(x) = \frac{1}{\sigma}\left(1 + \frac{\xi(x-\mu)}{\sigma}\right)^{\left(-\frac{1}{\xi}-1\right)}. \qquad (11)$$

where ξ, σ and μ are shape, scale and location parameters respectively.

The parameters are estimated from data by the L-moments method as

$$\xi = \frac{1 - 3\tau_3}{1 + \tau_3}$$

$$\mu = \lambda_1 - \frac{\sigma}{(1 + \xi)} \qquad (12)$$

$$\sigma = (1 + \xi)(2 + \xi)\lambda_2$$

where λ_1, λ_2 are first and second L-moments and τ_3 is L-skewness. They are obtained from Probability Weighted Moments (PWM) as

$$\begin{aligned} \lambda_1 &= L1 = M_{100} \\ \lambda_2 &= L2 = 2M_{110} - M_{100} \\ \lambda_3 &= L3 = 6M_{120} - 6M_{110} + M_{100} \\ \tau_3 &= L3/L2 \qquad \text{(L-Skewness)} \end{aligned} \qquad (13)$$

Where M_{1k0} are PWM computed from arranged data in ascending manner (lowest to highest) as

$$\begin{aligned} M_{100} &= \text{sample mean} = \frac{1}{N}\sum_{i=1}^{N} Q_i \\ M_{110} &= \frac{1}{N}\sum_{i=1}^{N} \frac{(i-1)}{(N-1)} Q_i \\ M_{120} &= \frac{1}{N}\sum_{i=1}^{N} \frac{(i-1)(i-2)}{(N-1)(N-2)} Q_i \end{aligned} \qquad (14)$$

<u>For GEV/L-moments</u>

$$f(x) = \frac{1}{\alpha}\left[1 + \kappa\left(\frac{x-\xi}{\alpha}\right)\right]^{-\frac{1}{\kappa}-1} e^{-\left[1+\kappa\left(\frac{x-\xi}{\alpha}\right)\right]^{-\frac{1}{\kappa}}} \qquad (15)$$

where κ, α and ξ are shape, scale and location parameters respectively.

The parameters are estimated from data by the L-moments method as

$$\kappa = 7.8590c + 2.9554c^2 \quad \text{in which } c = \frac{2}{3+\tau_3} - \frac{ln2}{ln3}$$

$$\alpha = \frac{\lambda_2 k}{(1-2^{-k})\Gamma(1+k)} \tag{16}$$

$$\xi = \lambda_1 - \alpha\{1 - \Gamma(1+k)\}/k$$

where λ_1, λ_2 are first and second L-moments and τ_3 is L-skewness.

- Estimating cumulative frequency, F(x), from

For GPA

$$F(x) = \begin{cases} 1 - \left[1 + \xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{\kappa}} & \kappa \neq 0 \\ 1 - e^{-\frac{x-\mu}{\sigma}} & \kappa = 0 \end{cases} \tag{17}$$

For GEV

$$F(x) = \begin{cases} e^{-\left[1-\kappa\left(\frac{x-\xi}{\alpha}\right)\right]^{\frac{1}{\kappa}}} & \kappa \neq 0 \\ e^{-e^{-\frac{x-\xi}{\alpha}}} & \kappa = 0 \end{cases} \tag{18}$$

- Estimating modified cumulative frequency, H(x)
- Establish time series of equivalent normal variate, $z_{p_i}(x)$, of elements x_{p_i} using H(x)
- Compare $z_{p_i}(x)$ with NRI thresholds (similar as SPI, **Table 2.2**) to identify dry and wet years, seasons and months

3.3.2 Results

Results of NRI generally indicate dry 1950s, wetter 1960s and some wet spells in the 1970s and 1980s (**Table 3.6**). Similar to SPI results, years are mostly normal and rarely categorised into different levels of dryness and wetness with only 2 dry and 4 wet years identified in the 1951/52 – 1984/85 period. However, seasons frequently experience different levels of dryness and wetness, which are sometime similar or opposing one another. In some wet years (1967/68, 1978/79), all three seasons (OND, JF, MAM) are wet while in very few years when the seasons OND and JF oppose each other i.e. one is wet and another dry. The most prevailing years with different combinations of dryness and wetness between OND, JF and MAM seasons are therefore

Table 3.6: Magnitudes of NRI for seasonal and annual flows at 1H3.

Year	GEV						GPA				
	OND	JF	MAM	JJAS	Ann		OND	JF	MAM	JJAS	Ann
1951/52	0.851	0.142	0.153	-2.062	0.041		0.793	0.156	0.148	-1.100	0.065
1952/53	-0.411	-1.985	-0.511	-0.821	-1.045		-0.312	-1.244	-0.395	-0.715	-0.928
1953/54	-0.364	-0.513	-0.554	-1.909	-0.934		-0.270	-0.399	-0.432	-1.315	-0.802
1954/55	-0.615	-0.028	0.706	0.835	0.361		-0.502	0.015	0.610	0.783	0.328
1955/56	-0.039	0.921	0.777	-0.115	0.507		0.014	0.833	0.673	-0.051	0.450
1956/57	-0.528	0.082	0.950	0.321	0.439		-0.420	0.106	0.834	0.325	0.393
1957/58	0.287	-0.509	0.567	0.114	0.192		0.294	-0.395	0.489	0.147	0.188
1958/59	-0.468	-0.429	-1.226	-3.980	-1.518		-0.364	-0.325	-1.152	0.126	-1.839
1959/60	-0.753	-0.335	0.493	-1.000	-0.126		-0.639	-0.243	0.426	-0.921	-0.071
1960/61	-1.371	-0.512	-0.712	-0.273	-1.033		-1.530	-0.398	-0.574	-0.190	-0.914
1961/62	1.974	2.081	0.770	0.432	1.618		1.952	2.171	0.667	0.422	1.581
1962/63	0.189	0.792	0.954	-0.118	0.620		0.209	0.715	0.838	-0.054	0.547
1963/64	1.754	1.279	1.099	0.928	1.446		1.704	1.186	0.983	0.869	1.367
1964/65	0.239	0.007	-0.172	0.096	-0.209		0.252	0.044	-0.114	0.131	-0.139
1965/66	1.039	0.841	0.235	0.247	0.499		0.970	0.760	0.214	0.261	0.443
1966/67	0.015	-0.748	-0.137	1.389	0.081		0.060	-0.619	-0.085	1.319	0.097
1967/68	1.936	1.187	1.856	1.117	1.883		1.908	1.092	2.013	1.049	1.960
1968/69	0.938	-0.738	0.406	0.130	0.264		0.874	-0.609	0.353	0.160	0.248
1969/70	0.106	1.339	0.032	-1.459	0.142		0.138	1.249	0.050	-1.812	0.147
1970/71	0.074	-0.235	-0.068	-0.462	-0.314		0.110	-0.158	-0.030	-0.360	-0.227
1971/72	-0.651	-0.331	0.907	0.432	0.357		-0.538	-0.239	0.794	0.422	0.324
1972/73	0.855	1.234	1.191	0.011	1.018		0.797	1.139	1.079	0.058	0.912
1973/74	-0.120	-1.039	0.257	0.212	-0.151		-0.056	-0.936	0.231	0.231	-0.092
1974/75	-1.007	-1.355	-0.160	0.141	-0.641		-0.925	-1.428	-0.104	0.170	-0.512
1975/76	-0.126	-0.076	0.059	-0.229	-0.212		-0.062	-0.025	0.072	-0.151	-0.142
1976/77	-0.412	-0.263	-0.728	-0.326	-0.848		-0.314	-0.182	-0.589	-0.237	-0.711
1977/78	1.031	1.216	-0.005	-0.892	0.378		0.962	1.121	0.021	-0.792	0.342
1978/79	1.582	1.854	2.485	1.807	2.292		1.517	1.856	2.695	1.760	2.773
1979/80	0.209	0.418	-0.681	-0.366	-0.489		0.226	0.388	-0.545	-0.273	-0.376
1980/81	1.096	0.389	-0.425	0.012	0.048		1.025	0.362	-0.322	0.059	0.071
1981/82	0.177	-0.650	-1.009	-0.079	-0.911		0.199	-0.525	-0.875	-0.020	-0.777
1982/83	1.835	1.061	-0.477	0.606	0.801		1.793	0.967	-0.366	0.576	0.708
1983/84	0.803	-0.623	1.160	1.023	0.940		0.750	-0.499	1.046	0.959	0.838
1984/85	1.399	0.936	0.107	-0.391	0.565		1.326	0.847	0.110	-0.295	0.500

Table 3.7: Summary of identified dry and wet years and seasons at 1H3.

Station	Dry			Wet		
	Extreme	Severe	Moderate	Moderate	Severe	Extreme
OND			1960/61, 1974/75	1965/66, 1977/78, 1980/81, 1984/85	1961/62, 1963/64, 1967/68, 1978/79, 1982/83,	
JF		1952/53	1973/74, 1974/75	1963/64, 1967/68, 1969/70, 1972/73, 1977/78, 1982/83	1978/79	1961/62
MAM			1958/59, 1981/82	1963/64, 1972/73, 1983/84	1967/68	1978/79
JJAS	1951/52, 1958/59	1953/54	1959/60, 1969/70	1966/67, 1967/68, 1983/84	1978/79	
Annual		1958/59	1952/53, 1960/61	1963/64, 1972/73	1961/62, 1967/68	1978/79

i) Dry/dry/dry (1952/53 or 1958/59)
ii) Dry/dry/Normal (1974/75)
iii) Dry/wet/wet (1971/72)
iv) Wet/dry/wet (1983/84)
v) Wet/dry/dry (1981/82)
vi) Wet/wet/dry (1982/83)
vii) Normal/wet/normal (1969/70)
viii) Wet/wet/wet (1961/62 or 1978/79)

The impacts of different flow conditions on SGR inundation patterns are assessed in these years.

4 ASSESSING IMPACTS OF RESERVOIR INUNDATION

4.1 GENERAL

Impacts of inundation of proposed Kidunda reservoir is assessed from the increase of reservoir storage due to larger inflows than outflows and vice versa. The storage change is assessed using a reservoir water balance model given as

$$\Delta S = \Sigma I - \Sigma O \qquad [4.1]$$

where ΔS is change in reservoir stored volume, ΣI is the total sum of reservoir inflows and ΣO is the total sum of reservoir outflows.

The terms on the right hand side comprise surface and subsurface water inflows into the reservoir. Expanding the above equation gives

$$\Delta S = I_{surf} + I_{gw} - O_{surf} - O_{gw} \qquad [4.2]$$

The surface inflow volumes into the proposed reservoir comprise flows of River Ruvu as measured at the Kidunda gauging station (1H3, V_{1H3}) and rainfall over the reservoir (V_{rain}). Surface outflows from the reservoir include reservoir bottom gates releases (V_{rel}), spills (V_{spill}), dam seepage (V_{seep}) and open water evaporation (V_{evap}). Owing to large surface inflows and outflows and reservoir storage compared to net groundwater flows, groundwater inflow and outflow can be neglected (Sokolov and Chapman, 1974). Consequently, the general water balance equation becomes

$$\Delta S = V_{1H3} + V_{rain} - V_{rel} - V_{spill} - V_{seep} - V_{evap} \qquad [4.3]$$

Reservoir water balance is carried out at the daily timescale and this equation is used to determine daily reservoir storage (S_t) from previous storage (S_{t-1}) as

$$S_t - S_{t-1} = V_{1H3} + V_{rain} - V_{rel} - V_{spill} - V_{seep} - V_{evap} \qquad [4.4a]$$

or

$$S_t = S_{t-1} + V_{1H3} + V_{rain} - V_{rel} - V_{spill} - V_{seep} - V_{evap} \qquad [4.4b]$$

The water balance is needed to study impacts of inundation speed and duration on the ecosystem of the Selous Game Reserve (SGR). It is therefore important to investigate these two phenomena in years with different hydroclimatological dryness and wetness conditions. Therefore, the conditions identified in Sec 3.3.2 are investigated. They are

i) Dry/dry/dry (1952/53 or 1958/59)
ii) Dry/dry/Normal (1974/75)

iii) Dry/wet/wet (1971/72)
iv) Wet/dry/wet (1983/84)
v) Wet/dry/dry (1981/82)
vi) Wet/wet/dry (1982/83)
vii) Normal/wet/normal (1969/70)
viii) Wet/wet/wet (1961/62 or 1978/79)

Water balance initiation assumes three conditions at the start of the wet period, i) a completely dry reservoir (altitude = 67.5 m), ii) a half deep reservoir (altitude = 72.75 m) and iii) a full reservoir (altitude = 79 m). The water balance computations are carried out in daily times step in order to satisfy the proposed release rules, which are based on magnitudes of river inflows at the daily time step. Carrying out water balance at other times steps could necessitate accumulation of releases into such time steps, not reflecting the proposed actual release pattern.

