hydrology and risk
CONSULTING

RURAL AND RENEWABLE ENERGY AGENCY
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Hydrology modelling for Kaiha II HPP

Final

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Contents

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Copyright and Limitation

1. Introduction

1.1 Objective

The primary objective of this study was to develop and calibrate a rainfall-runoff model of the catchment upstream of the proposed Kaiha II hydropower plant (HPP), in the Mano River basin of Liberia. The results from the rainfall-runoff model will be used to inform the design of the HPP.

To develop a rainfall-runoff model, the Source modelling platform was used. The inputs to Source (https://ewater.org.au/products/ewater-source/) include sub-catchments delineated using GIS software, and time-series of rainfall and evaporation. An auto-calibration tool is available in Source for selecting the parameters used to simulate runoff following rainfall.

1.2 Report Structure

In this report, the development and application of the rainfall-runoff model is described in the following sections:

- **Section 2** describes the climate and streamflow data available for calibrating the rainfall-runoff model.
- **Section 3** summarises the model calibration process.
- **Section 4** contains results from the rainfall-runoff model.
- **Section 5** makes recommendations regarding potential future improvements to the rainfall-runoff model.

2. Data Preparation

Climate (i.e. rainfall and evaporation) data and streamflow records were required to calibrate and apply the rainfall-runoff model. The following sections describe where this data was sourced from.

2.1 Climate Data

2.1.1 Rainfall Data

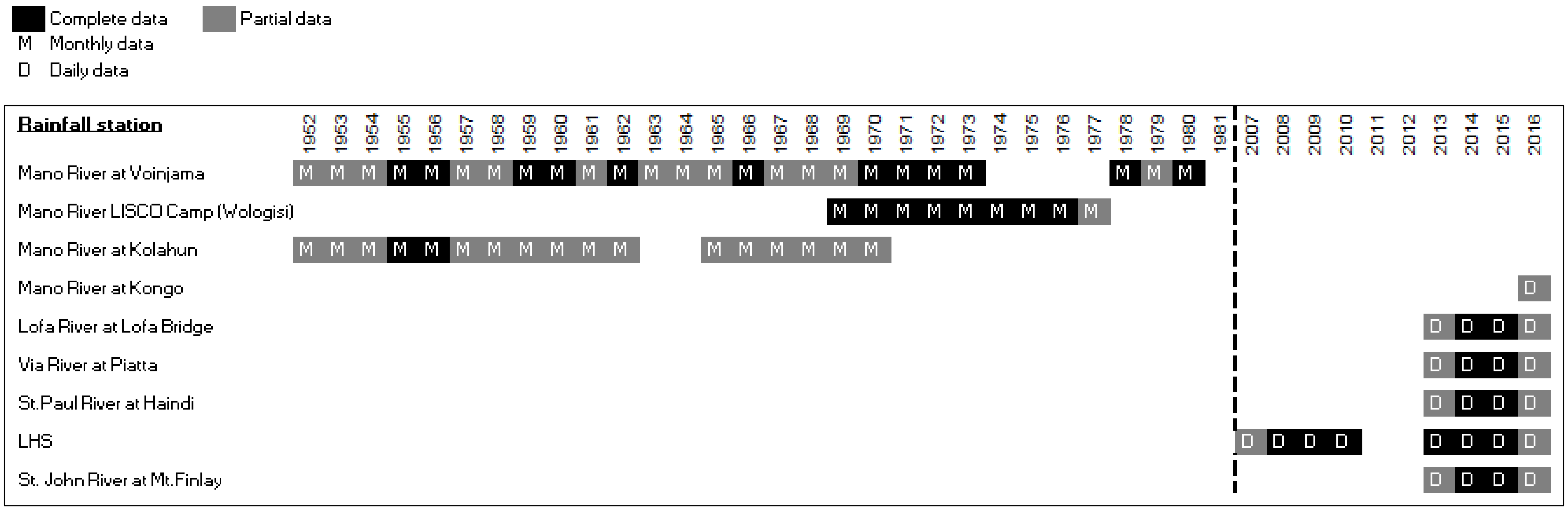
Rainfall data within Liberia is available from:

- The Liberia Historic Rainfall data book, containing monthly time-series of precipitation at gauged locations (http://lhsliberia.com/wp-content/uploads/2.-Rainfall-Data-Book-of-Liberia.pdf). The record lengths and quality vary with location, but typically begin in the 1950s and end by 1980.
- The Liberian Hydrological Services, which has published more recent daily rainfall records at 6 gauged locations (http://lhsliberia.com/rainfall-data/).

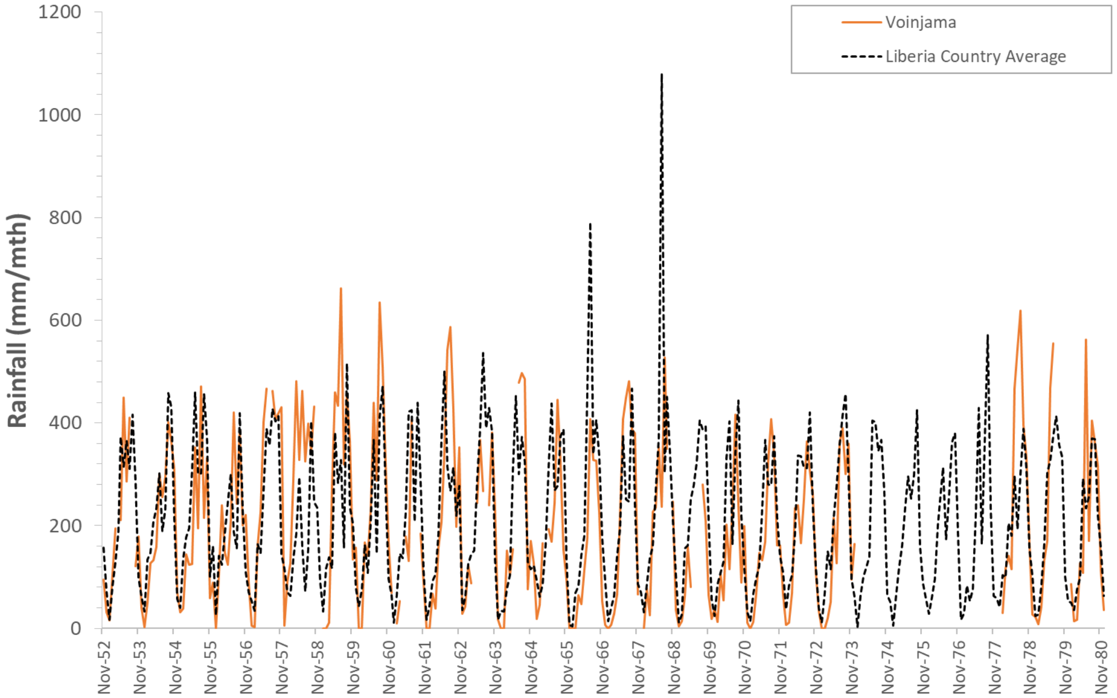
Within the vicinity of the Mano River basin, there are rainfall records available from the Liberia Historic Rainfall data book, as summarised by PMIC (2017) (Figure 2–1). The rainfall gauges for the Mano River at Voinjama and Kolahun are closest to the Kaiha II HPP; however Voinjama has a more complete dataset. Therefore in this study, the Voinjama record was the primary source of gauged data used to derive a rainfall time-series for the Kaiha II HPP catchment. The more recent data available from the Liberian Hydrological Services for the Mano River at Kongo was not used, because it is a significant distance downstream of the Kaiha II HPP.

