



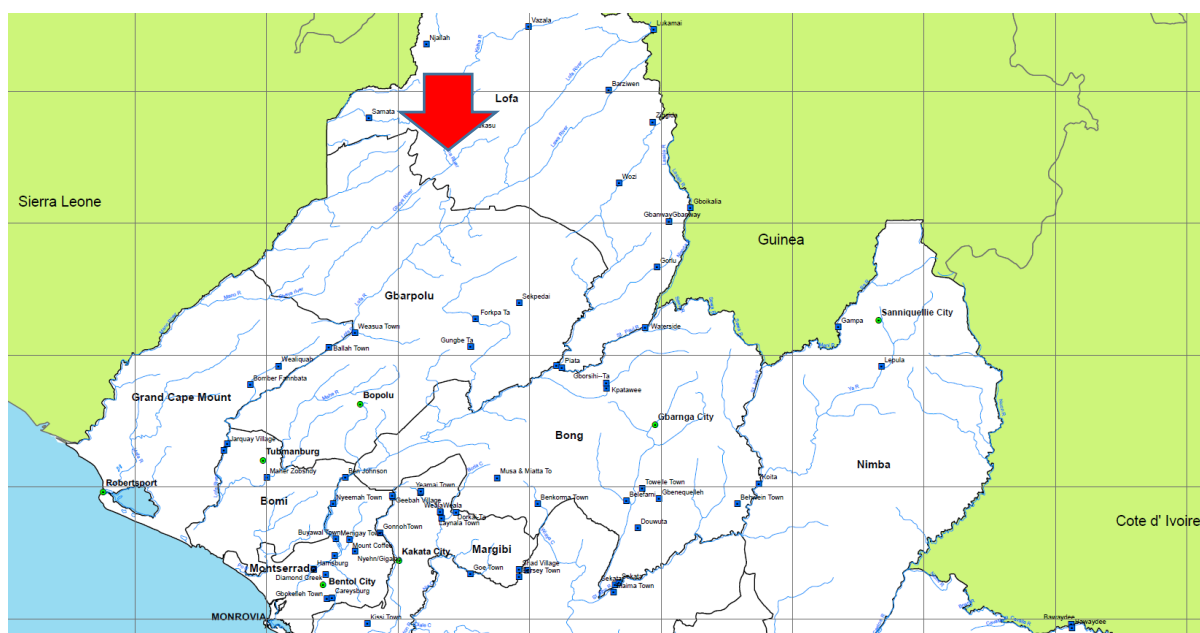
Rural and Renewable Energy Agency (RREA)



# Small hydropower plant Kaiha 2, Liberia

## Review of Hydrology & Hydraulic Works

### FINAL REPORT



1701/2003a

31.10.2017

| Date       | Contents                                                                                                                            | Prepared by: |
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## List of Acronyms /Abbreviations

|         |                                                        |
|---------|--------------------------------------------------------|
| ECOWAS: | Economic Community of West African States              |
| ESIA:   | Environmental and Social Impact Assessment             |
| EPC:    | Engineering Procurement & Construction                 |
| ESMP:   | Environmental and Social Management Plan               |
| GOL:    | Government of Liberia                                  |
| IFI     | International Funding Institutions (e.g. World Bank)   |
| LHS     | Liberian Hydrological Service                          |
| LEC:    | Liberia Electricity Corporation                        |
| MLME:   | Ministry of Lands, Mines and Energy                    |
| RREA:   | Rural and Renewable Energy Agency                      |
| TOR:    | Terms of Reference                                     |
| UNCED:  | United Nations Conference on Environment & Development |
| UNMIL:  | United Nations Mission in Liberia                      |
| USAID:  | United States Agency for International Development     |
| WAPP:   | West African Power Pool                                |

## 1 INTRODUCTION

|                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Project background    | The Kahia 2 project in the Mano River in Liberia is being developed by RREA. At present a prefeasibility study is available, as well as some preliminary investigations on site topography, catchment hydrology and catchment sedimentology. Project development is supported by the World Bank.                                                                                                                                                                 |
| Report contents       | <p>This report presents a collection of review activities and associated studies aiming at fulfilling the following scope of works:</p> <ol style="list-style-type: none"><li>1. Desk review of background hydrological data and studies</li><li>2. Design review of available studies for all hydraulic structures</li><li>3. Design review of the (diversion weir) control gates</li><li>4. Propose an action plan for hydrological data collection.</li></ol> |
| Contractual framework | The contract signature took place in May 2017 with RREA. RREA's project coordinator is Ms. Eunice Dahn.                                                                                                                                                                                                                                                                                                                                                          |

## 2 RECEIVED DOCUMENTS

|          |                                                                                                                                                                                                                                                        |
|----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Register | Appendix 1 presents the full list of received documents.                                                                                                                                                                                               |
| Remarks  | The set of documents received exceeds the contractual list of items. The additional information is included in the review process as much as possible considering the priorities defined by RREA in the scope of services and the updated methodology. |

## 3 SCOPE OF SERVICES

|                                         |                                                                                                                                                                                                                                                                                                                                                                 |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Interpretation of the scope of services | The scope of services set in the contract is in general clear. Additional clarifications were obtained during the mission to Liberia in August 2017 (see Mission Report in Appendix 2).                                                                                                                                                                         |
| Proposed changes and amendments         | The amount of hydrological data received positively exceeds previous estimates done at the offer and negotiation stages. This allows providing in this report recommendations for future studies with a sound overview of what is available and what should still be acquired/measured. Additional studies are out of the scope of the present review contract. |

## 4 MISSION

|          |                                                                                                                                                                                                                                       |
|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Contents | A four-day mission to Liberia was held during the last week of August. The journal of activities as well as detailed records of all the meetings and field visits are included in the mission report, herein presented as Appendix 2. |
|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

## 5 REVIEW OF THE HYDROLOGICAL DATABASE

### 5.1 Introduction

**Scope** This task aims at reviewing the quantitative assessment carried out in available studies with regards to (1) the availability of water resources for energy production and (2) the frequency and magnitude of extreme flood events pertinent for safe design of all infrastructure of the SHP Kaiha 2.

### 5.2 Methodology

**Methods** This activity comprises the following sub tasks:

- Inventory of available data (see Figure 2 and Figure 2);
- Desk study, including collection of additional data (LHS website, literature);
- Interviews during site mission (see Appendix 2);
- Inspection of LHS equipment and storage room;
- Inspection of LHS data collection procedures during field trip;
- Follow-up activities for double-check and cross-referencing.