The computed daily reservoir storages (S_t) are converted to obtain reservoir water surface altitudes (z_t) using a modified elevation-volume relation from that given by Studio Pietrangeli (2013). From the available data provided adjacent to the plotted elevation-area-volume curves (Studio Pietrangeli, 2013b), the provided elevation-volume curve given as

$$V_t = \left(\frac{z_t - 65.7}{5.96}\right)^{1/0.21} \quad [4.5]$$

$$= 0.000203(z_t - 65.7)^{4.761905}$$

overestimated the derived volumes indicated particularly at elevations exceeding 75.5 (**Table 4.1**). Therefore, a new elevation-volume as well as missing elevation-area relationships were established and used. They are

$$S_t = 0.00027293(z_t - 66.29)^{4.68569} \quad [4.6]$$

$$A_t = 0.00029796(z_t - 66.29)^{4.68569} \quad [4.7]$$

Elevation of reservoir water surface (zt) are computed from equation (4.6) as

$$z_t = \left(\frac{V_t}{0.00027293}\right)^{1/4.68569} + 66.29 \quad [4.8]$$

These altitudes of reservoir water surface are compared to altitude of Selous Game Reserve (SGR) to assess speed of reservoir inundation into SGR and the duration of inundation in different historical dry/wet conditions.

Table 4.1: Derived and estimated Kidunda reservoir areas and volumes.

Alt	Area		Vol		
				Estimated	
	Derived	Estimated	Derived	Valimba (2017)	SP (2013)
67.5	0		0		
71.5	0.6	0.570	1.1	0.624	0.877
75.5	5	4.329	10.2	9.001	10.657
79.5	16.5	16.729	50.1	48.781	54.387
83.5	45.6	46.192	167.4	168.476	182.758
84.5	58.2	57.504	218.4	219.519	237.091
85.5	70.7	70.798	283.7	282.009	303.454

4.2 RESERVOIR INFLOWS

4.2.1 Reservoir rainfall

Closest spatial proximity of the Mikula climate station to and small area extent of the proposed reservoir makes the station suitable for estimating rainfall onto the reservoir. The station is just downstream of the proposed dam axis. The Mikula station has daily rainfall since 1st September 1966 and several missing observations particularly between June 1973 and December 1975. Therefore, available Mikula record misses the first three selected years (1952/53, 1958/59 and 1961/61) while some months are missing in other years (**Table 4.2**).

Table 4.2: Availability of rainfall for selected years at Mikula climate station (09638016).

Period	Available record	Size of missing data
1st Oct 1952-30th June 1953	No data	All season (273 days)
1st Oct 1958-30th June 1959	No data	All season (273 days)
1st Oct 1961-30th June 1962	No data	All season (273 days)
1st Oct 1969-30th June 1970	1st Oct 1969-30th June 1970	0 days
1st Oct 1971-30th June 1972	1st Oct 1971-30th June 1972	0 days
1st Oct 1974-30th June 1975	No data	All season (273 days)
1st Oct 1978-30th June 1979	1st Oct 1978 – 30th Jun 1979	Jan, Mar & May 1979 (93 days)
1st Oct 1981-30th June 1982	1st Oct 1981-30th June 1982	0 days
1st Oct 1982-30th June 1983	1st Dec 1982-30th June 1983	Oct & Nov 1982 (61 days)
1st Oct 1983-30th June 1984	1st Dec 1983-30th June 1984	Oct & Nov 1983 (61 days)

Therefore, daily rainfall data from closet stations were used, which are Mvuha (09737014 – up to 1962) and Duthumi Estate (09737000) being 21 and 32 km from the proposed reservoir highest level boundary. The Mvuha station provided data for the 1952/53 and 1958/59 while Duthumi station provided data for 1961/62 and other missing months in 1978/79, 1982/83 and 1983/84 (**Table 4.3**). Comparison of mean annual rainfall (MAP) between Mikula and the other two stations indicates that Kidunda area (represented by the Mikula station) received MAP of 900 mm while Mvuha has 1,164 mm and Duthumi Estate 1,100 mm annually. The use of data from these stations necessitated debiasing these records to Mikula amounts. The debiasing of Mvuha daily rainfall record used multiplication of ratios of monthly average between Mikula and Mvuha (**Table 4.4**) to daily rainfall amounts in respective months. The ratios were computed for each year and average over the 1971-1989 period. Similar debiasing of daily Duthumi record was carried out.

Table 4.3: Availability of rainfall for selected years at *Mvuha* (*09737014*) and Duthumi Estate (09737000).

Period	Available record	Size of missing data
1st Oct 1952-30th June 1953	*1st Oct 1952-30th June 1953*	*0 days*
1st Oct 1958-30th June 1959	*1st Oct 1958-30th June 1959*	*0 days*
1st Oct 1961-30th June 1962	1st Oct 1961-30th June 1962	0 days
1st Oct 1974-30th June 1975	1st Oct 1974-30th June 1975	0 days
1st Oct 1978-30th June 1979	1st Oct 1978 – 30th Jun 1979	Oct & Nov 1978 (61 days); Jan & Feb 1979 (59 days)
1st Oct 1982-30th June 1983	1st Dec 1982-30th June 1983	Oct, Nov & Dec 1982 (92 days)
1st Oct 1983-30th June 1984	1st Dec 1983-30th June 1984	Oct 1983 (31 days)

Table 4.4: Ratios of monthly Mikula rainfall to Mvuha (09737014), Duthumi Estate (09737000) and Singiza Mission (09737005) monthly amounts.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Duthumi	0.75	0.64	0.78	0.84	0.72	0.22	0.47	0.37	0.74	1.09	0.35	1.33
Mvuha	0.71	0.42	0.83	1.16	0.64	0.28	0.44	0.25	0.55	0.71	0.39	1.01
Singiza	0.60	0.53	0.60	0.61	0.45	0.38	0.32	0.37	0.67	0.63	0.43	0.71

The daily reservoir rainfall volumes are computed as

$$V_{rain} = D_{rain}\,(\text{mm}) \times A_{reservoir}\,(\text{km}^2) \div 10^3\ \text{Mm}^3 \qquad [4.6]$$

4.2.2 Reservoir surface inflows

Surface inflows into the reservoir are simply represented by discharges of River Ruvu as measured at the Kidunda gauging station. The reconstructed daily discharge data is available for 1st August 1951 – 30th September 1985 period. The daily surface inflow volumes are computed as

$$V_{1H3} = Q_{1H3}\,(\text{m}^3/\text{s}) \times 86400\ \text{s} \div 10^6\ \text{Mm}^3 \qquad [4.7]$$

4.3 RESERVOIR OUTFLOWS

4.3.1 Reservoir releases

The reservoir releases are from 2 bottom gates and 2 power intakes. The power intakes are at 73 m altitude and the design release rules for power discharge (**Table 4.5**) are the function of inflow discharges and reservoir water levels indicating that there will be no power releases from the reservoir when water surface altitude is below 79.6 m while above this altitude, the releases are the function of inflow discharges. The two bottom gates will ensure a constant flow of 24 m^3/s when there is not power production. The gates are 1.5 m in diameter with the top gate at 73.0 m and the bottom one at 71.5 m. Consequently, below 73 m, only the bottom gate releases 12 m^3/s and above 73 m, both gates release a total of 24 m^3/s.

Table 4.5: Proposed Kidunda reservoir release rules for power production.

Elevation (m)	Condition	Release	
		Amount	Units
EL > 79.6	Q_{infl} > 160 m^3/s	160	m^3/s
	24 m^3/s < Q_{infl} < 160 m^3/s	Q_{infl}	m^3/s
	Q_{infl} < 24 m^3/s	24	m^3/s
EL < 79.6		0	m^3/s

The daily reservoir released volumes are computed as

$$V_{rel} = Q_{rel}\ (m^3/s) \times 86400\ s \div 10^6\ Mm^3 \qquad [4.8]$$

4.3.2 Reservoir spills

According to operating rules, water spills (Q_{spills}, m^3/s) are estimated from the established reservoir crest outflow equation given as

$$Q_{spill} = CL_eH^{3/2} \qquad [4.9]$$

where C ($m^{1/2}/s$) is the discharge coefficient, H (m) is the head on the crest and L_e (m)is the effective crest length computed from

$$L_e = L - N \times L_p - 2H(K_a + N \times K_p) \qquad [4.10]$$

where L is the total crest width (117 m), N is the number of piers (7), L_p is the pier width (3 m), K_a is the abutments contraction coefficient (for rounded abutments with headwalls proposed for Kidunda, K_a = 0.1) and K_p is the pier contraction coefficient (for proposed round-nosed piers, K_p = 0.01). Equation (4.10) becomes

$$\begin{aligned} L_e &= 117m - 7 \times 3m - 2H(0.1 + 7 \times 0.01) \\ &= 96 - 0.34H \end{aligned} \quad [4.11]$$

Substituting equation (4.11) and adopted the discharge coefficient of 2.2 $m^{1/2}/s$ (Studio Pietrangeli, 2013a) into equation (4.9) yields

$$\begin{aligned} Q_{spill} &= 2.2 \times (96 - 0.34H)H^{3/2} \\ &= 211.2 - 0.748H^{5/2} \end{aligned} \quad [4.12a]$$

From the spillway rating curves, the standard spillway equation adopted for a single gate is

$$Q_{spill} = 26.039957H^{1.494787} \quad [4.12b]$$

According to dam design, the spillway sill is at an altitude of 79 m with inclined gates (7 m long) extending to an altitude of 84.5 m. Spills will occur whenever reservoir water surface exceeds the gate top altitude of 84.5 when gates are opened to protect dam and the spillway will be fully opened to become uncontrolled spillway. The head at the crest H in a particular day is the difference between reservoir water surface altitude (h) and crest sill altitude (H = h – 79) and daily spill discharges estimated using equation (4.12b). At 85.5 m, a total release from fully opened gates is 408 m^3/s summing up to a total release of 3,264 m^3/s, the spillway design capacity. This is a huge discharge not recorded and that could bring devastation downstream. The highest discharge of 680 m^3/s was estimated to have been conveyed historically and therefore it is recommended to release such a discharge through fully opened 8 spillway gates in which each gate can pass 85 m^3/s to protect downstream ecosystem, settlements and properties. Daily spilled volumes are therefore computed as

$$V_{spill} = Q_{spill}\ (m^3/s) \times 86400\ s \div 10^6\ Mm^3 \quad [4.13]$$

4.3.3 Reservoir seepage

Seepage from the proposed Kidunda dam will occur across the rockfill dam and seepage water collected by the downstream drain. According to estimates of the total amount of water filtering through and under the embankment (Studio Pietrangeli, 2013c), seepage was estimated as

i) Filtering through upstream sheetpile to upstream drain: 4.52 x 10^{-5} $m^3/s/m$

ii) Filtering through sheetpile to downstream drain: 2.32 x 10^{-5} $m^3/s/m$

iii) Filtering through the dam to downstream drain: 8.27 x 10^{-7} $m^3/s/m$

The total seepage flow (Q_{seep}) was considered the sum of the three equalling 6.92 x 10-5 $m^3/s/m$ and with total dam length of 860 m, this seepage is equivalent to 59.5 l/s. The corresponding daily seepage volume is computed as

$$V_{seep} = Q_{seep}\ (m^3/s) \times 86400\ s \div 10^6\ Mm^3$$
$$= (59.5/1000)\ m^3/s \times 86400\ s \div 10^6$$
$$= 0.0051\ Mm^3$$

4.3.4 Reservoir evaporation

4.3.4.1 Methodology for reservoir evaporation estimation

Owing to the requirements of only wind speed and temperature data, the Priestley-Taylor method as modified by de Bruin (1978) is used. It has an advantage of eliminating the need for radiation data in the original Priestley-Taylor and Penman methods. It is given by

$$E = \left(\frac{\propto}{\propto-1}\right)\left(\frac{\gamma}{\Delta+\gamma}\right) f(u)(e_s - e_a) \quad [4.14]$$

where E is evaporation (mm/d), α is a Priestley-Taylor coefficient (unitless), γ is the psychometric constant (kPa/°C), Δ is the slope of the saturated vapour pressure-temperature curve at air temperature (kPa/°C), $f(u)$ is a wind function for wind speed (mm/d/kPa), e_s is saturated vapour pressure of the air at the water surface temperature and e_a is the saturated vapour pressure of the air at air temperature.