Using only gauged data would have unduly constrained the simulation period for the rainfall-runoff model. Therefore, country-averaged estimates of historical rainfall for Liberia were also obtained on a monthly time-step from 1950 to 2015 from the World Bank Climate Change Knowledge Portal. The benefit of the data from the Knowledge Portal is that it provides a continuous time-series of rainfall for 65 years (http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=LBR). The disadvantage is the rainfall estimates are not specific to the Mano River basin.

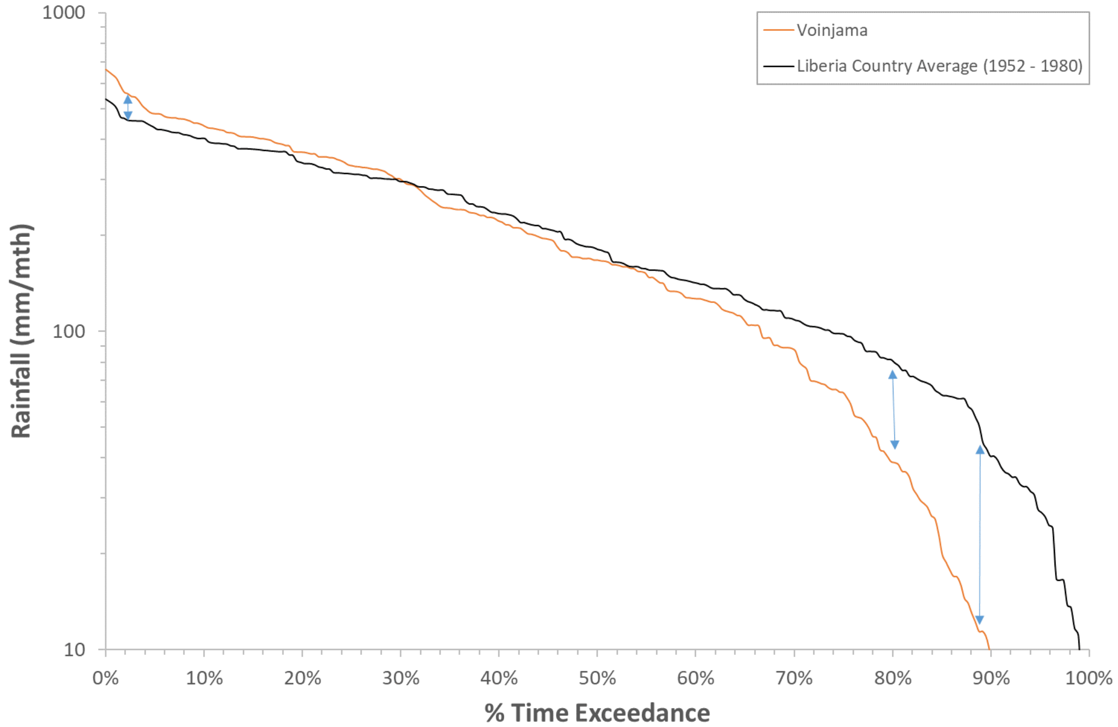
The country-averaged estimates of rainfall from 1952-1980 were compared to the rainfall recorded at Voinjama (Figure 2–2). This comparison showed that there was close correlation between the two time-series, but that the country-average tends to overestimate rainfall in the dry months and underestimate it during the wet season (with the exception of peaks in July 1966 and 1968 which were assumed to be outliers). Therefore, decile-based scaling was applied to the country average (Figure 2–3, Figure 2–4) so that it better matched the Voijama record. These scaling factors were then applied to the 1950-2015 country-average rainfall to generate a monthly time-series for use in the runoff modelling (Figure 2–5).



■ **Figure 2–1 Rainfall records available in the Mano River basin (PMIC, 2017).**



- **Figure 2–2 Estimates of country-averaged rainfall versus rainfall recorded at Voinjama.**



- **Figure 2–3 Scaling of the Liberian country-averaged rainfall series.**

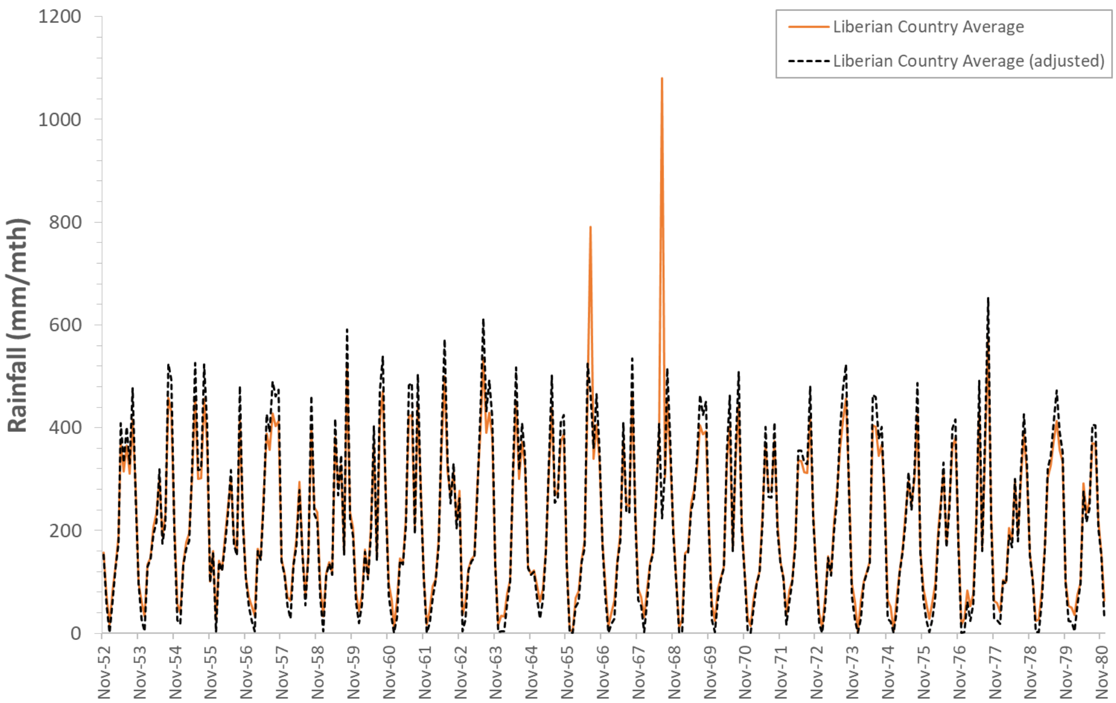


Figure 2–4 Scaling of the Liberian country-averaged rainfall series.