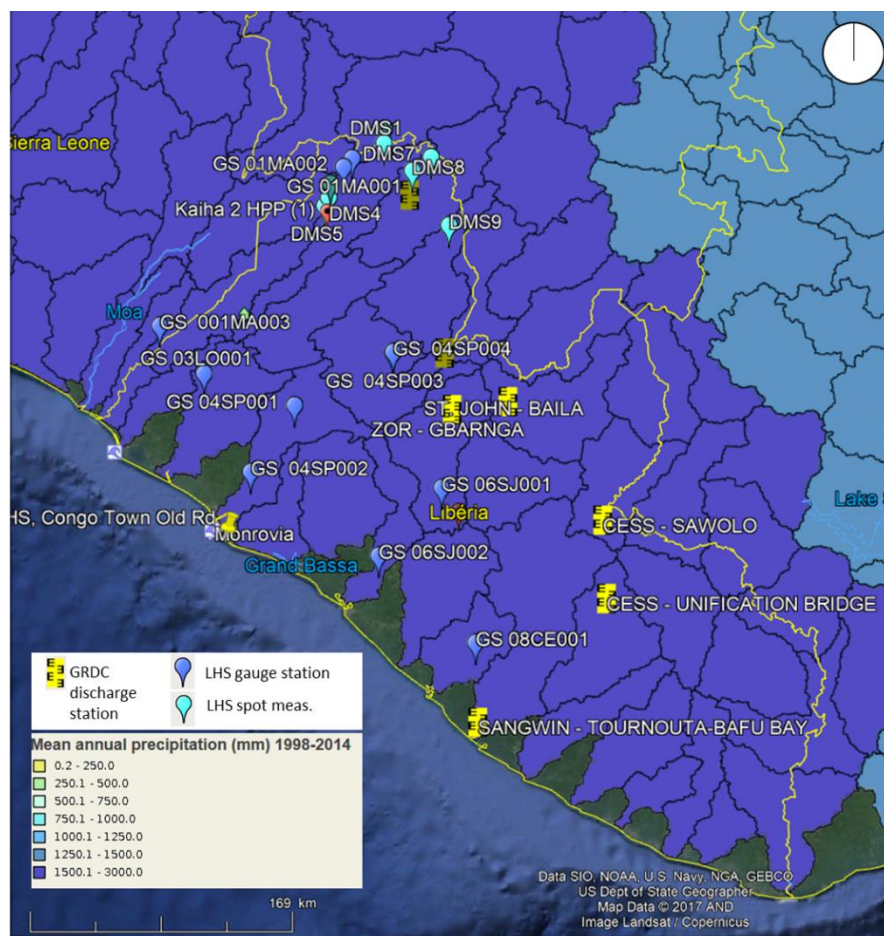


Figure 1 – Summary plot of the location of available streamflow gauging station or spot discharge measurements (from LHS) and historical runoff data records available at the General Runoff Data centre. [image and base plot produced using Google Earth]. Mean annual precipitation data from ECREE-ECOWAS (2016).

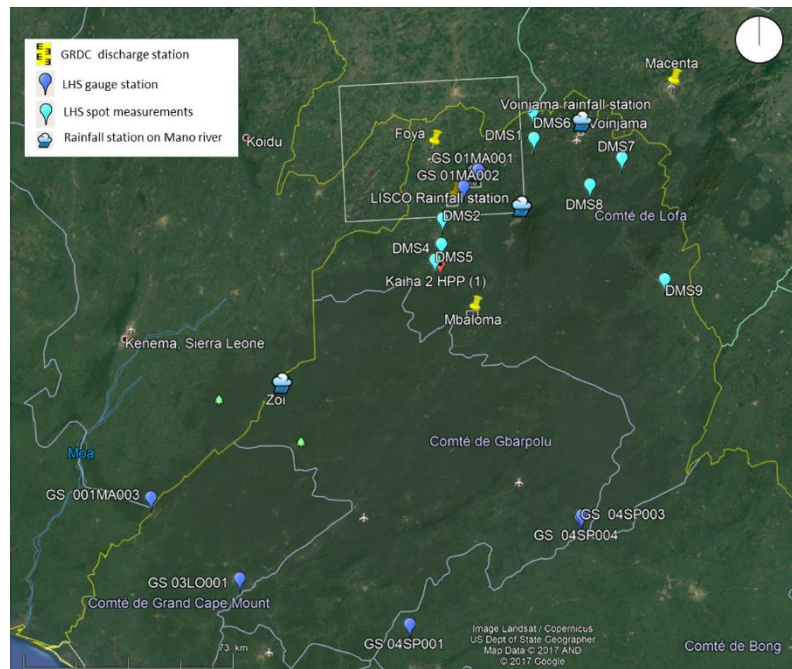


Figure 2 – Summary plot of the location of available rainfall stations (from LHS), streamflow gauging station or spot discharge measurements (also from LHS) and historical runoff data records available at the General Runoff Data centre. [image and base plot produced using Google Earth].

#### Streamflow data

Streamflow is one of the two main resources used in hydropower, along with hydraulic head. There are two gauging stations on Kaiha River both upstream of the Kaiha 2 HPP site. There are available hydrological data and gap analysis from 2013 to present date (MTC 2015).

LHS personnel obtains daily reading of water levels. Periodically LHS carries out velocity measurements at multiple river transects for river discharge estimation. The velocity profiles are obtained using an ADCP (acoustic doubling current meter and profile) installed in a raft. The simultaneous water level readings and discharge estimates are used to develop a rating curve for a specific river section and a flow duration curve with the use of a software called AQUARIUS.

#### Rainfall data

The main source of historical rainfall data available is the “Rainfall data book of Liberia”, available publicly from LHS website. For the Mano River basin several rainfall stations were found with data ranging from the 1950’s until 1980 the latest.

The only stations with data after 1980 is said to be the one in Foya, for which no data was found.

During one preliminary skype meeting Mr. Kennedy from LHS said that the Liberian Hydrological Service has established a rain gauge at the project site (Kaiha 2 River) to collect rainfall information. The location could not be confirmed during the mission.

Data from new rain gauge stations installed since 2012 is available at daily time steps from the LHS website. Unfortunately none of these stations is located in the Mano River catchment or even close. The longest (modern) rainfall records available are those for Haindii in the Saint Paul River catchment (see below).

During follow-up exchanges after the mission, the LHS indicated that one rainfall stations was being installed (late October/early November) at Walker Bridge, Beyan Town, Lofa County (River St. Paul catchment).

A summary of the most pertinent data available is presented in Appendix 4.

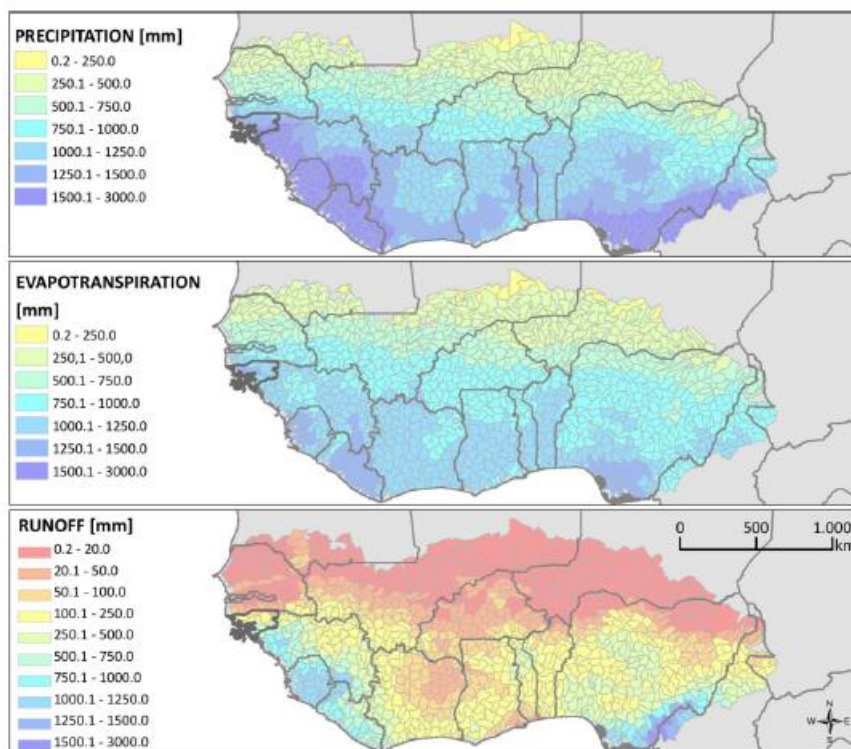


Figure 3 – Overview of annual precipitation, evapotranspiration and runoff for the ECOWAS region obtained from large-scale water balance studies [source: ECREE-ECOWAS (2016) GIS Hydropower Resource Mapping and Climate Change Scenarios for the ECOWAS region, Country Report for Liberia, <http://www.ecowrex.org/document/liberia-country-report-gis-hydropower-resource-mapping-and-climate-change-scenarios-ecowas>]