Priestley-Taylor coefficient, α

The Priestley-Taylor coefficient, α, varies with response advection conditions. An average value of 1.26 has been used in several studies (Stewart and Rouse, 1976, 1977; Mukammal and Neumann, 1977) for open water and saturated surfaces although de Bruin and Keijman (1979) indicated its validity at the daily timescale with variations between 1.25 ± 0.01. A value of 1.26 is therefore used for Priestley-Taylor coefficient as water balance computations are carried out at the daily timescale.

Estimation of γ and Δ

Psychometric constant (γ) was computed from

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = \frac{(1.013\times10^{-3} MJ/kg/°C)\times P}{0.622\times2.45 MJ/kg/°C} = 0.665P \times 10^{-3}\ kPa/°C \quad [4.15]$$

where C_p is the specific heat of air at constant pressure (1.013 x 10^{-3} MJ/kg/°C), ε is the ratio of molecular weight of water vapour to dry air (0.622), λ is the latent heat of vaporisation of water (2.45 MJ/kg/°C) and P is the atmospheric pressure given by

$$P = 101.3\left(\frac{(T+273)-0.0065Z}{T+273}\right)^{5.26} \quad kPa \qquad [4.16]$$

where T is the average air temperature (°C) and Z is altitude (m), which is taken as altitude of the reservoir water surface.

The slope of the saturated vapour pressure-temperature curve at air temperature (Δ) is computed from

$$\Delta = 4098\,\frac{0.6108e^{\frac{17.27T}{(T+237.3)}}}{(T+237.3)^2} \quad kPa/°\mathrm{C} \qquad [4.17]$$

Estimation of wind function, f(u)

The wind function ($f(u)$) is normally empirically obtained from fitting mathematical equation ($f(u) = a + bu_2$) at sites where measurements of wind speed at 2m (u_2) are recorded. Sometimes, a correction for lake area (A) is introduced to provide $f(u) = a + \frac{bu_2}{A^c}$. The many available wind functions are given in **Table 4.6**.

The Shuttleworth (1993) $f(u)$ containing a lake area correction is more suitable for Kidunda reservoir as it is applicable for (semi)arid environment and for lake surface area between 2,500 m^2 and 10,000 km^2 (Maximum Kidunda reservoir area at an altitude of 86 m: 78 km^2). However, it indicates that reservoir evaporation cannot be estimated when the area is missing, which could sometimes be the case. To avoid such a drawback, the McMillan (1971) wind function ($f(u) = 1.16 + 1.07u_2$) developed from data for Fiddlers Ferry Lagoon is adopted as it yields results almost similar to those using Shuttleworth (1993) wind function for Kidunda reservoir for periods with available inflow and outflow data for the reservoir that provide estimations of stored volume and area from reservoir characteristic equations.

Estimation of vapour pressure deficit ($e_s - e_a$)

Daily saturated vapour pressure of air at constant temperature (e_s) was computed as recommended by FAO (www.fao.org/docrep/x0490e/x0490e07.htm) as an average of saturated vapour pressures computed from daily minimum and maximum temperatures using the Tetens (1930) model

$$e^o(T) = 0.6108e^{\frac{17.27T}{(T+237.3)}} \quad kPa \qquad [4.18]$$

and therefore

$$e_s = \frac{e^o(T_{min})+e^o(T_{max})}{2} = \frac{0.6108e^{\frac{17.27T_{min}}{(T_{min}+237.3)}}+0.6108e^{\frac{17.27T_{max}}{(T_{max}+237.3)}}}{2} \qquad [4.19]$$

Table 4.6: Some developed wind functions in use (Helferet al., 2012).

Original source	Wind function	Units
Carpenter, 1889,1891	$F(u2) = 2.93 + 1.95u2$	mm $day^{-1}kPa^{-1}$
Rohwer, 1931	$F(u2) = 3.29 + 1.01u2$	mm $day^{-1}kPa^{-1}$
Penman,1948	$F(u2) = 2.65 + 1.38u2$	$mmday^{-1}kPa^{-1}$
Harbeck,1962	$F(u2) = 9.17A^{-0.05}u2$	$Wm^{-2}mbar^{-1}$
WMOUSSR, 1966	$F(u2) = 1.30 + 1.80u2$	$mmday^{-1}kPa^{-1}$
WMOUSA, 1966	$F(u2) = 1.31u2$	mm $day^{-1}kPa^{-1}$
Brutsaert andYu, 1968[1]	$F(u2) = 3.623\ A^{-0.066}u2$	mm $day^{-1}kPa^{-1}$
Shuttleworth, 1993	$F(u2) = 2.909\ A^{-0.56}u2$	mm $day^{-1}kPa^{-1}$
Brutsaert and Yu, 1968[1]-Small pan	$F(u2) = 2.71 + 2.54\ u2$	m $day^{-1}kPa^{-1}$
Brutsaert and Yu, 1968[1]-Mediumpan	$F(u2) = 2.31 + 2.11u2$	$mmday^{-1}kPa^{-1}$
Brutsaert and Yu, 1968[1]-Large pan	$F(u2) = 2.46 + 1.71u2$	mm $day^{-1}kPa^{-1}$
McMillan, 1971-FiddlersFerrymodel	$F(u2) = 1.76 + 0.86u2$	mm $day^{-1}kPa^{-1}$
McMillan, 1971-FiddlersFerrylagoon	$F(u2) = 1.16 + 1.07u2$	mm $day^{-1}kPa^{-1}$
McMillan, 1971-FortColorado	$F(u2) = 1.59 + 1.06u2$	$mmday^{-1}kPa^{-1}$
McMillan, 1973 (overwater)	$F(u2) = 3.67 + 2.70u2$	$Wm^{-2}mbar^{-1}$
McMillan, 1973 (overland)	$F(u2) = 4.4 + 2.20\ u2$	$Wm^{-2}mbar^{-1}$
Sweers, 1976	$F(u2) = (5\ x10^{6}/A)^{0.05}(1.29 + 0.95u2)$	$mmday^{-1}kPa^{-1}$
Thom etal.,1981	$F(u2) = 1.20 + 1.62u2$	$mmday^{-1}kPa^{-1}$
Smithetal.,1994	$F(u2) = 2.25 + 1.39u2$	$mmday^{-1}kPa^{-1}$
Molina et al.,2006	$F(u2) = 2.06 + 2.28u2$	$mmday^{-1}kPa^{-1}$
Rayner, 2007	$F(u2) = (1 + 4.1\ U2)/(1 + 0.32u2)$	$mmday^{-1}kPa^{-1}$
Alvarez, 2007	$F(u2) = 0.037\ log10A^{2} – 0.578log10A + 3.583$	$mmday^{-1}kPa^{-1}$
McJannet et al., 2011	$F(u2) = (2.59 + 1.61u2)\ A^{-0.05}$	$mmday^{-1}kPa^{-1}$

Daily actual vapour pressure of air (e_a) is computed from dew point temperature (T_{dew}) as

$$e_a = e^o(T_{dew}) = 0.6108e^{\frac{17.27T_{dew}}{(T_{dew}+237.3)}}\ kPa \qquad [4.20]$$

However, dew point temperatures (T_{dew}) are not measured within and closest to proposed Kidunda reservoir catchment. T_{dew} is estimated from relative humidity and mean air temperature (T) as (Lawrence, 2004)

$$T_{dew} = T - \left(\frac{100-RH)}{5}\right)\left(\frac{T}{300}\right)^2 - 0.00135(RH-84)^2 + 0.35 \quad [4.21]$$

where relative humidity is computed from

$$RH(\%) = \frac{e^o(T_{wet}) - [0.00066(1+0.0115T_{wet})(T_{dry}-T_{wet})P]}{e^o(T_{dry})} \times 100\% \quad [4.22]$$

where P is atmospheric pressure (kPa), T_{wet} and T_{dry} are wet and dry bulb temperatures (^oC).

This empirical estimation equation gives T_{dew} within $\pm$ 0.3^{o}C for relative humidity exceeding 50%, which is the observation at climate stations within and closest to the Kidunda reservoir catchment. The daily volume of water that will be evaporated from the Kidunda reservoir is computed as

$$V_{evap} = E \times A_{res} \times 10^{-3}\ Mm^3 \quad [4.23]$$

where daily evaporation (E) is in mm/d and reservoir area (A_{res}) in km^2 in a particular day.

4.3.4.2 Data

4.3.4.2.1 Availability

The closest climate station to proposed Kidunda reservoir is the Mikula station located just downstream of the proposed dam axis (**Figure 4.1**) at an altitude of approximately 66 m. Daily climate data available were obtained from the Directorate of Water Resources of Ministry of Water and Irrigation spanning the 14th December 1966 – 31st May 1973 comprising wind speed, maximum and minimum air temperatures, dry and wet bulb temperatures, pan evaporation, and solar radiation (**Table 4.7**). Monthly climate records were obtained from the Wami-Ruvu Basin Water Office (Morogoro), which spans the January 1970 – March 1973 comprising data for mean temperature, relative humidity, pan evaporation, solar radiation and wind speed (**Table 4.7**).

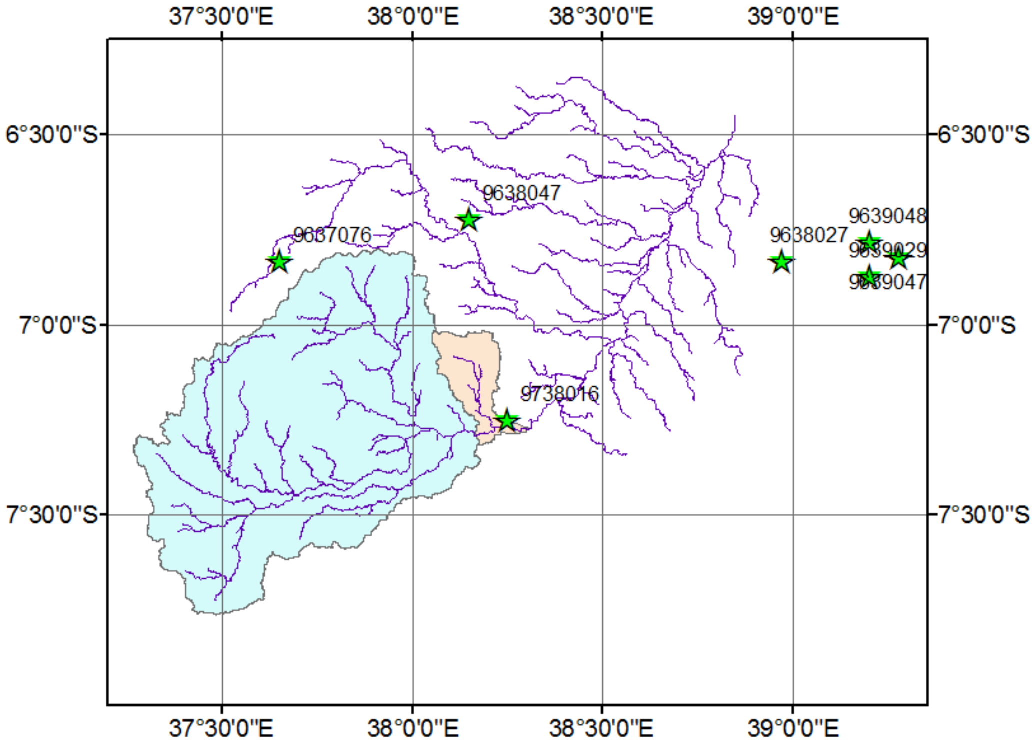

Figure 4.1: Spatial distribution of climatic stations around Kidunda dam axis.