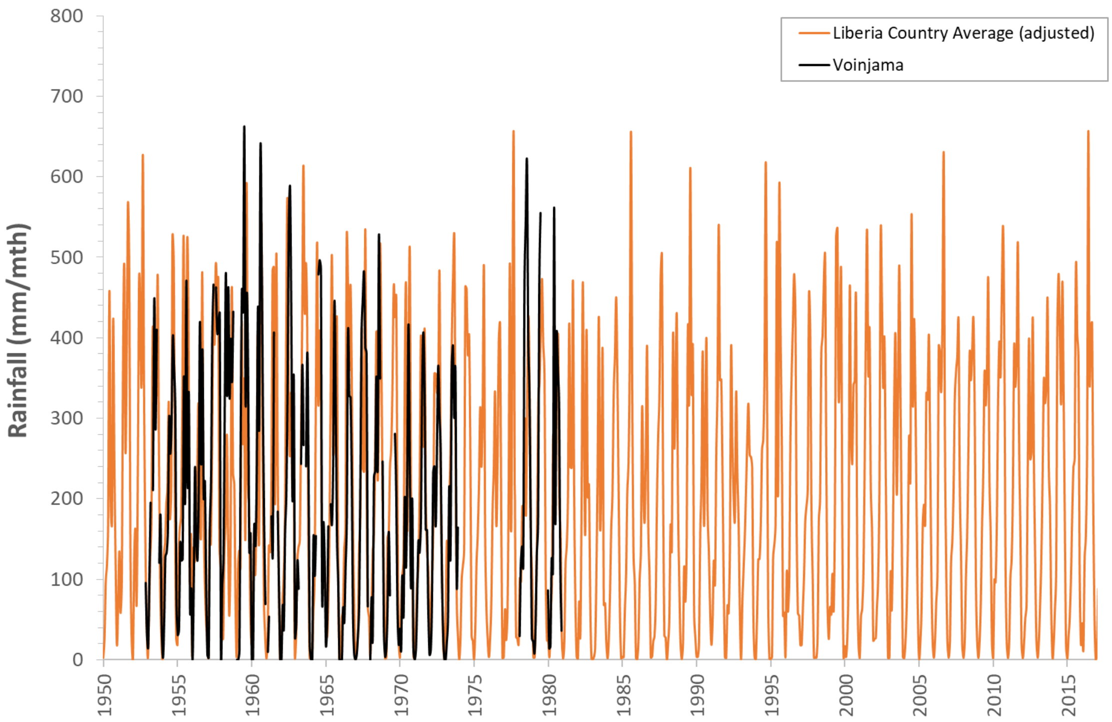


Figure 2–5 Adjusted Liberian country-average rainfall series (compared to Voinjama).

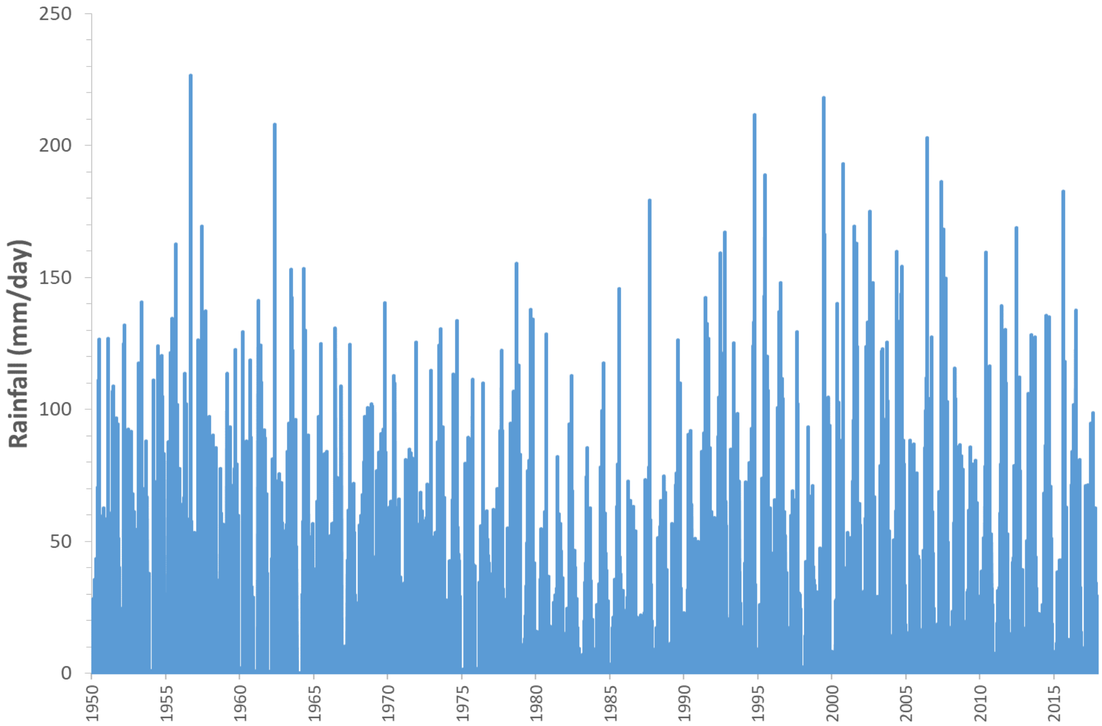
The rainfall-runoff model developed for this study was based on a daily time-step. Therefore, regional precipitation datasets were used as a pattern to disaggregate the monthly rainfall data to daily values. Specifically:

- The CPC Global Unified Precipitation dataset from Earth System Research Laboratory was used to disaggregate the data from 1979 onwards (https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globalprecip.html).
- A daily rainfall pattern extracted from the Global Historical Climatology Network at gauge IV000005528 in Odienne within neighbouring Cote D'Ivoire was used to disaggregate the monthly rainfall data from 1950 to 1979 (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn). This dataset was missing 1966, so for this year gauge IV000005539 (Ferkessedougou) was used instead.

The results are shown in Figure 2–6.

The data extracted from the CPC Global Unified Precipitation Data rainfall grids was also used to extend the adjusted time-series of country-averaged rainfall from the end of 2015 to 2017. In doing this, the CPC Global Unified Precipitation Data was factored to match the characteristics the adjusted country-averaged rainfall, using the same decile-scaling approach described on page 4.

This approach to generating estimates of daily rainfall means there is significant uncertainty associated with the time-series of rainfall used in this study (Figure 2–6). Consequently, the outputs of the rainfall-runoff model will only be suitable for use at monthly or longer time-steps.