**Evaporation & Evapotranspiration** The LHS confirmed that no measurements have been done in Liberia. Data from neighbouring countries is not available in Liberia.

Based on available literature<sup>1</sup> and analogous reservoirs in the regions (Ivory Coast, Guinea-Conakry) we recommend assuming an average value of 100 mm/month for evaporation from the Kaiha 2 reservoir until detailed studies are carried out.

Recent large scale water cycle balance studies based on a thorough use of available satellite data indicate evapotranspiration rates between 750 and 1250 mm/year for most of the Mano River basin, in particular for the Lofa County (Figure 3). Such large scale analysis have the merit of allowing an overview of the water cycle at a regional scale and within an annual time frame, but have limited interest for specific locations and projects for which data obtained from the ground is more suitable.

Based on the above review of available literature, we recommend assuming at this stage, that 50% of the annual rainfall over the Kaiha 2 catchment area becomes

<sup>1</sup> For instance, J.P. Brunel - B. Bouron (1992) « *Evaporation des nappes d'eau libre en Afrique Sahélienne et tropicale* », ORSTOM.

runoff and the remainder 50% evaporate/transpires. This provides a practical order of magnitude of the water cycle at the annual time scale.

Haindi

The LHS confirmed having one (1) manual rainfall station, two (2) automatic water level stations, and one (1) manual water level station. The table below summarises the characteristics of the equipment and the corresponding acquisition periods.

| No. | Stations Description                                                                                                     | Date Installed    | By Whom                                                       |
|-----|--------------------------------------------------------------------------------------------------------------------------|-------------------|---------------------------------------------------------------|
| 1   | Station Type: Water Level<br>Observation Time: 08:00 AM and 18:00 PM<br>Equipment Type: Staff Gauge graduated in cm      | March 8, 2012     | LHS Staff and Project Advisor                                 |
| 2   | Station Type: Rainfall<br>Observation Time: 08:00 AM<br>Equipment Type: NOVALYNX                                         | December 13, 2012 | LHS Staff                                                     |
| 3   | Station Type: Water Level<br>Observation Time: Every one hour<br>Equipment Type: OTT Opheus Mini data logger             | February 21, 2014 | LHS Staff and NVE Staff                                       |
| 4   | Station Type: Water Level<br>Observation Time: Every one hour<br>Equipment Type: Sutron Satellite Telemetry & Datalogger | February 27, 2017 | LHS Staff and NVE Staff by request from Mount Coffee project. |

### 5.3 Results

Rating curves

There is no gauging station at the project site. The flow duration curve (FDC) for the project is presently transposed from the Kolahun station located upstream.

The procedure followed by LHS to obtain the rating curves is robust. Selection of the staff gage location is arguable. It may silt up and show no reading of low flows, if no river channelling and/or maintenance is done.

On water availability for energy production

The work presented by Multiconsult ((hereafter “MTC”, 2016) is in general sound and raises a few preliminary remarks:

- The assessment of the geology of the catchment area’s role on surface water retention and delayed supply to the river network is yet unclear. It may play an important role in the scale up of hydrological properties (specific discharge in l/s/km<sup>2</sup>, discharge time series) from Kolahun to Kaiha2 river sections.
- The procedure to build a 3-year daily discharge time series at Kaiha 2 is robust, although its presentation lacks important details necessary to assess its representativeness and accuracy. It anyway merits updating in subsequent design stages, as more data becomes available.
- The reasons for discarding the Sambahun gauging station are unclear and merit clarification of the doubts on the rating curve.
- There is little information of available rainfall data.

Insofar, the reviewed documents do not include any specific analysis on droughts and/or on the expected impacts (positive or negative) of climate change.

Catchment morphology

The Kaiha creek catchment is compared with neighbouring ones in Table 1, based on available hypsometric curves available at LHS website. The Kaiha 2 catchment is clearly smaller and with a higher average elevation. Another specific geomorphic feature is the low shape factor, typical of an elongated catchment, with specific impact of the catchment response to extreme rainfall events and flood generation.

**Rainfall data review** Rainfall data is presented in Appendixes 3 and 4. Available monthly rainfall at three stations was collected and reviewed. There are few periods with simultaneous recordings in at least two stations, allowing cross-check (i.e. double-mass plots, see Appendix 4).

The Voinjama station can be considered quite representative of the catchment area given its altitude, closer to the mass centre of the catchment. Kolahun is located at lower altitude and show slightly low cumulated rainfall. This is somewhat expected with regards to altitude but counter-intuitive with regards to the overall isohyet patterns in Westerns Liberia (i.e. with higher average annual rainfall closer to the Atlantic Coast).

Data from different stations are fairly well correlated (Appendix 4) and could be combined to define rainfall scenarios for specific events using the specific weight obtained using the Thiessen Polygon analysis (Appendix 4).

In terms of quantity of rainfall per year, or per months, no up/down-wise is evident, with direct implication in securing the yearly/monthly water balance values which have been presented by MTC.

In terms of extreme rainfall events, the available records are fairly short but allow some conclusions:

- 1) Monthly cumulated rainfall of up to 800 mm has been recorded at Lisco camp. Should this be consistently applied over the catchment of Kaiha 2 in extreme conditions of wet soil and high humidity (i.e. no or little infiltration, no or little evapotranspiration), one would expect a flood volume of approx. 900 hm<sup>3</sup>. Assuming a simple triangular hydrograph shape, one obtains an estimated peak discharge of 696 m<sup>3</sup>/s, clearly higher than the value proposed so far by MTC.
- 2) For the wettest month (and neighbouring) minimum monthly rainfall can be three times the maximum monthly rainfall. Despite important, this variability is not as high as it can be observed in the Sahel region further North. The lower inter-annual variability is a positive indicator for run-of-the-river hydropower production over the years and should be confirmed by compiling longer hydrological records.

Future studies should look at the relationship between altitude and location closely, especially for extreme rainfall events leading to extreme floods.