Table 4.7: Climate data availability at Mikula station.

Variable	Data availability	
	Daily	Monthly
Wind speed	14 Dec 1966 – 31 May 1973	
Max temperature	15 Dec 1966 – 31 May 1973	-
Min temperature	15 Dec 1966 – 31 May 1973	-
Mean temperature	-	Jan 1970 – Mar 1973
Dry bulb temperature	14 Dec 1966 – 31 May 1973	-
Wet bulb temperature	14 Dec 1966 – 31 May 1973	-
Relative humidity	-	Jan 1970 – Sep 1972
Solar radiation	14 Dec 1966 – 31 May 1973	Jan 1970 – Mar 1973
Pan evaporation	1 Sep 1966 – 31 May 1973	Jan 1970 – Dec 1972

The available daily data contains varying sizes of periods with missing observations. Dry and wet bulb temperature records are the most continuous while wind speed records contains a lot of missing daily observations followed by minimum temperature record (**Figure 4.2**).

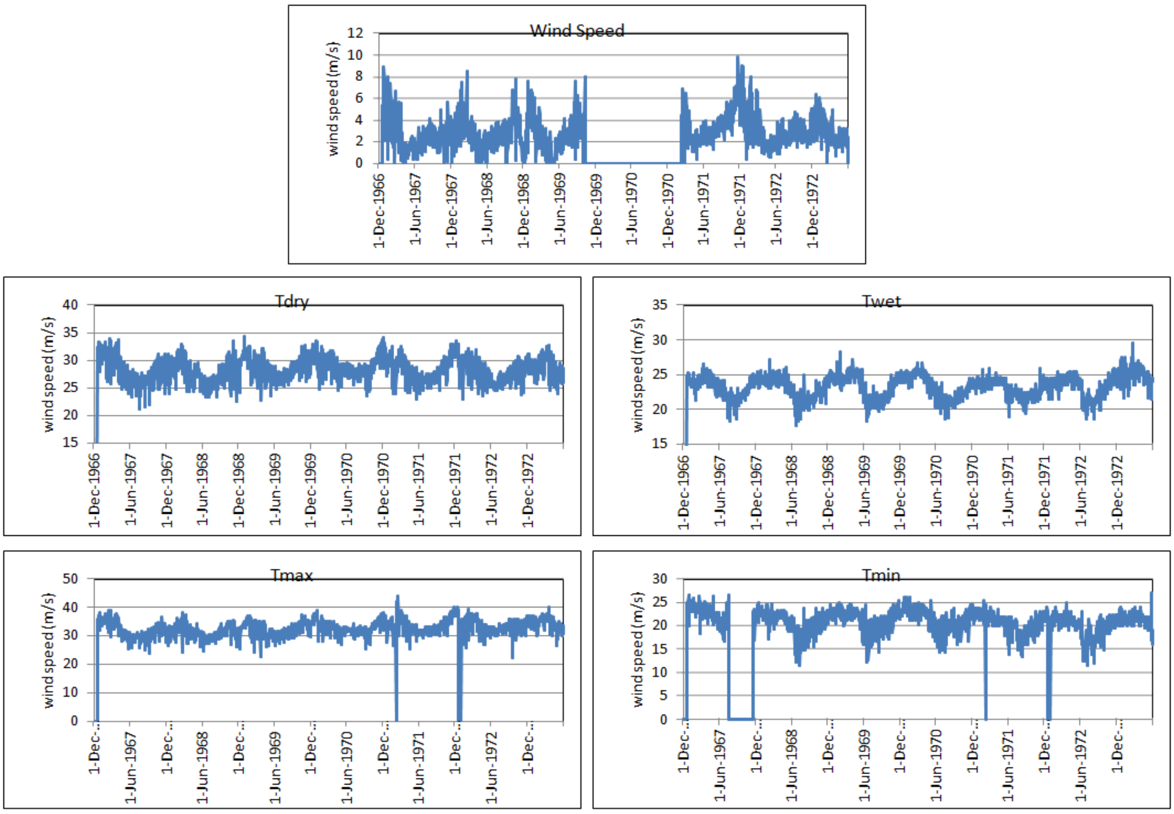

Figure 4.2: Availability of daily climate data at Mikula station.

4.3.4.1.2 Daily record reconstruction at Mikula

Visual analysis of daily climate records (**Figure 4.2**) indicates some sort of periodic fluctuations reflecting the annual (12-month or 365 days) cycle. Consequently, Fourier series were fitted to complete years (**Table 4.8**) of each variable. The Fourier series for estimating a daily value of fluctuating climate variable in day *t* ($\hat{y}_t$) is represented by

$$\hat{y}_t = a_0 + \sum_{i=1}^{n} a_i \cos\left(\frac{2\pi i}{365}t\right) + \sum_{i=1}^{n} b_i \sin\left(\frac{2\pi i}{365}t\right) \qquad [4.24]$$

where a_i and b_i are Fourier coefficients and n is the number of significant coefficients.

Fourier coefficients were estimated from available daily data (y_t) in each year as

$$\begin{aligned} a_0 &= -\frac{\sum_{t=1}^{365} y_t}{365} \\ a_i &= \sum_{t=1}^{365} y_t \cos\left(\frac{2\pi i}{365}t\right) \\ b_i &= \sum_{t=1}^{365} y_t \sin\left(\frac{2\pi i}{365}t\right) \end{aligned} \qquad [4.25]$$

Table 4.8: Years used in fitting Fourier series to daily climate data at Mikula.

Variable	Year definition	Years used
Wind speed	1st Oct – 30th Sep	1967/68, 1971/72
Dry bulb temperature	1st Jan – 31st Dec	1967, 1968, 1969, 1970, 1971
Wet bulb temperature	1st Jan – 31st Dec	1967, 1968, 1969, 1970, 1971
Maximum temperature	1st Jan – 31st Dec	1967, 1968, 1969
Minimum temperature	1st Jan – 31st Dec	1968, 1969, 1970

Results of Fourier fitting to all climate variables using the first 20 coefficients (n = 20) indicate good agreement to patterns and magnitudes in daily observations (**Figure 4.3**). The fits are equally comparable when coefficients for individual years are fitted (**red lines**) as when average coefficients are used (**green lines**). In fact, the Fourier fits represent smoothed variations of variable against noisy fluctuations in the original observations. The smoothed climate records reproduced very closely daily evaporation values as estimated using observational records in the 14th December 1966 – 31st May 1973 period (**Figure 4.4**). The average coefficients were therefore used to generate smoothed daily climate data between 1st January 1951 and 31st December 1985 (**Figure 4.5**).

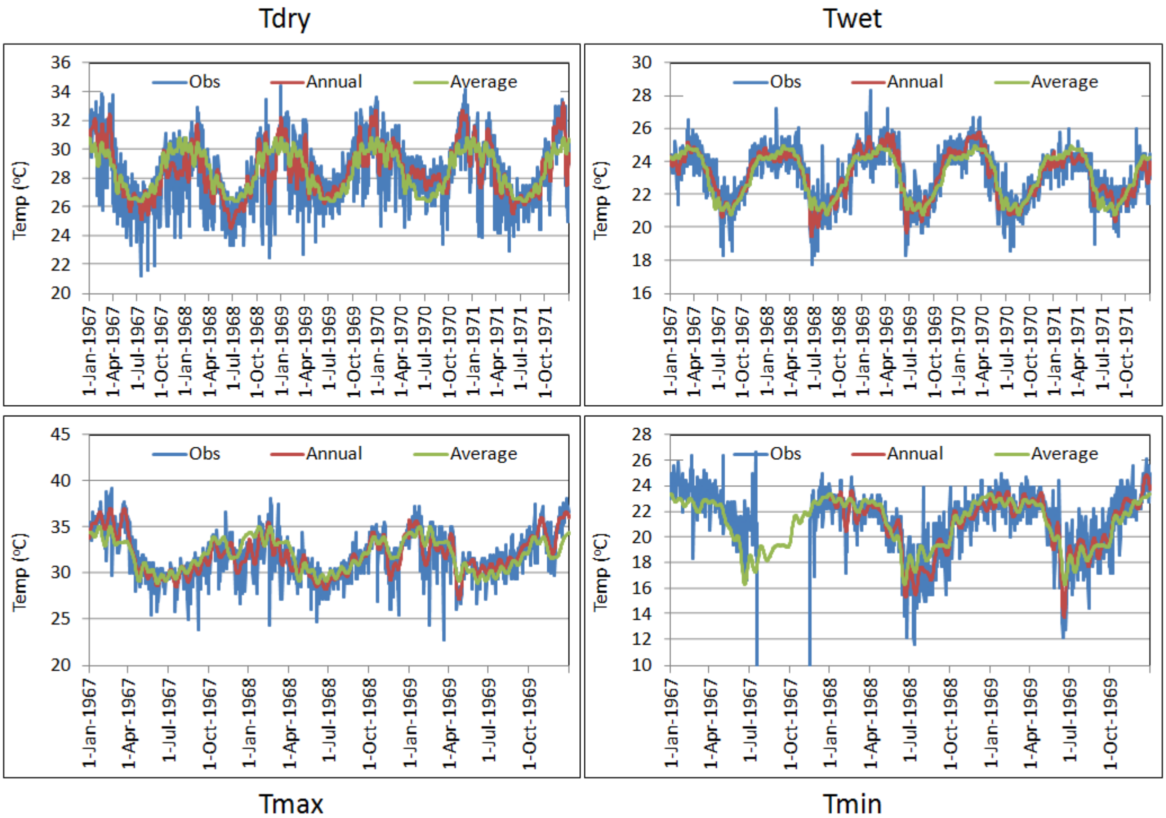

Figure 4.3: Fourier fits to observational climate records at Mikula.