- **Figure 2–6 Daily rainfall time-series used for the rainfall-runoff model.**

2.1.2 Evaporation Data

Estimates of monthly average potential evapotranspiration at Voinjama were sourced from the CLIMWAT database of the Food and Agriculture Organization of the United Nations (http://www.fao.org/land-water/databases-and-software/climwat-for-cropwat/en/). The estimates are based on the Penman-Monteith equation.

The average monthly estimates of potential evapotranspiration at Voinjama (Table 2–1) were disaggregated uniformly to a daily time-step for use in the rainfall-runoff model. Uniform disaggregation is acceptable, because the potential evapotranspiration is relatively constant from month-to-month and day-to-day.

- **Table 2–1 Mean monthly potential evapotranspiration for Voinjama.**

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
106.3	105.3	120.9	117.3	120.0	116.4	114.7	113.2	114.3	115.0	108.6	97.0

2.2 Streamflow Data

Table 2–2 summarises the streamflow data in the Mano River basin that was available for this study. The data is presented as monthly time-series in Figure 2–7 and Figure 2–8, and the gauge locations are shown in Figure 2–9 (Section 2.3).

- **Table 2–2 Available streamflow data.**

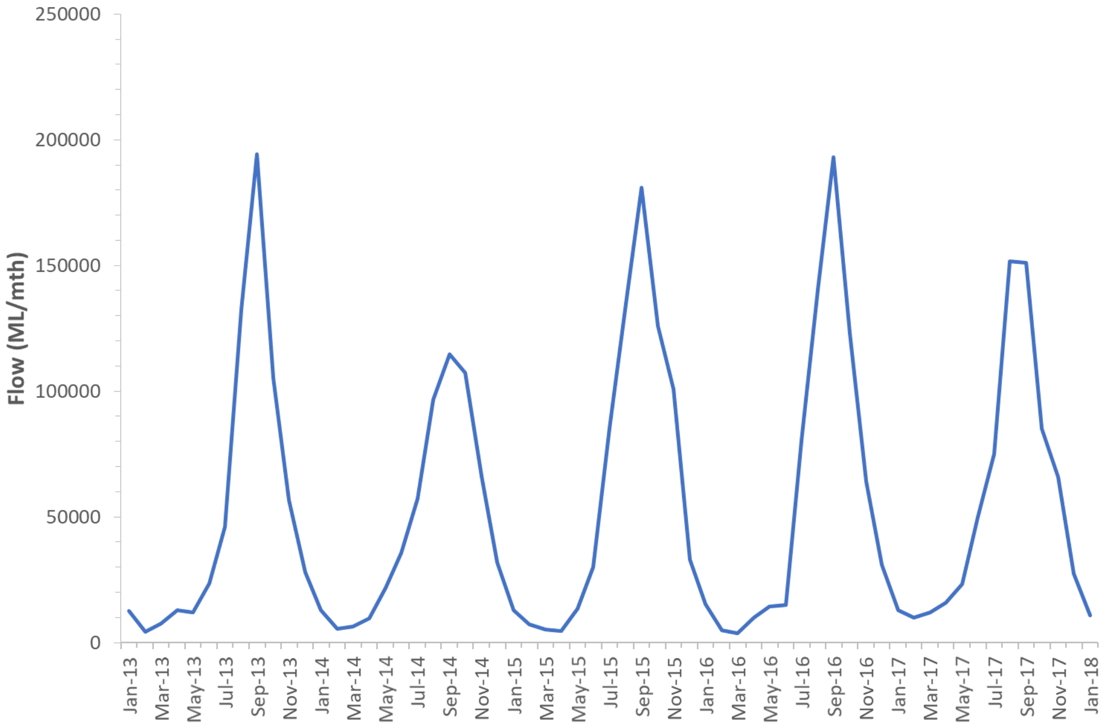
Gauge	Time-step	Period of Record
Kaiha River at Kolba	Daily	January 2013 – December 2017
Mano River at Kongo	Daily	December 2015 – December 2017

2.3 Catchment Delineation

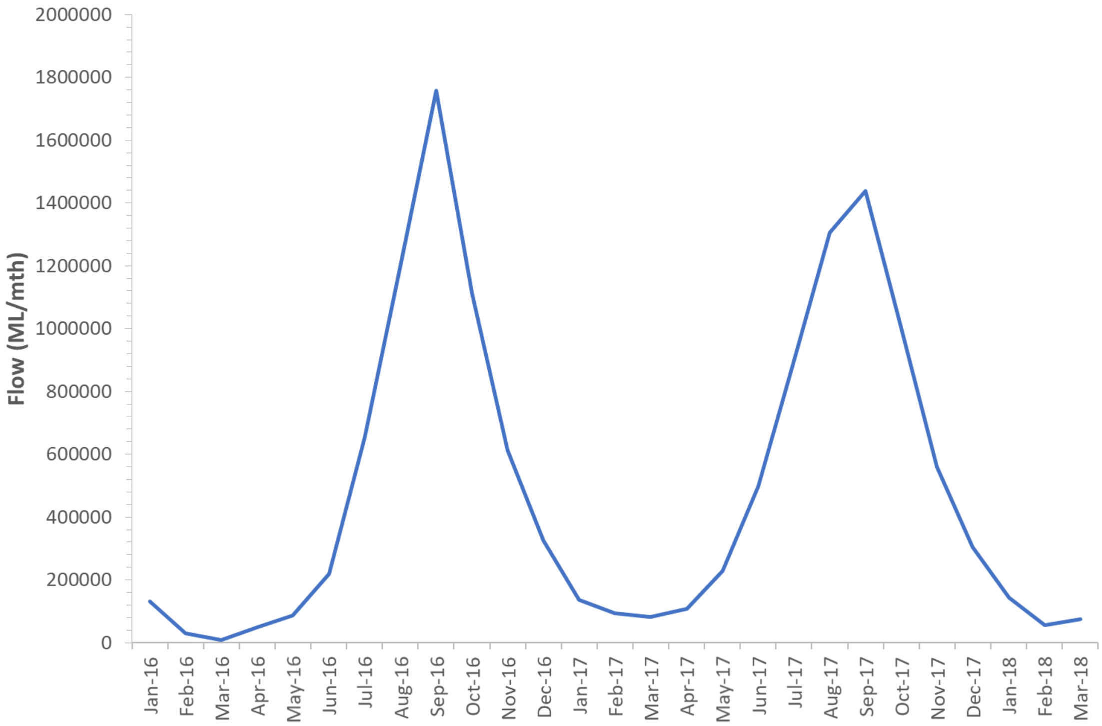
The Mano River basin was delineated into smaller sub-catchments as per Figure 2–9. The focus of the rainfall-runoff modelling was the catchment upstream of the Kaiha II HPP, and this part of the river basin is shown in Figure 2–10. The location of the Kaiha II HPP site was sourced from PMIC (2017). The sub-catchment areas are summarised in Table 2–3.