*Table 1 – River basin characteristics in the region of Kahia 2 project*

| Country                       | River          | River basin outlet | Elevation | Gravity center | Catchment surface  | River length | Shape factor        |
|-------------------------------|----------------|--------------------|-----------|----------------|--------------------|--------------|---------------------|
|                               |                |                    | [masl]    | [masl]         | [km <sup>2</sup> ] | [ km]        | [S/L <sup>2</sup> ] |
| Liberia, Sierra Leone, Guinea | Moa River      | Ocean              |           | 410            | 19617              |              |                     |
| Liberia, Sierra Leone, Guinea | Mano River     | Ocean              |           | 310            | 7520               |              |                     |
| Liberia, Guinea               | Lofa River     | Ocean              |           | 375            | 10612              |              |                     |
| Liberia, Guinea               | St. Paul River | Ocean              |           | 410            | 20281              |              |                     |
| Liberia, Guinea               | St. John River | Ocean              |           | 260            | 16930              |              |                     |
| Liberia, Guinea, Ivory Coast  | Cestos River   | Ocean              |           | 240            | 12709              |              |                     |
| Liberia                       | Mano River     | Kahia 2 site       | 440       | ~550           | 1129               | 100          | 0.11                |

**Streamflow gauging stations** Streamflow data in Liberia is only available since few years, following capacity building of LHS since approximately 2010. The longest record available are of approximately 5 years for Haindi station in River St. Paul. Several watersheds are being monitored but staff gauges (water levels) and discharge estimates (via integration of velocity profiles) are mainly available in the lower reaches of the main rivers, closer to the coast.

Kolahun station is one of the farthest from the Monrovia and also at higher altitude (El. 480 masl). Also, the Kahia River catchment defined at the Kahia 2 site cannot directly compare with most of the catchments being permanently followed by LHS (see Table 1). It is much smaller and has a mass centre at higher latitude. However, its shape factor is similar to several larger catchments in the region which may allow for future analogies in terms of catchment response to extreme rainfall events and flood generation.

*Table 2 – Specific discharge for flood events analysis (based on maximum daily flows measured/estimated) and for available water resources analysis (based on mean annual runoff or mean flow). Data from LHS database. Assumptions are shown in green cells.*

| Basin          | Station Location        | Name     | Elevation  | Catchment surface  | Discharge recorded period |   | Mean Annual Runoff |                                   |       | Maximum daily flow |       |       | Mean measured daily flow |    |       |
|----------------|-------------------------|----------|------------|--------------------|---------------------------|---|--------------------|-----------------------------------|-------|--------------------|-------|-------|--------------------------|----|-------|
|                |                         |          | [masl]     | [km <sup>2</sup> ] |                           |   |                    |                                   |       |                    |       |       |                          |    |       |
| St. Paul River | Haindi                  | 04SP001  | 130        | 18276              | 2012-2016                 | 5 | 763                | 24                                | 0.024 | 2200               | 120   | 0.120 | 442                      | 24 | 0.024 |
| St. John River | Frank Diggs             | 06SJ001  | 170        | 10862              | 2013-2016                 | 4 | 673                | 21                                | 0.021 | 1041               | 96    | 0.096 | 232                      | 21 | 0.021 |
| St. John River | Mt. Finlay              | 06SJ003  | 65         | 15723              | 2013-2014                 | 4 | 702                | 22                                | 0.022 | 1640               | 104   | 0.104 | 350                      | 22 | 0.022 |
| Cestos River   | Iti                     | 08CE001  | 170        | 11585              | 2013-2015                 | 3 | 673                | 21                                | 0.021 | 1041               | 90    | 0.090 | 232                      | 20 | 0.020 |
| Lofa River     | Lofa Bridge             | 03LO001  | 85         | 8194               | 2012-2016                 | 5 | 947                | 30                                | 0.030 | 1401               | 171   | 0.171 | 246                      | 30 | 0.030 |
| Mano River     | Kaiha River at Kolahun  | 01MA001  | 478        | 673                | 2013-2016                 | 4 | 637                | 20.1991375                        | 0.020 | 152.22             | 226   | 0.226 | 20.21                    | 30 | 0.030 |
| Mano River     | Kaiha River at Sambahun | 01MA002  | 464        | 731                | 2013-2016                 | 4 |                    |                                   |       |                    |       |       |                          |    |       |
| Mano River     | Kaiha2                  | dam site | 440        | 1129               |                           |   |                    | Hypothesis MTC (2016) =>          |       |                    | 450   | 399   | 0.399                    |    |       |
| Mano River     | Kaiha2                  | dam site | 440        | 1129               |                           |   |                    | Hypothesis 800 mm event =>        |       |                    | 696   | 616   | 0.616                    |    |       |
| Mano River     | Kongo                   | 001MA003 | 87         | 5514               | 1976-1979                 | 4 |                    |                                   |       |                    |       |       |                          |    |       |
| St. Paul River | Mount Coffee            |          | (estimate) | 20000              |                           |   |                    | From literature (IDF scenario) => |       |                    | 10000 | 500   | 0.500                    |    |       |

**Review of mean discharge at Kaiha 2 site** The mean annual discharge of 20 m<sup>3</sup>/s for the Kolahun 2 site is confirmed as the average of a three years recent periods (2013-2015) for which LHS has complete records. The extrapolation to Kaiha 2 site based on a catchment area ration is a sound assumption at this stage, in the absence of locally measured data. A mean annual discharge around 30 m<sup>3</sup>/s must be confirmed timely with direct local measurements and rainfall-runoff hydrological modelling (calibrated & validated).

**Review on extreme flood events** Available discharge record are too short to carry out frequency analysis of peak flow discharges. The pre-feasibility studies do not include any analysis of precipitation data leading to flood events.

The design flood peak discharge of 450 m<sup>3</sup>/s proposed by MTC (2016) must be seen as a first attempt only. There is no specific annual exceedance probability associated to this value. It is based on the maximum daily flow measured at Kolahun in 2015 (152.22 m<sup>3</sup>/s) upstream from Kaiha 2 site. As shown in Table 2, MTC proposal leads to a specific maximum discharge value of nearly 400 l/s/km<sup>2</sup> much higher than other values obtained from available measurements. This is not at all surprising since we are trying to estimate extreme events and comparing with short-duration records. However, when such comparison is carried out with our own estimate of an extreme event leading to a peak discharge of 696 m<sup>3</sup>/s it becomes clear that the 450 m<sup>3</sup>/s may likely be a low boundary value of a not-so-extreme flood event resulting from an already measured historical maximum rainfall. The same table also presents, for illustrative purposes only, a comparison with the Inflow Design Flood (IDF) considered for the

Mont Coffee dam in River Saint Paul in Liberia, which somewhat fits between MTC and our tentative values for Kaiha 2.

In conclusion, the present design flood peak discharge is not sufficiently high to cover events with moderate likelihood (as those already observed). Unless a low flood protection criteria is acceptable for RREA, which we do not recommend, such peak discharge should be considered unacceptable to carry out design activities and obtain work quantities.

Climate  
change

By definition “change” is a relative comparison between steady conditions.

Regarding climate change, the comparison between present and past climate or past and future climate requires the availability of a past benchmark. The difficulties to establish such a reference in the Liberian context are evident: there are no data of river discharge from before 2012 (nothing at LHS, nothing at GRDC) although there are data of monthly rainfall at few locations since the late 1920's / early 1930's in the Central as Eastern parts of Liberia.

According to the publication “Rainfall data book of Liberia” the longest records available are those of the Firestone Cavalla station (53 years, between 1928 and 1980), followed by those of the Harbel station (45 years, between 1936 and 1980). Recent recording at higher frequency (daily) are now available for these stations, and could be used for climate-change assessment studies.