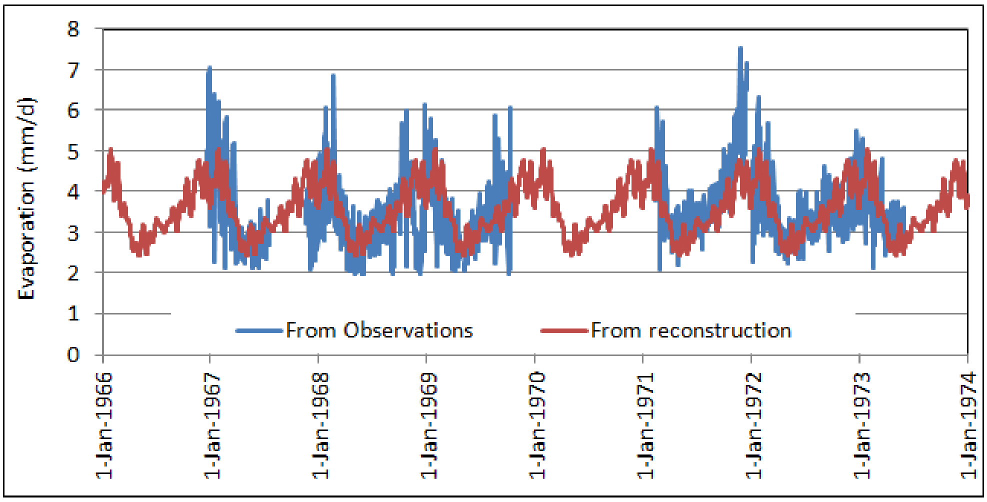

Figure 4.4: **Comparison of estimate daily evaporation using observational and Fourier smoothed climates at Mikula.**

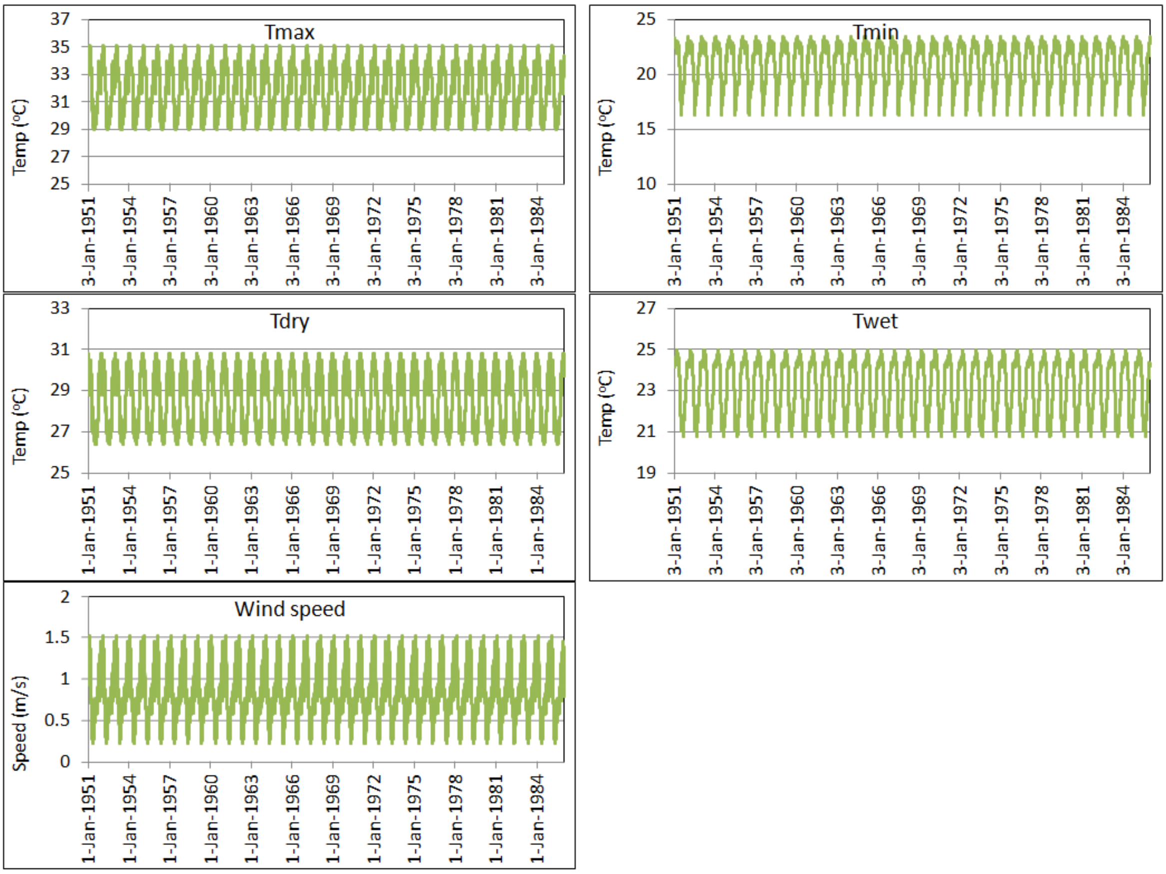

Figure 4.5: **Reconstructed daily climate records at Mikula.**

It is immediately noted the non-trending nature of the extended climate records. It was therefore important to verify this observation using data from other climate stations. The inventory indicated existing of several distant climate stations (**Figure 4.1**) at different altitudes, the closest being Morogoro Met (09637076, altitude 526 m) and Ngerengere Met (09638047, Altitude 258 m). Morogoro Met Station was therefore selected due to availability of data (**Table 4.9**) and being used in the hydrology study (Studio Pietrangeli, 2013) despite being higher than Mikula station.

Table 4.9: Availability of monthly climate data at Morogoro Met station.

Variable	Data availability
Wind speed	Aug 1975 – Dec 1989
Max temperature	Jan 1971 – Jul 1989
Min temperature	Jan 1971 – Jul 1989
Mean temperature	Jan 1971 – Jul 1989
Dry bulb temperature	-
Wet bulb temperature	-
Relative humidity	Jan 1971 – Jul 1989

Monthly values of climate variables at Mikula were computed and time series compared with Morogoro Met monthly series to verify magnitudes and depict trends. Relative humidity at Mikula was computed from dry and wet bulb temperatures. Long Morogoro Met records do not show any trending patterns in temperature except for very slight decreasing wind speed and increasing relative humidity trends (**Figure 4.6**). However, despite comparable daily minimum temperatures, maximum temperatures at Mikula are higher than those at Morogoro Met resulting in higher mean daily temperatures at Mikula than at Morogoro Met. Similarly, relative humidities are higher at Mikula than at Morogoro Met while winds are stronger at Morogoro Met than at Mikula (**Figure 4.6**). The use of Morogoro Met records could result in underestimation of potential evaporation from the reservoir. Owing to lack of trends in Morogoro Met station, reconstructed climate records at Mikula were used to estimate daily reservoir evaporation from modified Priestley-Taylor model (**Figure 4.5**). The daily reservoir evaporated volumes are computed evaporation depth (D_{evap}) as

$$V_{evap} = D_{evap}\,(mm/d) \times A_{reservoir}\,(km^2) \div 10^3\ Mm^3 \qquad [4.26]$$

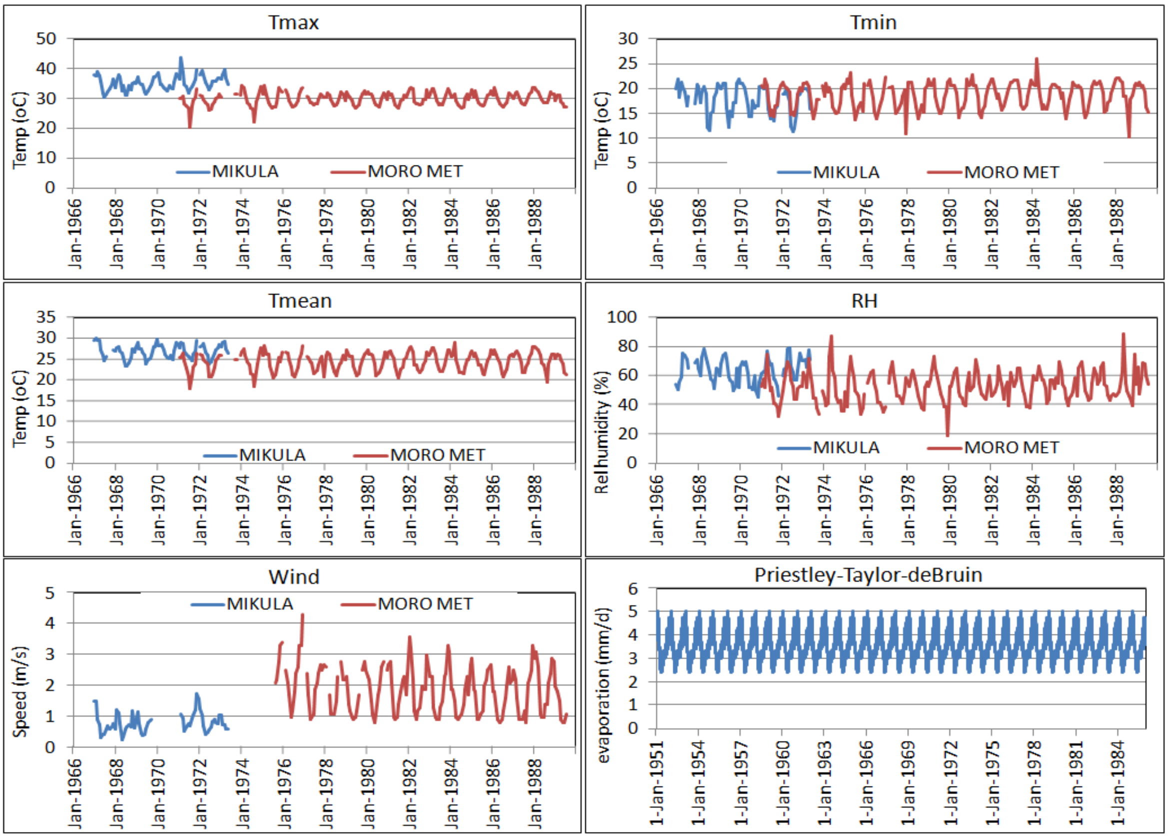

Figure 4.6: Comparison of monthly climate records at Mikula and Morogoro Met stations.

4.4 ASSESSMENT OF RESERVOIR INUNDATION INTO SGR

Owing to availability of reconstructed daily inflows into and outflows from the proposed Kidunda reservoir, water balance model (equation 4.4b) was used to estimate daily storages, which were in turn, used estimate water surface elevations using equation (4.8) in different years for different initial conditions. According to Kidunda dam design, the highest operational altitude of reservoir water surface will be 84.5 m while highest flood level will reach 85.5 m while the spillway sill altitude will be 79 m. The 79 m reservoir will correspond to surface areas of 14.5 km^2 inundating SGR in discontinuous patches (**Figure 4.7**) with total area of 0.237 km^2. The 84.5 m reservoir with an area of 70.7 km^2 will have large spatial extent within the SGR inundating an area of 5.646 km^2 (**Table 4.10**).

The area of SGR occupied by the reservoir is confined on the northern half up to reservoir elevation of 81.5-82 m (**Figure 4.8ab**). At these altitudes, the longest distance between the western SGR boundary and eastern reservoir shoreline is about 810-850 m (**Table 4.10**). The reservoir area in SGR enlarges rapidly into the southern half at elevations above 82 m to largest extent from 84.5 m (**Figure 4.8cd**). However, even at these higher reservoir elevations, the longest distance remains moderate between 1180 and 1260 m.

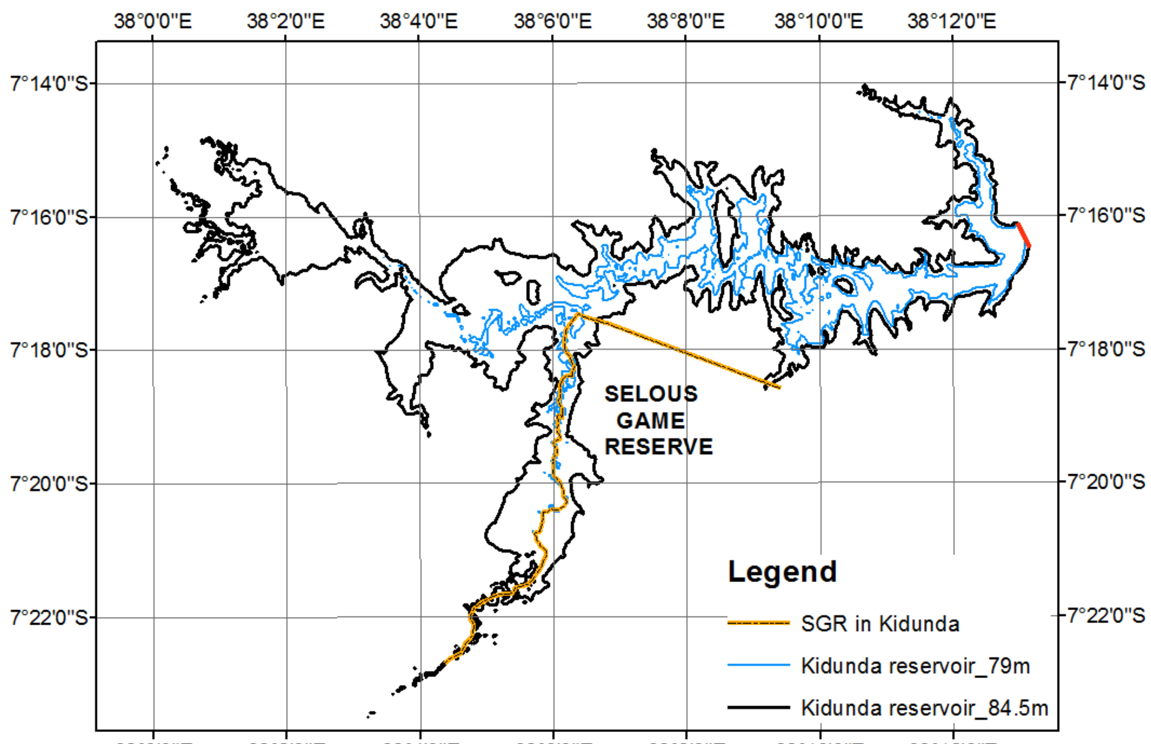

Figure 4.7: Spatial extents of Kidunda reservoir.