- **Table 2–3 Sub-catchment areas.**

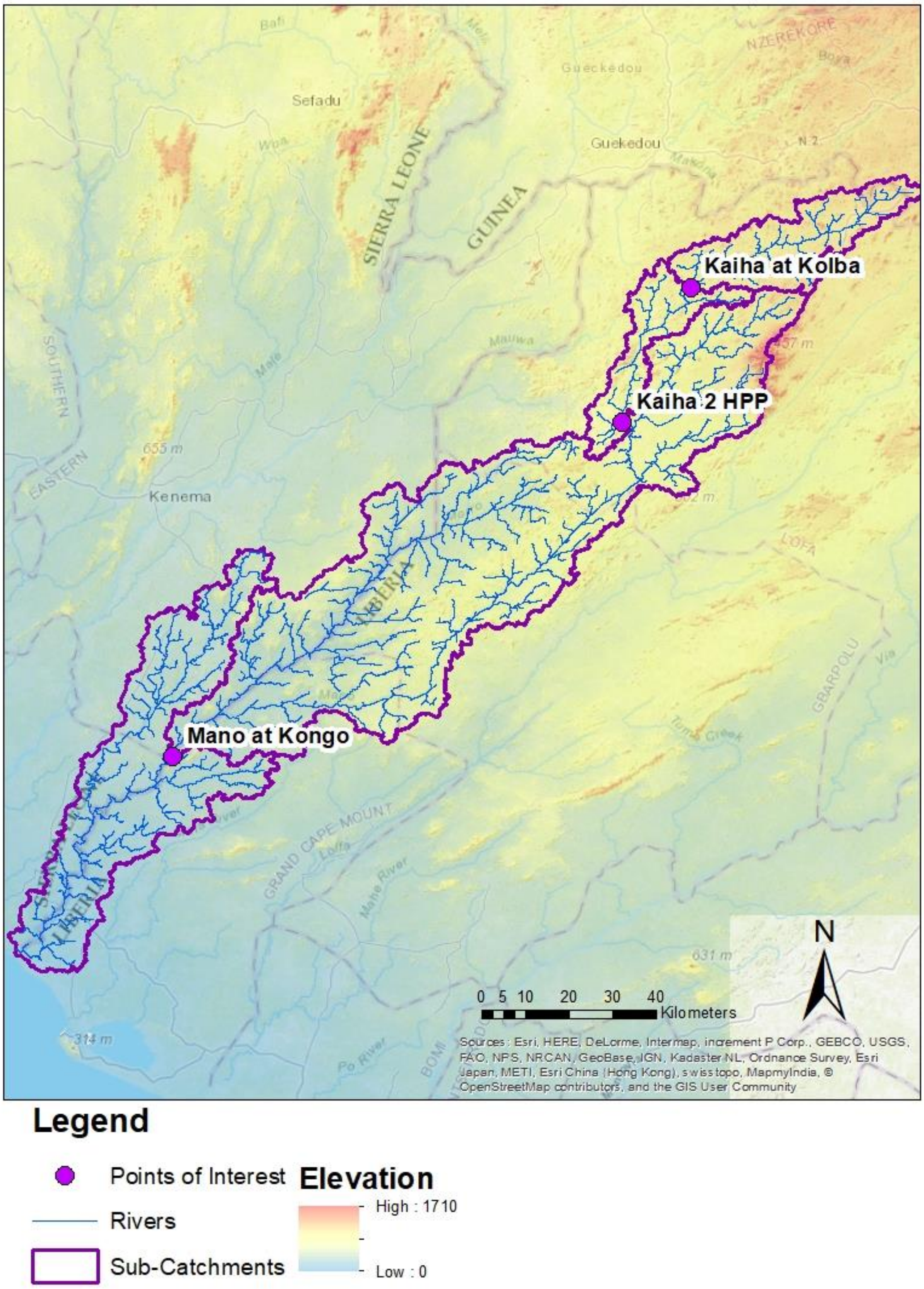
Sub-Catchment	Area (km^2)
Kaiha River upstream of Kolba	698
Kaiha River between Kolba and Kaiha II HPP	460
Mano River upstream of Kongo	4717
Mano River downstream of Kongo	1981



- **Figure 2–7 Gauged monthly flow for the Kaiha River at Kolba.**



- **Figure 2–8 Gauged monthly flow for the Mano River at Kongo.**



- **Figure 2–9 The streamflow gauge and Kaiha II HPP sites within the Mano River basin.**