The ECOWAS study cited in Figure 1 indicates that Liberia, and in particular the Mano River basin is situated in a region where no significant changes are expected: the country fall in the regions where a +/- 2% variation is indicated based on available climatic modelling at West Africa regional scale. In comparison with other regions in the World and even in the sub-region this is can be today seen as highly positive and in favour of the project.

## 5.4 Recommendations

Hydrological  
database  
review

We strongly recommend engaging additional hydrological studies to improve quantification of the water resources and water-related hazards. A non-exhaustive list is presented below, ranked per priority:

- 1) Streamflow measurement at the Kaiha 2 site;
- 2) Specific approach for quantification of low flows on site;
- 3) Rainfall-runoff hydrological modelling, calibrated and validated with recently acquired data by LHS, progressively updated during the design stages, and later on used for commissioning and operation;
- 4) Study of Regional Maximum Floods;
- 5) Study of Reservoir Evaporation (note: there are no measurement in Liberia);
- 6) Study of water quality (physical/chemical);

The first two are field activities that required specific preparation and scheduling, whereas the second pair of activities are desk studies that can be started anytime.

Specific measurements of low flows are paramount for the definition of the ecological residual flow that should be left in the river, as well as the minimum discharge for start/stop of turbine operation, the corresponding efficiency as well as the firm power output of the power plant during the dry season. Assessment of the

low flows is a key activity of the Environmental and Social Impact Assessment studies that are soon to start for Kaiha 2 project. Low flows are particularly sensitive to local (undocumented) activities such as irrigation and potential changes in land cover in the upstream catchment.

These additional studies should confirm/improve current assumptions and reduce the uncertainty range of design parameters.

Available  
runoff for  
hydropower  
generation

The mean annual discharge of 20 m<sup>3</sup>/s for the Kolahun 2 site is confirmed as the average of a three years recent periods (2013-2015) for which LHS has complete records. The extrapolation to Kaiha 2 site based on a catchment area ration is a sound assumption at this stage, in the absence of locally measured data.

As the total duration of LHS data records at Kolahun becomes larger, this extrapolation must be updated/corrected and the economic analysis of the project revised accordingly. In the meantime, a more extended dataset (for instance 30 years) can be generated through rainfall-runoff modelling. However, modelling requires calibration and validation, for which 3 years are scarce. Therefore:

- 1) There is no better estimate than direct measurements on site, and the sooner the better;
- 2) Rainfall-runoff modelling of the Kaiha river will be of limited use in the short term, but will be increasingly useful as more local streamflow data becomes available for calibration and validation;
- 3) Rainfall-runoff modelling from a neighbouring catchment for which simultaneous long records (i.e. 30 years) of both rainfall and runoff are available would be the most efficient way to obtain adequate inflow series for the energy and economic studies of Kaiha 2, provided the selected catchment is geomorphological and hydrologically a valid analogy.

A higher value of mean annual discharge at Kaiha 2 than at Kolahun is plausible, considering the larger drainage area.

A mean annual discharge value around 30 m<sup>3</sup>/s must be confirmed timely with direct local measurements and rainfall-runoff hydrological modelling (calibrated & validated). These two activities would allow as well consolidating the analysis of the mean annual specific discharge (in l/s/km<sup>2</sup>) initiated by MTC. In our view, similar values at Kaiha and Kolahun may results from the specific regional distribution of annual rainfall (i.e. increasing values from Northeast to Southwest), which overruns the influence of altitude.

Extreme flood  
event  
recurrence  
and  
magnitude

Rainfall-runoff hydrological modelling of historical events must be carried out using available historical rainfall data. It must be calibrated & validated using measured streamflows at locations with consolidated rating curves. Once the model is calibrated and validated, exploratory computations can be carried out for different extreme rainfall scenarios of selected exceedance probability. Modelling provides deep insight into catchment response based on physical processes, allowing obtaining not only peak discharges at several selected locations but also flood hydrograph shape and volume. A comparison of computed values with values obtained with empirical analysis and statistical analysis should be carried out.

## 6 REVIEW OF ADOPTED DESIGN STANDARDS

### 6.1 Introduction

**Scope** We understand that the main aim of this task is to review the design criteria presented in the pre-feasibility study conducted by MTC in 2016, in view of its adequacy to the local project context. A too demanding standard may render the project unfeasible/expensive, whilst a low standard may lead to unacceptable levels of plant outages and damages, rendering project funding and insurance more difficult.

We separate the review in hydrological design and hydraulic design. Explicit assessment of geological risk and geotechnical design criteria is out of the scope of the present review.

This review includes all works of the Kaiha 2 HPP, in particular the diversion works, the flood release structures, the dams and the hydropower waterways (e.g. water intake, conveyance channel, penstock and tailrace).

The review focus on general design criteria (e.g. general layout, site selection, hydraulic) and not yet on detailed design criteria (e.g. stresses and deformations of foundations, reinforced concrete works or penstocks).

**Hydrological design** Hydrological design is meant here as the establishment of criteria for:

- i) Energy production: meaning the selection of the SHP installed capacity and installed discharge;
- ii) Safety: meaning the selection of the Extreme Flood events for safe design of all structures;
- iii) Life expectancy: selection of an adequate level of hydrological risk with regards to the project lifetime, operation goals and local context.

**Hydraulic design** Hydraulic design corresponds to the establishment of criteria for:

- i) Adequate layout of the different works considering isolated/joint operation, in all operation scenarios (i.e. normal, floods, flushing and so on) as well as foundation and stability conditions, access conditions and costs.
- ii) Adequate flow conditions through the hydropower infrastructure;
- iii) Adequate flow conditions through the dam ;
- iv) Preventing flow-induced damage to structures (e.g. cavitation, vibration, overload);
- v) Provide for safe and performant operation of all equipment.

The review will focus on the criteria used in the pre-feasibility study for the design of all hydraulic structures (including the dam), both for the construction and the operation periods.

### 6.2 Methodology

**Activities** This activity comprises the following sub tasks:

- Desk review of MTC pre-feasibility report
- Desk review of GregMorris Engineering report
- Interviews

## 6.3 Results

**Initial project lifetime** There is no clear definition of what is the initial project lifetime, neither in the PFS nor from the interviews and meeting with stakeholders.

Infrastructure lifetime is function of the Owner's objectives and risk assessment. In remote areas and politically unstable economies, the Owner or Developer tends to fix a short lifetime, as short as 1-2 political mandates, say 10 years, in particular if funding is private. Public developers may accept longer project horizons, as they tends to consider infrastructure projects as socially structuring projects and look for benefits across several generations. However, the longer the considered periods is, the higher the costlier the infrastructure: in fact, for an identical extreme event magnitude (hydrological or seismic) the risk will be higher the longer the exposure period and therefore the costlier will be to guarantee safety of the works.

Given the above, RREA faces three alternatives:

- 1) An expected project lifetime typical of large infrastructure, e.g. 80 years;
- 2) An expected project lifetime typical of unstable contexts, e.g. 10 years;
- 3) A compromise between the above, between 25 and 40 years.

We are clearly in favour of the latter alternative. The IFIs are providing support for a societal-structuring project, which will require several years to reach cruise level, if not from the production, transmission and distribution side of the works ((e.g. electricity consumption per capita in the region), from the tangible results on social and economic indicators side (e.g. more industry, improved healthcare, food storage/supply and education).