Table 4.10: Extent of Kidunda reservoir in Selous Game Reserve.

Alt (m)	Reservoir area (km²)	Area in SGR (km²)	Longest path (m)	Volume (Mm³)		
				storage	Change	Cum change
79.0	14.5	0.237	328	40.71		
79.5	16.7	0.549	460	48.78	8.07	8.07
80.0	19	0.761	730	58.06	9.28	17.34
80.5	16.5	0.988	840	68.67	10.61	27.95
81.0	25.5	1.322	760	80.75	12.08	40.03
81.5	28.7	1.688	810	94.44	13.69	53.72
82.0	31.5	1.955	850	109.89	15.45	69.18
82.5	36.7	2.415	910	127.27	17.38	86.55
83.0	39.8	2.919	1105	146.74	19.47	106.02
83.5	46.2	3.565	1140	168.48	21.74	127.76
84.0	51.5	4.175	1160	192.67	24.20	151.96
84.5	58.0	4.346	1184	219.52	26.85	178.81
85.0	64.5	5.162	1210	249.23	29.71	208.51
85.5	70.7	5.646	1240	282.01	32.78	241.30
86.0	78.0	6.268	1260	318.09	36.08	277.38

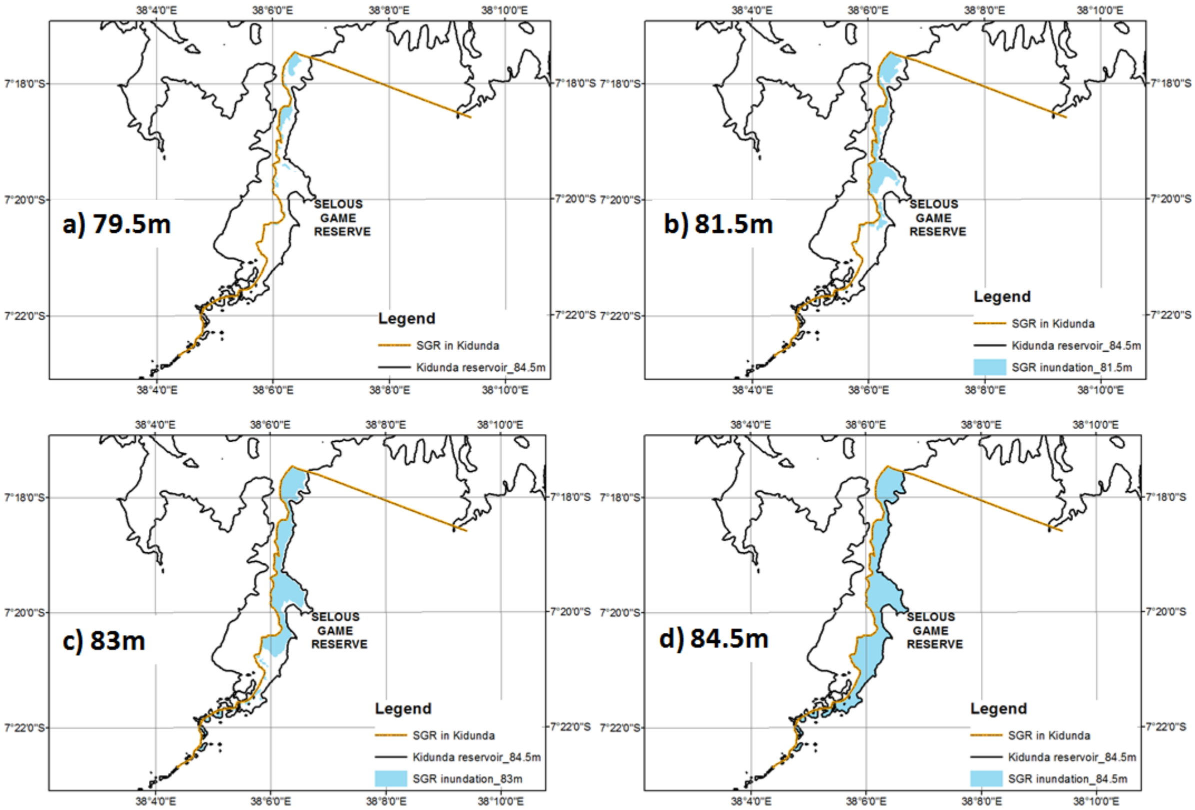

Figure 4.8: Inundations of SGR at different reservoir elevations.

Apart from inflows into the Kidunda reservoir, inundation of the SGR is dependent on the operations of gates on the dam. The bottom gates will be open as long as there is no power production and spillage while bottom intake gates are operated following rules provided in **Table 4.5**. Spilling will be carried out by fully opening of the 8 flap gates of the spillway to release water whenever reservoir water surface altitude is equal or exceeding 84.5 m, which is the altitude of the flap gate tips as otherwise water will overflow the gates. Therefore, the effects of following operations of the dam are investigated

i) Totally uncontrolled spillway (all 8 flap gates are open throughout)
ii) Partially controlled spillway (1-4 flap gates left open throughout)
iii) Completely controlled spillway (gates are fully opened when water surface elevation reaches 84.5 m and above)

4.4.1 Uncontrolled spillway

Results of water balance computations for different combinations of dry, normal and wet seasons within the wet period (October-June) indicate that the most important variables for reservoir storage changes are river inflows, spills and releases (bottom gates and power intakes) (**Table 4.11**). Small size of the reservoir results in insignificantly small contributions of reservoir rainfall and evaporation. Spills contribute the largest outflows followed by turbine outflow and bottom gate discharges. The total dam outflow discharges vary from 24 m³/s to 651 m³/s, which are within the observed discharge range. Moreover, the outflow pattern mimics the seasonal regime of unregulated river with low, medium and high flow flows seasons reproduced (**Figure 4.9**) although some early pulses of December-February are missed by a rather constant outflow pattern in completely dry years.

Table 4.11: Annual water balance components magnitudes for Kidunda reservoir with uncontrolled spilway.

Year	Alt_Max	Flow	Rain	Evap	Power	Envir	Spill	Seep
1952/53	80.162	2.849	0.017	0.022	0.522	1.381	0.881	0.005
1958/59	**79.672**	2.259	0.033	0.028	0.051	1.705	0.500	0.005
1961/62	80.771	10.025	0.066	0.056	3.572	1.460	4.863	0.005
1969/70	80.063	4.926	0.038	0.042	1.176	1.760	1.935	0.005
1971/72	80.390	5.435	0.040	0.035	1.613	1.523	2.165	0.005
1974/75	80.029	3.416	0.024	0.024	0.636	1.412	1.228	0.005
1978/79	**80.874**	14.284	0.066	0.052	5.679	0.982	7.477	0.005
1981/82	79.960	2.823	0.007	0.034	0.159	1.889	0.655	0.005
1983/84	80.365	6.637	0.039	0.044	2.205	1.520	2.789	0.005
Average		**5.752**	**0.036**	**0.037**	**1.676**	**1.514**	**2.463**	**0.005**

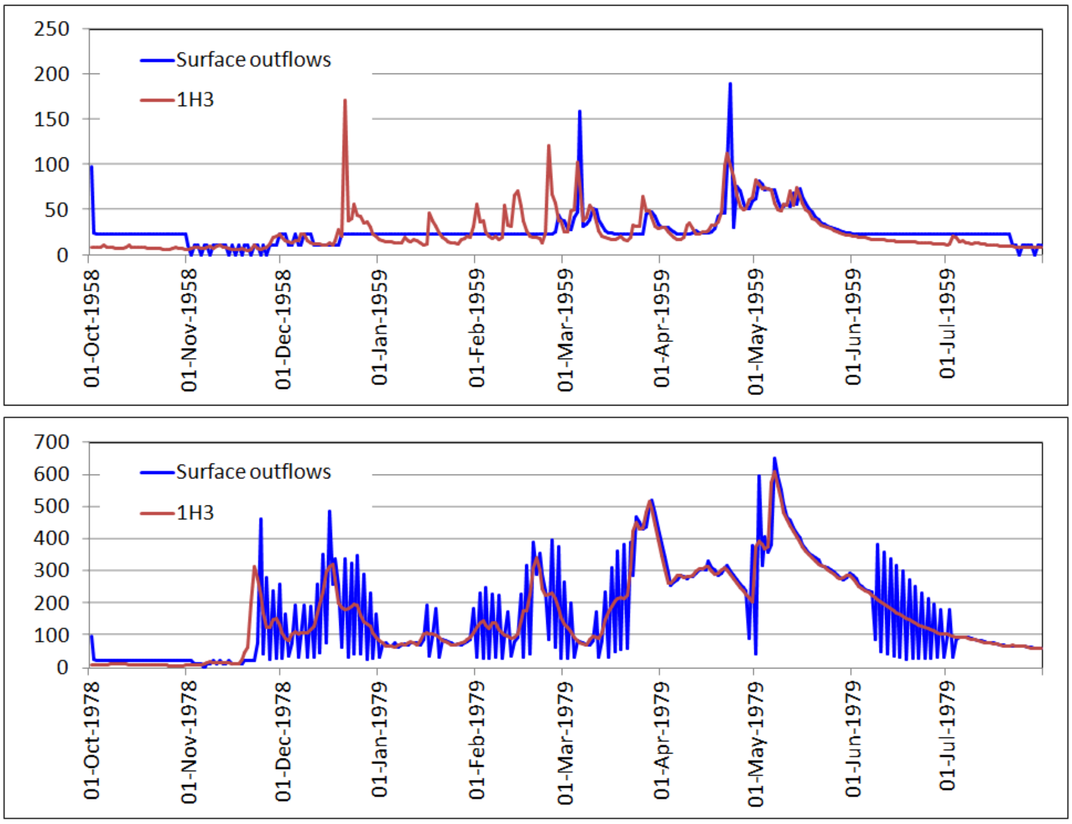

Figure 4.9: Total discharge from the dam for an uncontrolled spillway (all gates fully open).

Highest computed water surface elevations of the proposed reservoir in different historical dryness and wetness conditions as represented by various selected years will vary between 79.7 and 80.9 m (**Table 4.11**) regardless of the initial starting condition whether an empty or full reservoir. Comparison of computed reservoir elevations to altitudes of SGR within the Kidunda reservoir (78 – 86 m) indicates periods and length of inundation of SGR are affected by seasonality and abundance of inflows into the reservoir irrespective of starting conditions (empty, half-full or full) of the reservoir. In general, SGR up to 79 m altitude will be permanently inundated due to the presence of the dam with sill level at this altitude. For completely wet years (e.g. 1961/62, 1978/79) in which all seasons are classified as wet, reservoir elevations will rarely and for a short period of time (1-12 days) exceed 79.5 m but fluctuates between 79 and 79.5 m in much of the mid November – early June. In complete dry years (e.g. 1952/53, 1958/59), the highest reservoir water surface elevation will still vary between 79.7 and 80.2 m although rarely exceeding 79.3 m. Most of the time the reservoir will be below the SGR lowest altitude (78 m) and only between 78 and 79.5 m for few isolated days between 1st April and 31st May covering 0.237 – 0.549 km^2 of SGR. This observation indicates that for much of the period in dry years, SGR will occasionally and for few days be inundated. Considering the longest distance of 840 km that can be inundated in a day with high inflows (e.g. 3rd – 4th Nov 1961; whole May 1979), the inundation speed is equivalent to a coverage of 35 m in an hour or 59 cm every minute.