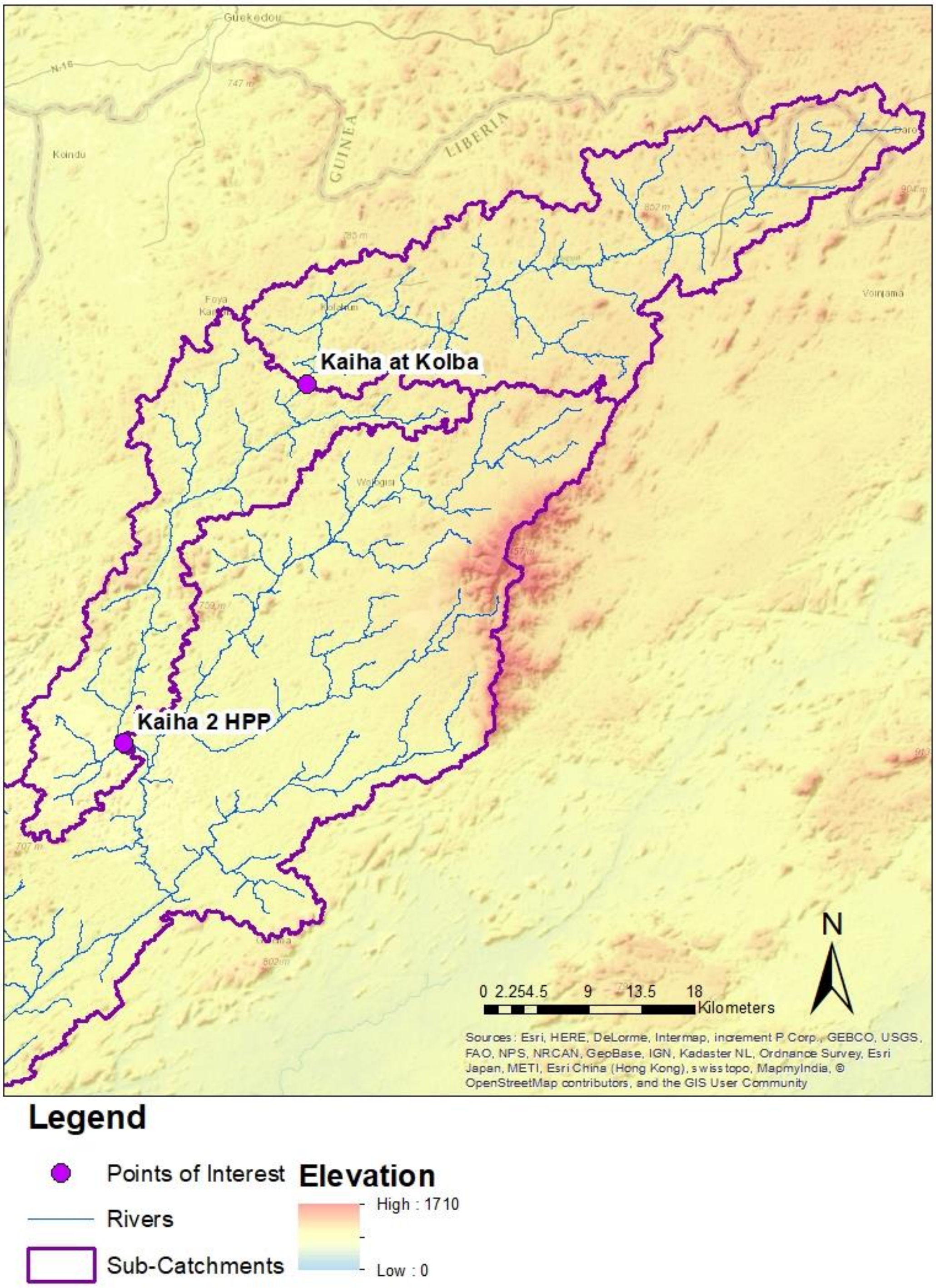


Figure 2–10 The catchment upstream of the Kaiha II HPP.

3. Rainfall-Runoff Modelling

Version 4.3.1 of the eWater Source hydrological modelling platform was used to develop a rainfall-runoff model of the Mano River basin (with a focus on the catchment of the Kaiha II HPP). The relevant elements of the rainfall-runoff model development and calibration are summarised below.

3.1 Conceptual model

Within Source, the GR4J rainfall-runoff model was chosen to simulate runoff from each sub-catchment of the Mano River basin. A schematic of the GR4J model (Perrin et al., 2003) is included in Figure 3–1. The model predicts streamflow (Q) based on rainfall (P), potential evapotranspiration (E), and the following parameters:

- Soil moisture storage capacity (x1), referred to as production store in Figure 3–1
- Groundwater exchange coefficient (x2)
- Routing storage capacity (x3)
- Duration of the unit hydrograph for surface routing (x4)

For further detail, refer to https://wiki.ewater.org.au/display/SD41/GR4J+-+SRG.

3.2 Calibration

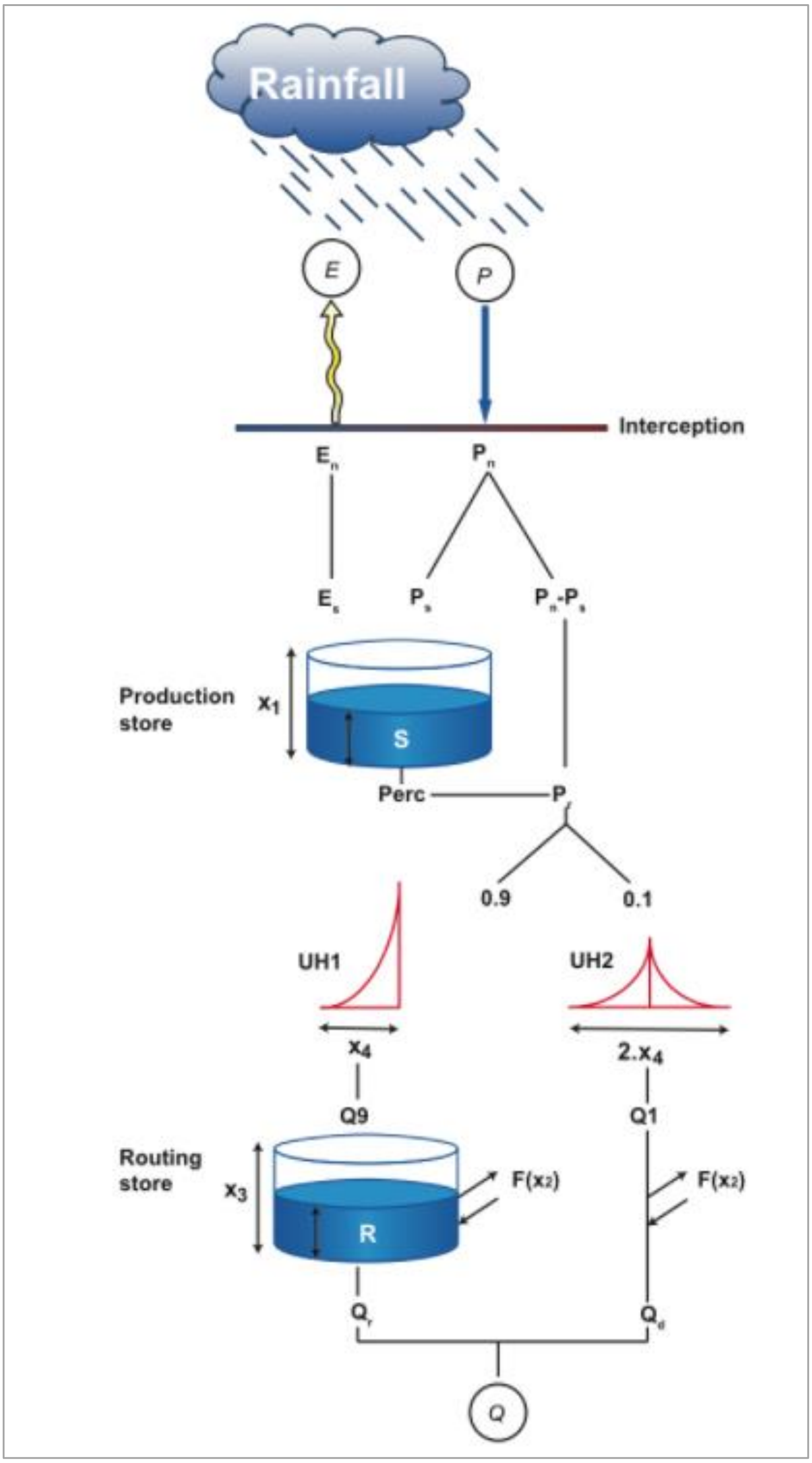
The delineation of the Mano River basin (Figure 2–9) provided two points at which the GR4J model parameters could be calibrated over varying periods, namely:

- Kaiha River at Kolba (2013-2017)
- Mano River at Kongo (2015-2017)

The Shuffled Complex Evolution (SCE) functionality within Source was initially used to automatically calibrate the GR4J model parameters for each sub-catchment moving from upstream to downstream. This was done using the default SCE parameters within Source (alpha = 3, beta = 27, P = 5, M = 27, Q = 14) and 25 shuffles (>8,000 iterations). The objective function for the calibration was Nash Sutcliffe Efficiency (NSE) with bias penalty. This was implemented on a monthly time-step, as per:

$$NSE\ Monthly\ and\ Bias\ Penalty = 1 - \frac{\sum_{i=1}^{N}\left(Q_{mod,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{N}\left(Q_{mod,i} - \overline{Q_{obs}}\right)^2} - 5|log_c(1 + |B|)|^2$$

where:
$Q_{obs,i}$ = observed flow for month *i*
$Q_{mod,i}$ = modelled flow for month *i*
N = number of months
B = total modelling error divided by total observed streamflow for the calibration period



- **Figure 3–1 A schematic of the GR4J rainfall-runoff model (Perrin et al., 2003).**

The auto-calibration approach was found to overestimate the low flows and underestimate the high flows. The routing storage parameter (x3) was therefore manually adjusted (beyond the typical range) until a better match between modelled and recorded flows was obtained. The model parameters adopted via this process are summarised in Table 3–1.