We recommend using 40 years as initial project lifetime from now onwards, based on the available IFI backup and synergies with the new foreseen diesel plant at Voijama.

The scheme will likely be operated in the future in context conditions (climate, market, ecology) that may be quite different from those at project inception. Not only should the hydrological risks be within reason during this period given the present knowledge of hydrology, as they should be continuously monitored to anticipate risk aggravation or risk relief, with variable impact on insurance costs and asset value.

**Dam type** MTC design an embankment dam on downstream left abutment to protect powerplant and other infrastructures from flood. All reasons which lead to an embankment dam are not clearly described in MTC pre-feasibility studies (2016). A better understanding of what determines dam type could be done through comparative analysis between concrete and embankment dam.

1. Geological conditions: Concrete dam requires good to very good geological conditions because foundation settlements can lead to cracks into dam-body. It means high deformation modulus of rock:  $E_r > 4 \text{ GPa}$ , moderate to high bearing capacity. On the contrary an earthfill dam is more flexible and can adapt to poor geological conditions (soft ground):  $E_r < 4 \text{ GPa}$ , moderate to low bearing capacity. On Kaiha 2 project site, from geological mapping, ground

conditions seem favourable with *very strong to extremely strong, massive or medium thick to thick, granite and gneiss are observed. Bedrock is generally expected within 1-3 m below the surface of the superficial deposit.* In pre-feasibility studies (p.53), MTC indicates there is a considerable amount of soil covering the rock on downstream left abutment. Quality material and depth are unknown and lead MTC to choose an embankment dam.

2. Construction cost: Embankment dam construction material volumes are larger than concrete dam. With same operating level, embankment dam volume is 4 to 10 times larger. Total construction costs are determined from location, material, transport and working time regarding with construction methods. Cast-in-place concrete require more sophisticated equipment (formwork, temperature control technology, etc.), whereas embankment dams are built with landscaping machines (excavators, vibrating compactor etc.). That makes unit price of concrete dam volume (material and labour included) higher. However, when multiplying by the material volume, the total construction cost may be fairly close. A Roller-Compacted Concrete (RCC) could be an advantageous alternative to a conventional vibrated concrete with potential reduction in costs.

On Kaiha riverbank, sand and gravels are potentially available for concrete production but without any quantification. Cement should be transported from supplying place. MTC estimates there is enough earth-fill materials (reddish clayey silty sand or sandy silt) around the project site as assessment during a site visit. There is no confirmation of quantities or characteristics. For the time being no assessment of a rock-fill dam alternative has been carried out, in general more resistant to overflow than an earthfill dam. Excavating costs could be higher with concrete dam because larger ground material volume should be removed to reach firm rock. Geological investigation about ground permeability should determine if earth fill dam needs a core. Grouting curtain may be necessary in both cases.

3. Submersion-resistance: Concrete dam is submersible, and can be used as overflow spillway. Embankment dam is erodible and does not allow crest overflow. Embankment overflow may cause damage and lead to dam wash out. To avoid downstream damages from reservoir waves a freeboard is designed above flood water level. Following Swiss standards<sup>2</sup>, for a dam height  $H < 10\text{m}$  the safety freeboard requirements are :

- Concrete dam freeboard = 0.5m
- Embankment dam freeboard = 1.0m

Design considerations for same operating water level related to dam's type are shown on Figure 4.

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<sup>2</sup> Office fédérale de l'énergie (OFEN), Directive sur la sécurité des ouvrages d'accumulation, Partie C2: Sécurité en cas de crue et abaissement de la retenue, 15.02.2017

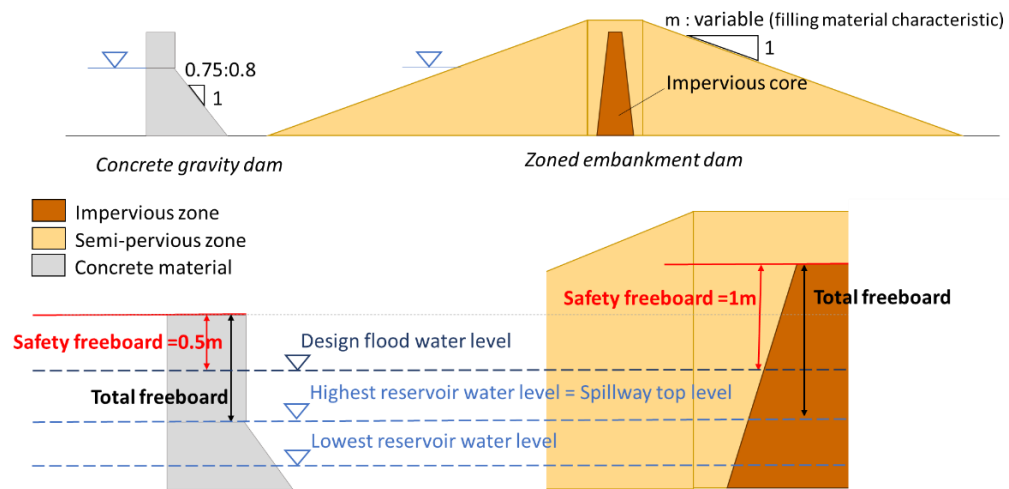


Figure 4 Freeboard design: concrete dam and embankment dam cross sections.

For a zoned embankment dam, the required freeboard provides the setting top level for the impervious core. Concrete dam freeboard value is lower because of its submersion ability which gives a stability margin against unexpected floods. Applying such standards to Kaihi 2 project leads to the reference levels on Figure 5.

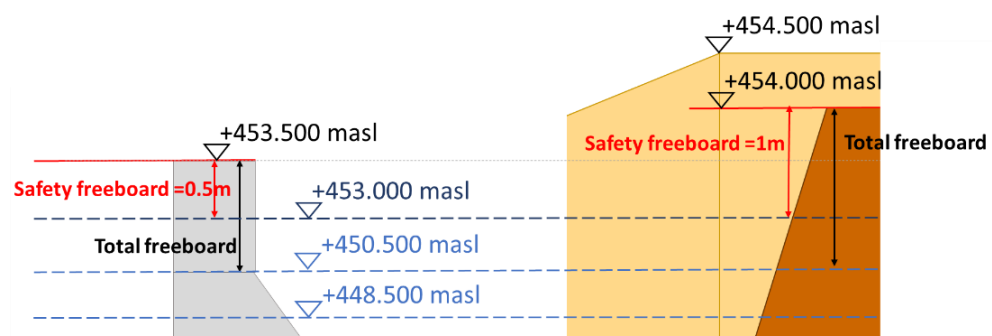


Figure 5 Freeboard design : levels and freeboard applied to Kaihi 2 project (not to scale)

The impervious core top level designed by MTC is in accordance with Swiss standards: freeboard of 1 m above design flood water level.

The above comparison provides some factual arguments for dam type choice.

A similar level of geological investigations must be done for both dam type, even if the ground quality requirements are lower for an earthfill or rockfill dam. Construction costs could rise if the foundation material is found permeable and requires extensive excavation and/or grouting. The project dam height is of up to 8 m, which corresponds to inducing limited stresses on the ground.