4.4.2 Partially controlled spillway

4.4.2.1 4 gates fully open

Results of water balance computations for different combinations of dry, normal and wet seasons within the wet period (October-June) indicate that the most important variables for reservoir storage changes remain river inflows, spills and releases (bottom gates and power intakes) (**Table 4.12**). Still, small size of the reservoir results in insignificantly small contributions of reservoir rainfall and evaporation. Turbine outflow discharges for power production and reservoir spills contribute the largest outflows followed by bottom gate discharges. The total dam outflow discharges vary from 24 m^3/s to 583 m^3/s, which are within the observed discharge range. Moreover, the outflow pattern mimics the seasonal regime of unregulated river with low, medium and high flow flows seasons reproduced (**Figure 4.10**) although some early pulses of December-February are still missed by a rather constant outflow pattern in completely dry years.

Highest computed water surface elevations of the proposed reservoir in different historical years will vary between 79.8 m in the completely dry year (1958/59) and 84.1 m in a completely wet year (1978/79) (**Table 4.12**) regardless of the initial starting condition of the reservoir. Part of wet seasons in a year (e.g. 1971/72) might result in a high reservoir water elevation comparable to a wet year (e.g. 1961/62). Reservoir elevations will mostly be below 82 m (SGR area: < 1.955 km^2) frequently exceeding 79.5 m but below 80 m during the wet November-June period of wet years. Occasionally, reservoir water elevation will vary between 79.3 and 79.5 m in January-mid February and largest part of Masika season (early April – mid June/early July). In complete dry years (e.g. 1952/53, 1958/59), however, the highest reservoir water surface elevation can occasionally reach 79.9 – 80.2 m although rarely exceeds 79.5 m. Most of the time the reservoir will be below the SGR lowest altitude except for the early March – late June period when it goes above 79.5 m for few isolated days. This observation indicates that for much of the period in dry years, SGR will occasionally and for few days be inundated. Considering the longest distance of 850 m that can be inundated in a day with high inflows (e.g. whole May 1979), the inundation speed is equivalent to a coverage of 36 m in an hour or 59 cm every minute.

Table 4.12: Annual water balance components magnitudes for Kidunda reservoir with four gate fully opened and no reservoir water level control.

Year	Alt_Max	Flow	Rain	Evap	Power	Envir	Spill	Seep
1952/53	80.089	2.849	0.017	0.022	0.753	1.327	0.704	0.005
1958/59	79.729	2.259	0.033	0.029	0.155	1.671	0.428	0.005
1961/62	80.910	10.025	0.070	0.059	4.840	1.201	3.855	0.005
1969/70	80.140	4.926	0.040	0.043	1.760	1.617	1.493	0.005
1971/72	80.764	5.435	0.042	0.036	2.143	1.428	1.731	0.005
1974/75	80.216	3.416	0.024	0.024	0.986	1.323	0.966	0.005
1978/79	**81.656**	14.284	0.071	0.056	7.022	0.696	6.413	0.005
1981/82	80.050	2.823	0.008	0.035	0.283	1.855	0.564	0.005
1983/84	80.628	6.637	0.042	0.045	2.827	1.397	2.290	0.005
Average		**5.752**	**0.038**	**0.038**	**2.243**	**1.390**	**2.019**	**0.005**

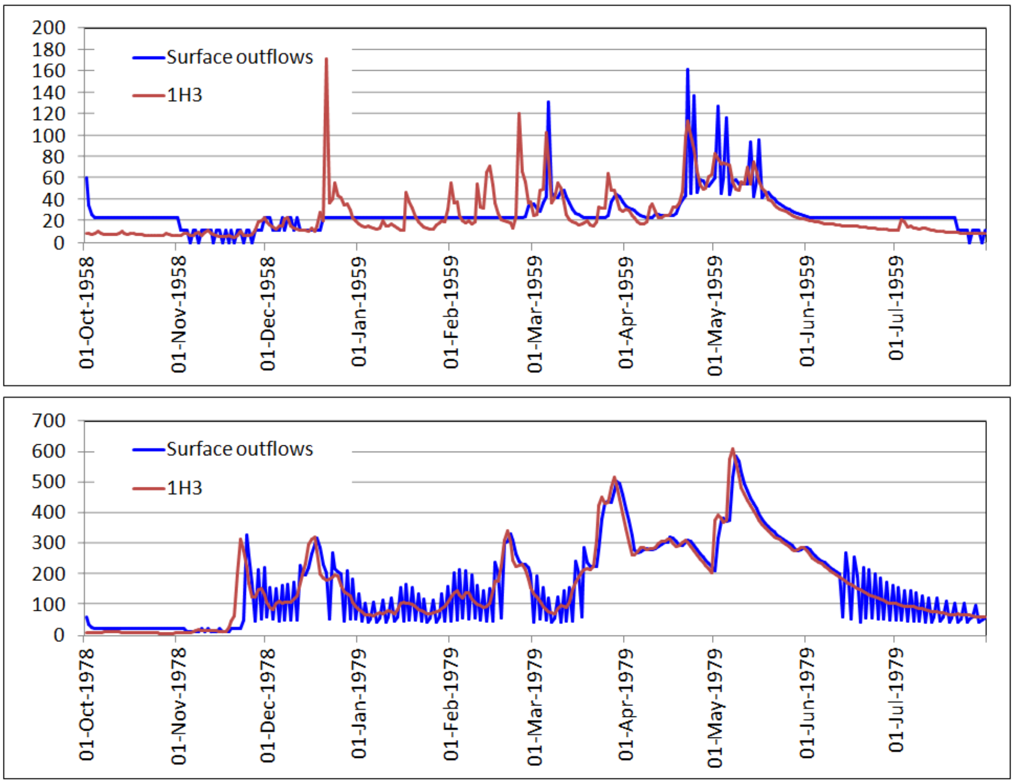

Figure 4.10: Total discharge from the dam for a partially controlled spillway (4 gates fully open).

4.4.2.2 1 gate fully open

Results of water balance computations for different combinations of dry, normal and wet seasons within the wet period (October-June) indicate that the most important variables for reservoir storage changes are river inflows, spills and releases (bottom gates and power intakes) (**Table 4.13**). Still, small size of the reservoir results in insignificantly small contributions of reservoir rainfall and evaporation. Turbine outflow discharges for power production contribute the largest outflows followed by reservoir spills and bottom gate discharges. The total dam outflow discharges vary from 24 m^3/s to 450 m^3/s, which are within the observed discharge range. Moreover, the outflow pattern mimics the seasonal regime of unregulated river with low, medium and high flow flows seasons reproduced (**Figure 4.11**) although some early pulses of December-February are still missed by a rather constant outflow pattern in completely dry years. The highest peaks of Masika (Mar-Jun) flow season are being smoothed out and under-reproduced, which might have an impact in ecosystem well-being.

Table 4.13: Annual water balance components magnitudes for Kidunda reservoir with one gate fully opened and no reservoir water level control.

Year	Alt_Max	Flow	Rain	Evap	Power	Envir	Spill	Seep
1952/53	80.223	2.849	0.018	0.023	1.338	1.177	0.261	0.005
1958/59	79.961	2.259	0.035	0.030	0.530	1.518	0.209	0.005
1961/62	**82.600**	10.025	0.077	0.067	7.010	0.662	2.216	0.005
1969/70	80.280	4.926	0.041	0.044	3.080	1.255	0.529	0.005
1971/72	**82.542**	5.435	0.051	0.041	2.711	1.244	1.345	0.005
1974/75	80.308	3.416	0.025	0.025	1.806	1.078	0.384	0.005
1978/79	**84.116**	14.284	0.095	0.071	8.661	0.314	5.160	0.005
1981/82	79.828	2.823	0.008	0.037	0.778	1.658	0.258	0.005
1983/84	**82.618**	6.637	0.056	0.051	3.333	1.268	1.916	0.005
Average		**5.752**	**0.044**	**0.042**	**3.239**	**1.113**	**1.295**	**0.005**

Highest computed water surface elevations of the proposed reservoir in different historical years will vary between 79.8 m in the completely dry year (1958/59) and 84.1 m in a completely wet year (1978/79) (**Table 4.13**) regardless of the initial starting condition of the reservoir. Part of wet seasons in a year (e.g. 1971/72) might result in a high reservoir water elevation comparable to a wet year (e.g. 1961/62). Reservoir elevations will mostly be below 82 m frequently exceeding 79.5 m but below 80 m during the wet November-June period of wet years. Occasionally, reservoir water elevation will vary between 79.3 and 79.5 m in January-mid February and largest part of Masika season (early April – mid June/early July). In complete dry years (e.g. 1952/53, 1958/59), however, the highest reservoir water surface elevation can occasionally reach 79.9 – 80.2 m occupying less than 1.0 km^2 although rarely exceeds 79.5 m. Most of the time the reservoir will be below the SGR lowest altitude except for the early March – late June period when it goes above 79.5 m for few isolated days. This observation indicates that for much of the period in dry years, SGR will occasionally and for few days be inundated. Considering the longest distance of 1160 m that can be inundated in a day with high inflows (e.g. whole May 1979), the inundation speed is equivalent to a coverage of 48 m in an hour or 81 cm every minute.

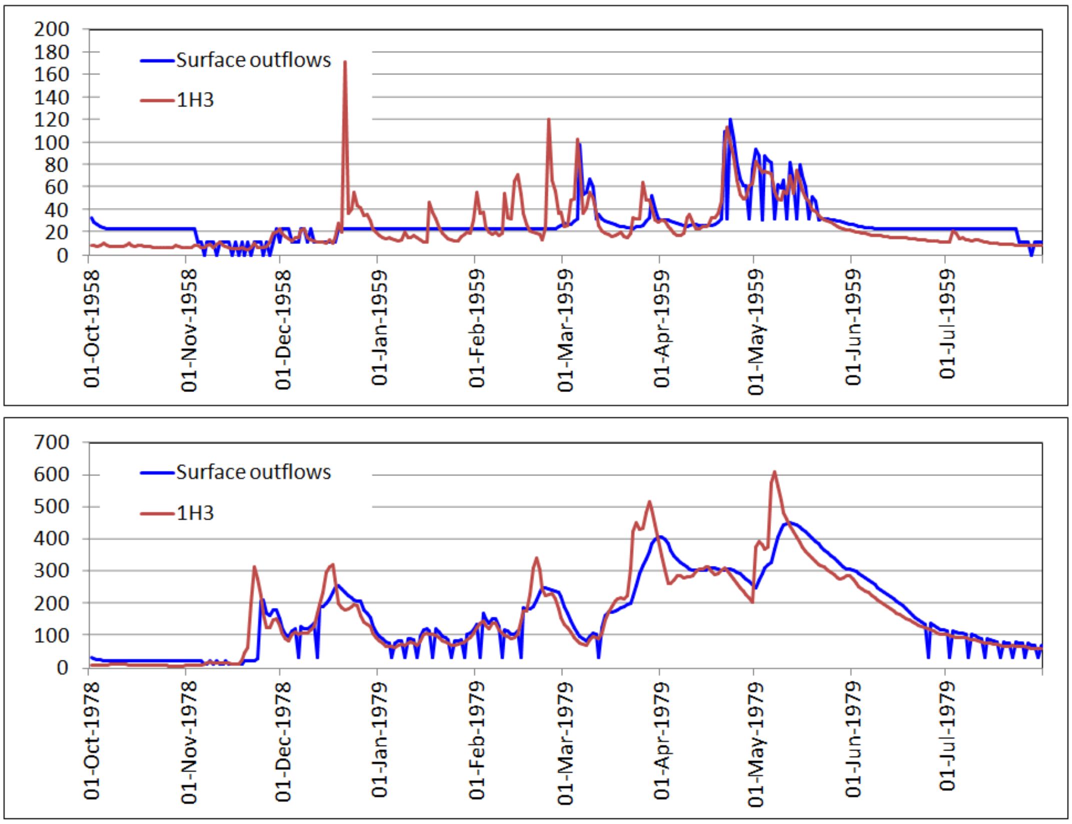

Figure 4.11: Total discharge from the dam for a partially controlled spillway (1 gates fully open).