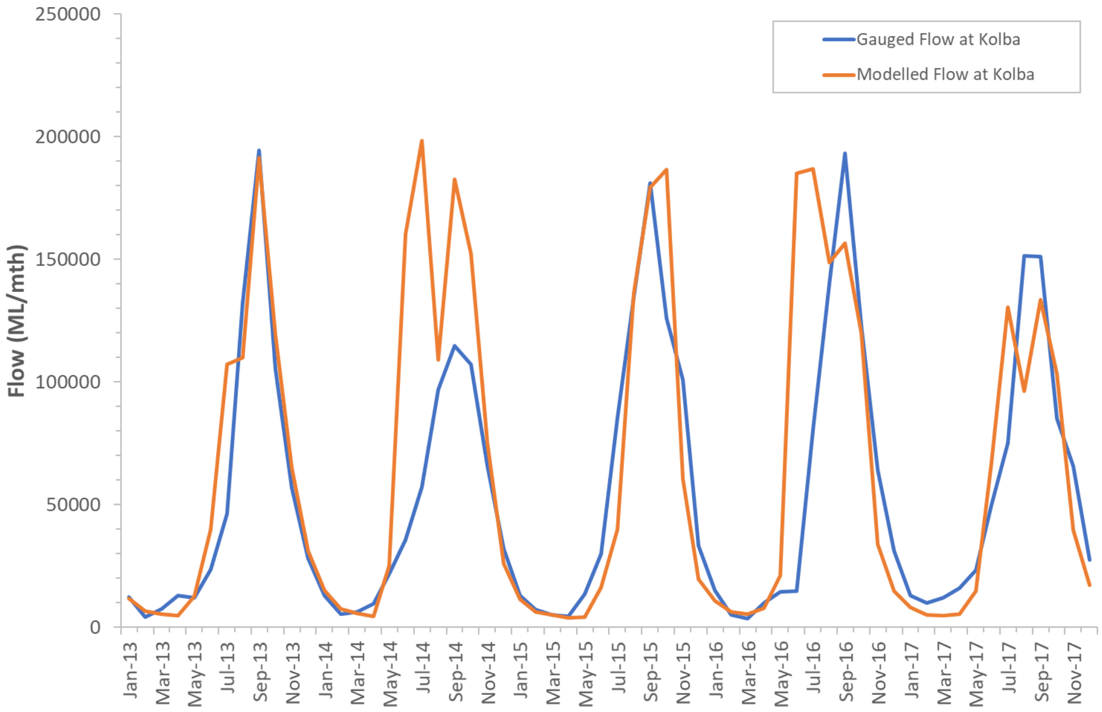
Table 3–1 Calibrated GR4J model parameters.

Sub-catchment	Model parameter			
	X1	X2	X3	X4
Typical range:	100-1200	-5-3	20-300	1.1-2.9
Kaiha River upstream of Kolba	300	-2.8	488	1.05
Between Kolba and Kongo	300	1.6	1905	1.09

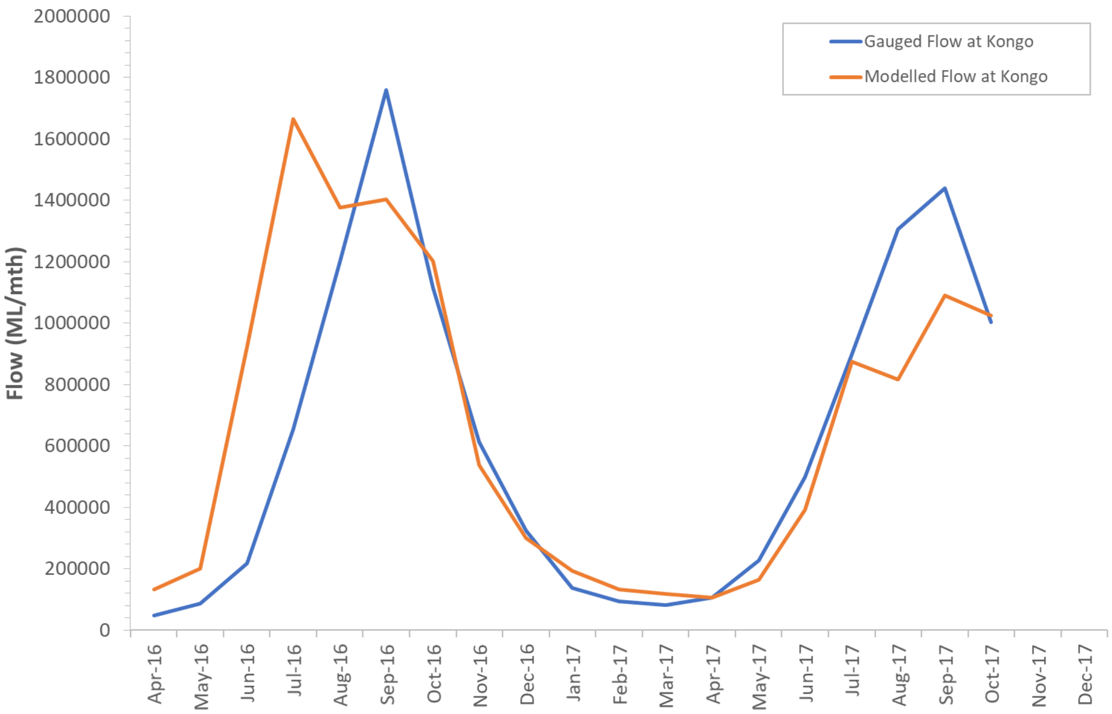
Time-series comparing the modelled and recorded streamflow at the gauged locations within the Mano River basin are shown in Figure 3–2 and Figure 3–3, and other relevant calibration statistics are summarised in Table 3–2. The calibration results are acceptable, but not excellent, and demonstrate the challenges of developing an accurate model using sparse rainfall and streamflow data.

Table 3–2 Statistics for the rainfall-runoff model calibration.