The length of the overflow concrete dam section is  $L=150\text{m}$  and must be revised considering flood routing, flow contraction, adequate weir profile and so forth. Flood routing should be carried out once reservoir storage curves are available.

MTC gives a rough large flood estimate at Kaiha 2 of  $450\text{m}^3/\text{s}$  due to lack of data. This value is not associated to any probability (return period). A flood HQ1000 defined by a return period  $\text{RP}=1000$  years is recommended to Kaiha 2 dam design (see paragraph 6.4). Concrete dam gives more safety against unexpected flood because it is submersible. Risk management approach is relevant to design flood protection structure including investments costs to mitigate risk (increase safety).

Flood  
management

The pre-feasibility studies (MTC 2016) present a selection of peak flood discharges based on available data and regional analogies, without setting exceedance probabilities. This is a starting point to define orders of magnitude but clearly not sufficient to obtain funding and insurances. The structures must be conceived to remain operational up to specific flood levels, generally defined in terms of magnitude and frequency, or otherwise undergo acceptable damage for given exceedance probability.

MTC did not set a project lifetime. This is normally function of the promotor's strategy within the legal requirements and funding opportunities. For small hydro plants in remote locations like the Lofa County a project lifetime between 25 to 40 years is conventional. Considering the low redundancy in electricity supply in the region a high level of plant availability is envisaged; therefore, tolerance to full plant outage is low. It is yet unclear how MTC plans to guarantee safety of the works and high levels of plant availability. One positive criteria already proposed by MTC is to have multiple penstocks and four units, which reduces the risk of plant outage derived from damage or failure of individual works or equipment. However, that criterion does not address the potential failure of the dams or the potential flooding of the powerhouse from downstream.

The reviewed documents do not present justification for selecting the tailwater levels.

There are five short-term possibilities of improving the current flood design criteria:

1. Carry out **rainfall-runoff modelling over several decades**, based on long time series of precipitation data from regional stations. The model must be properly calibrated and validated, namely with hydrometric data, within reason. The obtained time series of (daily) discharges at Kaiha section is then used to isolate flood events, built up series of annual (or seasonal) maxima as a basis for a frequency analysis.
2. Carry out **hydraulic studies of the tailwater levels**, which are paramount for powerhouse flood safety (also important for the energy studies).
3. Clarify **RREA's willingness to cope with dam wash out and resulting plant outage** during removal/repair/reconstruction, which are directly linked with accepting an embankment solution for the left bank closure, as opposed to a more resistance (and costly) submersible solution. In fact, comparing dam layout solutions for selected discharges (and return periods) should inform best decisions on the acceptable hydrological risks and consequences. Accepting washout may be acceptable for a strong Owner with multiple cashflow sources, while resisting submersion may be a more adequate

solution for an Owner strongly dependent on intermittent international funding for major works.

4. Continuously **update the frequency analysis adding recent measurements**, throughout the entire project development and implementation phase (can take years) and adjust project layout and budget along the way. If this option is selected, we recommend adding a provision for flood management contingencies to the pre-feasibility project budget.
5. Expand the available **database of extreme events with international data** from events in nearby regions in neighbouring countries.

**Powerhouse location** The relative location of the powerhouse and the main dam must be justified, with potential implication in the design of the flood protection wall. It remains unclear how the Designer plans to dissipate downstream the excess energy of flood discharges passing over the main dam. The effect of return currents and sediment settling must be addressed.

**Powerhouse elevation** The powerhouse elevation must be set adequately justified against flood levels of selected return period and confirmed based on tailwater hydraulic modelling.

**Diversion procedure** MTC must define the design criteria for the 1<sup>st</sup> stage cofferdam (intake and powerhouse construction), as well as for the 2nd stage cofferdam (main dam construction).

MTC proposed as 4-stage procedure for the dam and headworks, plus two stages for the powerhouse and switchyard. The general diversion concept of phased construction with several cofferdams stages, in alternate banks, is generally a good choice considering the seasonality of the river (low flow time windows lasting 3 to 6 months with average monthly flows below 20 m<sup>3</sup>/s). However, the amount of works for each phase must be adequately balanced and documented in a time schedule with explicit indication of work quantities and rates. The work rates must be properly justified with the specification of contractor qualification and equipment. In particular, the construction of the gated bottom outlet (primary flushing orifice) and associated wing walls upstream and downstream must be further justified.

The section of the flushing orifice is unjustified. This orifice is paramount for the performance of the proposed diversion concept (and later on, for the operation of the powerplant during the entire project lifetime).

**Operation (and overall layout design)** There is no evidence of having set the relative hydraulic and service levels of the different works considering flood protection and serviceability/safety, for instance of the intake platform, at the overflow weir, of the embankment dam crest and of the powerhouse machine hall level.

The drawings show a powerhouse layout for four units, two large plus two smaller ones. The reason for selecting two pairs of different machines is unclear.

The layout of the intake works is very preliminary and prone to problems. The design of the entrance sill must contribute to sediment diversion/exclusion. The location of the trashrack must be set in accordance with the flushing gates location and the

trashrack cleaning strategy (and equipment, if any). So far MTC does not present a trashrack cleaning concept, which has major influence the layout of the intake works and ultimately on plant availability for production (and during floods). There is no indication of the type of trashrack and bar spacing.

As mentioned before, the design of the flushing orifice (acting also as bottom outlet) is very preliminary and partly unjustified. Its location close to the intake and close to the actual thalweg of the riverbed is in general positive.

The layout of the concrete weir is preliminary. The overflow section does not have a sound hydraulic design; the present layout is prone to poor hydraulic behaviour starting at the crest level, as well as uncontrolled energy dissipation (and eventually uncontrolled scour) at the dam toe.

Spillway Given the previous, the design discharge cannot be validated and it is pointless to cross-check the spillway capacity for the mentioned discharge of 450 m<sup>3</sup>/s.

**Design Criteria.** First adequate design criteria must be proposed by the Designer, when one is appointed. This means selecting extreme design floods, characterized ad minima by peak discharges, flood volumes and flood hydrographs. Also, it means proposing adequate load scenarios considering combinations of design flood, available bays, dam freeboard and debris accumulation, with proposed acceptance criteria.

**Design floods.** We recommend that RREA accepts nothing less than an ICOLD practice of selection of a design flood with an acceptable exceedance probability of no less than 0.001 (i.e. return period of 1000 years) and a safety-check flood with lower exceedance probability.

**Spillway profile.** The design proposed by MTC does not follow the state-of-the-art. The weir and chute profiles do not allow for a smooth transition from reservoir subcritical flow to chute supercritical flow, with adequate pressure on the chute for overflow heads close to the design head. A standard weir profile (e.g. WES) should be the starting point for design. An adequate transition between the chute and the waterfall must be provided, to prevent direct scour close to the dam toe and potential undercutting. A zero (flat) outlet angle would be an adequate starting point at this stage, in the absence of detailed topography and geology. An adequate curved transition between the chute slope and the chute's outlet should be provided.