4.4.3 Controlled spillway

Results of water balance computations for different combinations of dry, normal and wet seasons within the wet period (October-June) indicate that the most important variables for reservoir storage changes are river inflows, spills and releases (bottom gates and power intakes) (**Table 4.14**). Turbine outflow discharges for power production contribute the largest outflows followed by far by reservoir spills and bottom gate discharges. The total dam outflow discharges vary normally from 0 m^3/s to below 500 m^3/s with some isolated days requiring huge pulse releases exceeding 3,000 m^3/s when the reservoir water surface is at 84.5 m. Moreover, the outflow pattern mimics the seasonal regime of unregulated river with lowflow of November and high flows of Masika reproduced (**Figure 4.12**) although some early pulses of December-February are still missed by a rather constant outflow pattern in completely dry years. The highest peaks of Masika (Mar-Jun) flow season are being smoothed out and under-reproduced, which might have an impact in ecosystem well-being. Such spills are highly outside the observed discharge range and modified seasonal regime might significantly impact downstream ecosystem well-being.

Table 4.14: Annual water balance components magnitudes for Kidunda reservoir with all gates closed to 84.5 m reservoir water surface elevation.

Year	Alt_Max	Flow	Rain	Evap	Power	Envir	Spill	Seep
1952/53	80.529	2.849	0.018	0.027	1.906	0.795	0.000	0.005
1958/59	79.806	2.259	0.037	0.032	1.097	1.160	0.000	0.005
1961/62	**85.583**	10.025	0.189	0.130	7.703	0.297	1.918	0.005
1969/70	81.186	4.926	0.052	0.058	4.100	0.641	0.000	0.005
1971/72	**85.435**	5.435	0.077	0.064	3.182	0.884	0.932	0.005
1974/75	80.803	3.416	0.027	0.030	2.460	0.716	0.000	0.005
1978/79	**85.594**	14.284	0.151	0.128	8.696	0.246	4.783	0.005
1981/82	79.978	2.823	0.009	0.040	1.553	1.105	0.000	0.005
1983/84	**85.637**	6.637	0.079	0.059	3.755	0.806	1.903	0.005
Average		**5.752**	**0.070**	**0.064**	**3.837**	**0.730**	**0.954**	**0.005**

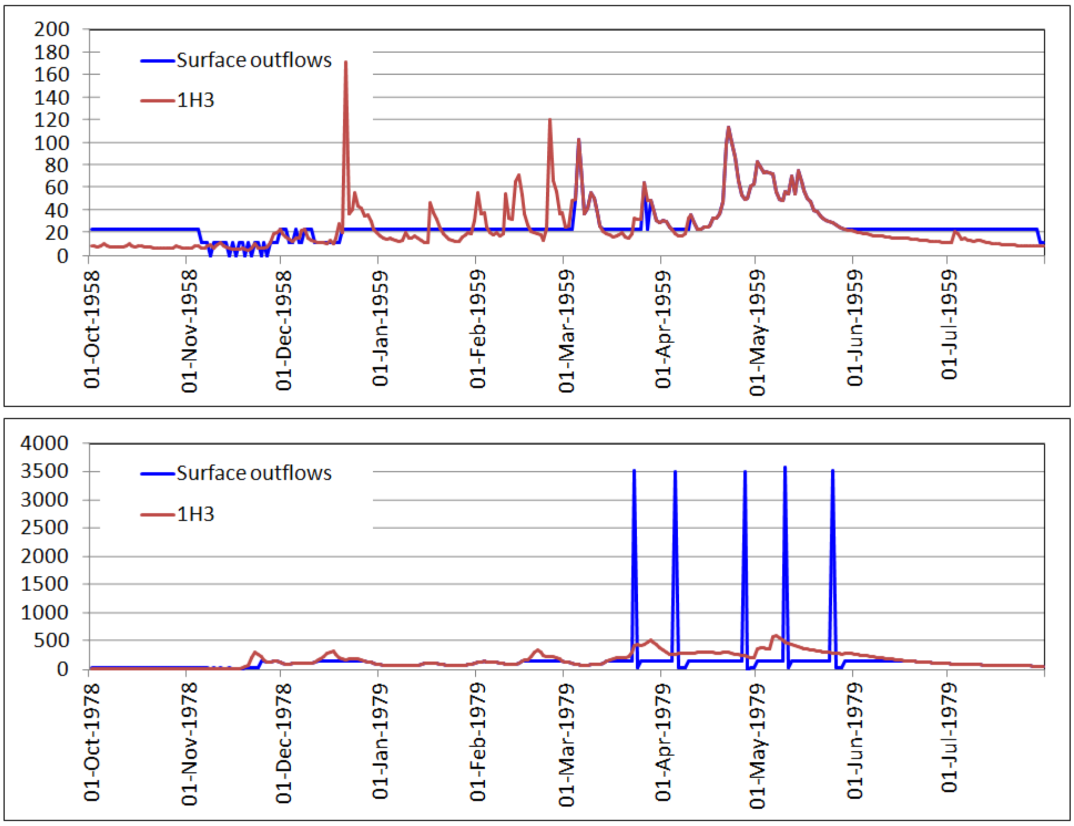

Figure 4.12: Total discharge from the dam for a fully controlled spillway (all gates closed).

Highest computed water surface elevations of the proposed reservoir in different historical years will vary between 79.8 m (SGR area: < 0.761 km^2) in the completely dry year (1958/59) and 85.6 m (SGR area:> 5.646 km^2) in a completely wet year (1978/79) (**Table 4.14**) regardless of the initial starting condition of the reservoir. Part of wet seasons in a year (e.g. 1971/72, 1983/84) might result in a high reservoir water elevation comparable to a wet year (e.g. 1961/62, 1978/79). This is due to the accumulation of water behind the dam to reach the 84.5 altitude of the flap gate tip. However, reservoir elevations will mostly be below 84 m (SGR area: < 4.175 km^2) during the wet November-April period of wet years. In complete dry years (e.g. 1952/53, 1958/59), however, the highest reservoir water surface elevation can occasionally reach 79.9 – 80.5 m (SGR area: 0.988 km^2) although rarely exceeds 79.5 m. Most of the time the reservoir will be below the SGR lowest altitude except for the early April – late July period when it goes just below 79.5 m (SGR area: 0.549 km^2). This observation indicates that for much of the period in dry years, SGR will occasionally and for few days be inundated. Considering the longest distance of 1,240 m that can be inundated in a day during a wet year, the inundation speed is equivalent to a coverage of 52 m in an hour or 87 cm every minute.

4.4.4 Summary of reservoir elevation fluctuations and releases

Operation of the reservoir according to release rules and several scenarios for operating the spillway flap gates indicates varying highest elevations of reservoir water surface from 80.9 m to 85.6 m corresponding to reservoir storage variation of 77.56 to 291.56 Mm^3 (**Table 4.15**). The required minimum release of 24 m^3/s is ensured through even in dry years. Although a minimum capacity of 150 Mm^3 reservoir is proposed to ensure reliable water supply to the City of Dare s Salaam, the analyses using historical records in dry, wet and mixed years indicates that such a large reservoir volume is not be necessarily required given the historical inflows are reproduced in the future that will provide at least 24 m^3/s throughout the year.

Table 4.15: Summary of highest reservoir water surface elevation for different scenarios.

Spillway scenario	Highest elevation (m)	Highest volume (Mm^3)	Total reservoir outflow (m^3/s)	
			Min	Max
Water Supply Only	73.0	5.25	24.00	24.00
Uncontrolled spillway	80.874	77.56	24.00	651.14
4 flap gates opened	81.656	99.06	24.00	583.83
3 flap gate opened	82.060	111.88	24.00	555.84
2 flap gate opened	82.738	136.26	24.00	519.09
1 flap gate opened	84.116	198.66	24.00	450.00
Controlled spillway	85.637	291.56	24.00	3,608.98

5 CONCLUSIONS

The analyses have indicated that SGR will be inundated in various periods and for variable lengths in different years defined by the combinations of wetness and dryness of main seasons (Oct-Dec, Jan-Feb and MAM) of the wet period. In completely dry years, SGR will be inundated in small patches mostly between April and June/July. In wet years, continuous inundation will be observed between November and June/July although in similar patches with total area within SGR of less than 0.8 km^2 as for dry years.

Dam operations related to opening and closing of the 8 flap gates of the spillway will have significant on the inundation extents of Kidunda reservoir within SGR. Full closure of all gates to wait for releases when reservoir water level exceeds 84.5 m will result in large extent of inundation within SGR (areal extent: 5.646 km^2 corresponding to highest elevation of 85.5 m), which can significantly be lowered by opening of at least 4 gates on fulltime basis.

Inundations of SGR following implementation of the Kidunda dam project and its operations might have little impacts on surface organisms due to low inundation speeds of the order 32-52 cm a minute that can allow small organisms to flee the area being inundated. However, long inundation durations (3-8 months) that will be related to full closure of spillway gates might significantly affect vegetation that intolerable to long periods of being in or under water and which cannot flee the area. Moreover, with full closure of gates, high releases are anticipated in wet years to rapidly lower reservoir water elevation to prevent overtopping the flap gates. The release of the order of 3,000 m^3/s or more are expected that will be highly outside the range of observations and they might significantly affect downstream ecosystem well-being. This impact can be reduced by operating the reservoir up to the highest water surface altitude of 82 m or with at least 4 flap gates fully opened.

REFERENCES

de Bruin, H.A.R. (1978). A simple model for shallow lake evaporation, *J. Appl. Met*., **17**, 1132 – 1134.

de Bruin, H.A.R. and Keijman, J.Q. (1978). The Priestley-Taylor evaporation model applied to a large, shallow lake in the Netherlands, J. Appl. Met., 18, 898 – 903.

Helfer, F., Zhang, H. and Lemckert, C. (2012). Influence of bubble plumes on evaporation from non-stratified waters.

Lawrence, M.G. (2005). The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications, *Bul. Amer. Met. Soc*., **86(2)**, 225 – 233.

McKee, T.B., Doesken, N.J. and J. Kleist, (1993). The relationship of drought frequency and duration ot time scales. Eighth Conference on Applied Climatology, American Meteorological Society, Jan 17-23, 1993, Anaheim CA, pp. 179-186.

McMillan, W. (1971). Heat dispersal – Lake Trawsfynydd cooling studies. In *Symposium on freshwater biology and electrical power generation*, Leatherhead (UK), 41 – 80.

Mkhandi, S.H. (1997). Evaluation of procedures and development of statistical models for determining frequency of floods with special reference to Southern Africa, PhD Thesis, University of Dar es Salaam, Tanzania.

Mukammal, E.I. and Neumann, H.H. (1977). Application of the Priestley-Taylor evaporation model to assess the influence of soil moisture on the evaporation from a large weighing lysimeter and Class A pan, *Bound.-Layer Meteor*., **12**, 243 – 256.

Shuttleworth, W.J. (1993). Evaporation. In Maidment, D.R. (Ed). Handbook of Hydrology, McGraw-Hill (NY), 4.1 – 4.53.

Sokolov, A.A. and Chapman, T.G. (1974). Methods for water balance computations. An international guide for research and practice. Studies and Reports in Hydrology 17. The UNESCO Press (Paris), 124p.

Stewart, R.B. and Rouse, W.R. (1976). A simple method for determining the evaporation from shallow lakes and ponds, *Water Resour Res*., **12**, 623 – 628.

Studio Pietrangeli Consulting Engineers (2013a). Reservoir operation and water release study. DAWASA Kidunda Dam Project, 21p.

Studio Pietrangeli Consulting Engineers (2013b). Kidunda dam, Part 2 – Works Requirement: Vol 2 of 4 - Drawings, 108p.

Studio Pietrangeli Consulting Engineers (2013c). Dam embankment Report. DAWASA Kidunda Dam Project, 61p.

Valimba, P. (2012). Environmental Flow Assessment for Mara River Sub-basin: EF recommendations Harmonisation, LVBWB-GLOWS, 64p.