Statistics	Kaiha River at Kolba	Mano River at Kongo
Period of record	2013 - 2017	2015 - 2017
Number of months	60	21
Coefficient of determination (R^2)	0.61	0.66
Monthly NSE	0.60	0.59
Average recorded flow (ML/month)	662,468	7,271,286
Average monthly flow (ML/month)	772,305	7,784,336
Difference (%)	17%	7%



■ **Figure 3–2 Modelled versus recorded streamflow in the Kaiha River at Kolba.**

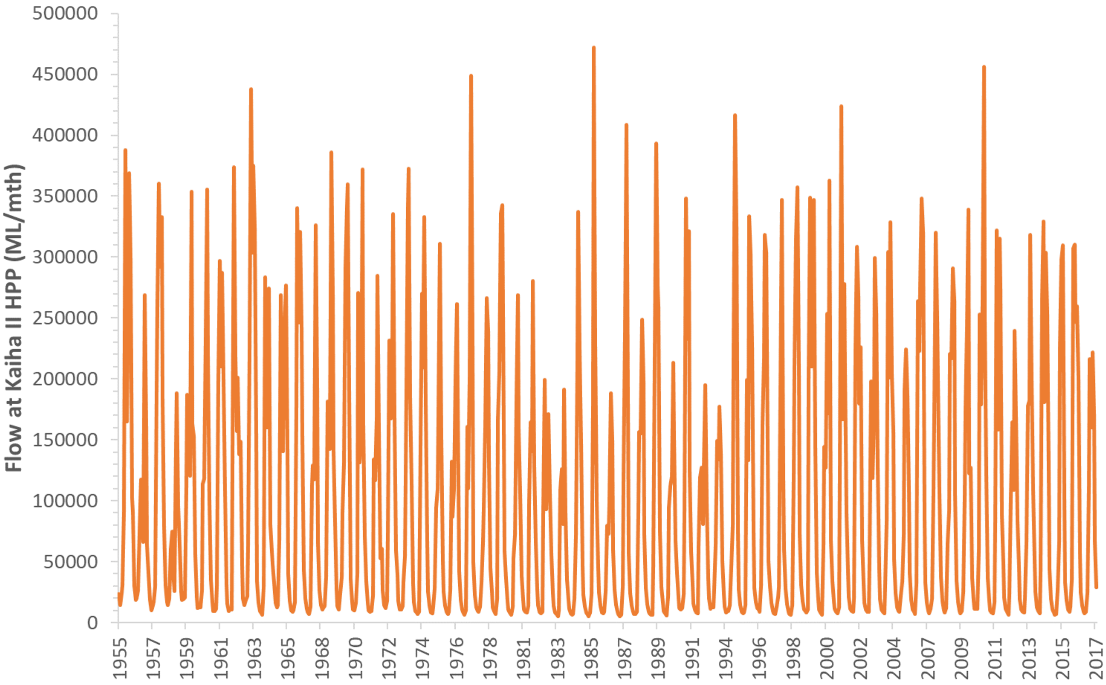


■ **Figure 3–3 Modelled versus recorded streamflow in the Mano River at Kongo.**

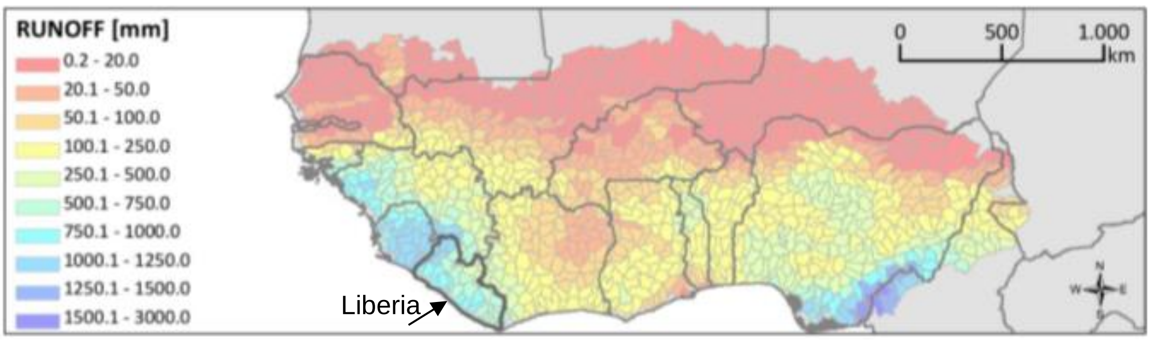
4. Results

The calibrated rainfall-runoff model was run from 1950-2017, and a time-series of monthly streamflow was extracted at the Kaiha II HPP location from 1955-2017 (the first five years of the simulation were treated as a model warm-up period). The results are summarised in Figure 4–1. The mean annual flow simulated for 1955-2017 was approximately 1,200,000 ML (1,200 Mm^3).

As a final check of the model outcomes, the mean annual flow was converted to runoff in mm (based on a catchment area of 1,158 km^2) and compared with ECOWAS (2017) predictions of runoff in Liberia (Figure 4–2). This comparison showed a reasonable match between the datasets. ECOWAS (2017) estimated average runoff from the Mano River basin to be 1,000 – 1,500 mm per year, and the average annual runoff modelled for the Kaiha II HPP site was 1,100 mm.



- **Figure 4–1 Final modelled time-series of streamflow at Kaiha II HPP.**



- **Figure 4–2 Estimates of mean annual runoff, as published by ECOWAS (2017).**

5. Recommendations

For this study, the rainfall-runoff modelling has used historic climate and streamflow data. No attempt has been made to simulate the expected future changes attributable to climate change. This could be done in future as needed. However, it is worth noting that ECOWAS (2017) have recently investigated the likely impacts of climate change on runoff from Liberan rivers, and found that when *the median result of 30 climate model runs is considered then discharge is expected to increase by 5% to 10% in the far future* (i.e. for the periods 2026-2045 and 2046-2062 compared with 1998-2014).

The development of a rainfall-runoff model for the Mano River basin has made good use of the available data. However, because the rainfall inputs were disaggregated from monthly totals, and the objective function was implemented on a monthly time-step, the outputs can only be used on a monthly basis.

The rainfall-runoff model for the Mano River basin could be improved in future by calibrating and applying it on a daily time-step. This would increase its potential use (e.g. for the modelling and management of environmental flows if the river becomes more regulated). However, the ability to develop a daily rainfall-runoff model, either upstream of the Kaiha II HPP or for the Mano River basin in general, will be limited until there is longer periods of gauged rainfall and streamflow in more locations.

The major recommendation of this study therefore, is for additional rainfall and streamflow gauges to be implemented within the Mano River basin (including at the Kaiha II HPP). Once stable flow rating curves, and reasonable periods of daily streamflow and concurrent local rainfall data are available at other locations, the calibration of the rainfall-runoff model should be revisited. The potential future availability of additional daily streamflow and rainfall data was the primary reason why the GR4J rainfall-runoff model was chosen for simulating runoff in the Mano River basin. The GR family of models does contain a monthly version (GR2M) which could have been adopted for this study. However, establishing a monthly model may have constrained the potential for the model’s future improvement as additional daily data is collated.

6. References

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Perrin, C., Michel, C., Andréassian, V. (2003), Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology*, 279 (1-4), 275-289.

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