**Spillway surface protection.** It is not expected that the flow boundary layer will fully develop in such a short structure and therefore the chute surface should be cavitation resistant. Also, considering the high-sediment content of the river, the design of the spillway must take into account the possibility of long seasonal overflow and include design & construction provisions to prevent surface abrasion. There are several possibilities, from low water/cement concrete finishing, to adding chalk-derivatives, to prevent surface fissures. A more conventional alternative is the use of tightly packed masonry blocks, however providing adequate jointing and mortar may be an issue in such remote area. An intermediate solution is a binder of both previous solutions, where a stoned-face surface is provided, although with irregular jointing and surface, using a low water/cement ratio.

**Overall assessment** The general layout of the works is very preliminary, which is not surprising given the early stage of the studies. However, basic issues such as access roads, availability of materials for dam construction, river tailwater levels and sediment/debris inflows must be addressed at the earliest in subsequent phases, since they may considerably influence the layout of the works and the overall business plan of the SHP.

## 6.4 Recommendations

**Design criteria for hydraulic works** The general layout of the project should reflect the context uncertainty.

We recommend adopting a “robust” design, meaning that the project should be able to adapt and keep operating in different context conditions (e.g. climate, political, market). Reduction of performance efficiency can be acceptable but without non-availability of the powerhouse. In practical terms it means design may be done for a flood peak discharge of  $X \text{ m}^3/\text{s}$  with assumed return period, while several years later more detailed analysis with longer data records reveal that such magnitude corresponds after all to a larger or lower return period. The uncertainty on hydrological, seismological and logistical (supply, access) conditions must be embedded in the design choices.

We recommend using the available funding to implement a project as follows:

Initial project lifetime (or horizon)..... 40 years  
Dam and saddle dam ..... concrete, overflow-resistant RP 1000 years, risk 4 %  
Powerhouse setting level..... RP 1000 years, risk 4%  
Uncertainty coverage margin@2017 .....100-1000 years, risk 33% to 4%  
Dam main gate .....with manual drive, freeboard RP 1000 years, risk 4%  
Number of units ..... at least 3  
Penstock layout..... one per group (no complex bifurcations/manifolds)  
Tailwater levels .....consolidate rating curve for power and energy dissipation  
Spillway .....ungated, WES profile, plunge pool  
Substation ..... RP 1000 years, risk 4%

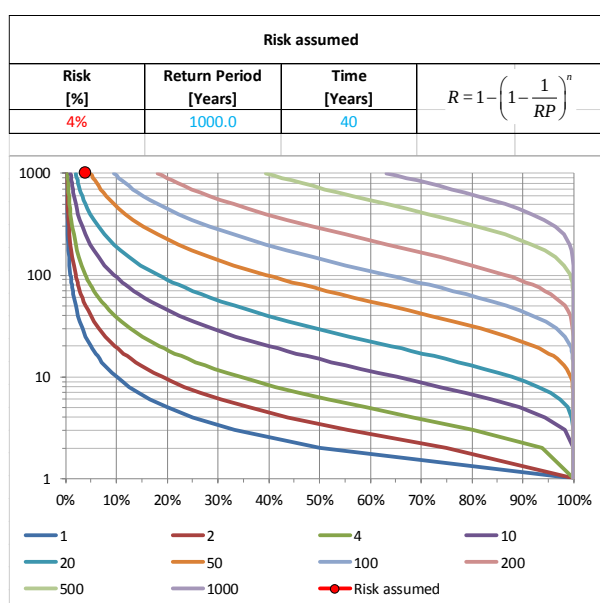


Figure 6- Risk map showing risk associated with an event with exceedance probability of  $1 - 1/1000$  during a period of 40 years. The coloured curves correspond to different exposure periods. The return period is indicated in the y-axis.

Site  
investigations  
and studies

Additional site investigations and studies are recommended before launching further design studies, for instance in terms of:

- Transport of large woody debris (LWD)
- Fish migration (descending/ascending)
- Foundation geological conditions for dam (overflow + lateral extension)
- Availability of material for embankment dam
- Tailwater levels

## 7 REVIEW OF CONTROL GATE DESIGN

### 7.1 Introduction

**Scope** The main aim of this task is to review the present design of the control gates of the diversion weirs, and other inlet/outlet structures.

We consider that the “diversion” control gates are those installed between the overflow part of the dam and the intake structure. In fact there is just one gate in MTC’s design. This single gate will be used to manage river diversion during some construction phases. It will act as bottom outlet and flushing gate during the operational lifetime of the dam.

### 7.2 Methodology

**Activities** This activity comprises the following sub tasks:

- Desk review of MTC pre-feasibility report
- Desk review of GregMorris Engineering report
- Interviews

### 7.3 Results

**Debris** There are no studies of large wood debris (LWD) despite the common knowledge that wood loggers historically use the river flow for transportation in Liberia. Also, since the catchment is densely covered with forest, it is highly likely that large amounts of LWD will converge into the river network during/after extreme floods.

**Sediment** A specific study on sedimentology was recently carried out by GLM Engineering.

Our interpretation of the available sources is as follows:

- Large amount of sediment inflow, 24’500 ton/year (GLM report)
- High likelihood that reservoir will silt up after first decade of operation following reservoir impounding;
- Given the long and sinuous shape of the reservoir, full drawdown flushing and even sluicing operations may not restore original storage;
- Since the scheme will be operated as run-of-the-river (there is no expected interest to do otherwise for decades to come), silting up of the reservoir is only a problem if it hampers the operation of the dam gates or of the power intake. Therefore, the priority in terms of sediment management is to be able to locally clear and maintain clear the vicinities of both the power intake and dam gate(s).
- Sediment is mainly sandy and contains up to 70% of crystalline rock minerals such as Quartz and Feldspar.

**Structural design** We consider it is generally too early to address the structural design of the gates, normally carried out once the general layout of the works is consolidated and technical specifications are available. Therefore, we recommend consolidating the (hydraulic) design of the orifice first, considering flood management during construction and flushing/drawdown requirements during operation.

MTC's concept includes stoplogs for maintenance and likely a vertical service gate. There is no indication of the stoplogs' layout and type of handling (e.g. lifting beam). There is no indication of the service gate type (e.g. dimensions), type of handling or type of drive.

In general, the service gate will be of steel construction and allow operation with partial openings. A proper frame and sill but be provided and guaranteed, for adequate approach flow conditions and stable gate operation. An adequate transition to the downstream water levels must be guaranteed, including energy dissipation.

Electro-mechanical design

In general, an overhead crane (eventually combined with a trashrack cleaner) is the most conventional solution for gate handling.

In general, the service gate have electro-mechanical manoeuvring as well as manual manoeuvring in case of power failure. Power supply should be redundant.

MTC must clarify the type of gates, including type of drive and handling.

## 7.4 Recommendations

Current stage of design

Gate design is highly dependent on the layout solutions, namely the functionalities and the number and size of the equipment necessary to implement the foreseen operation concept.

Given the preliminary stage of the design documents available for review, It is evident that the layout will undergo major changes in coming years until a solution is retained for (structural) gate design. Therefore, our review recommendations focus mainly on the concept and functionalities that any of the gates on site should guarantee.

Robust design concept

Our recommendations focus on developing a low-maintenance & robust design concept for "adequate" performance of the scheme throughout its expected lifetime, as opposed to implementing sophisticated solutions for which lack of locally-available O&M skills and (simple) spare parts may lead to operation disruption. The main aim is to guarantee the long-term availability of the plant for operation, with high safety standards.

Key words for further gate design should be:

- High plant availability;
- Autonomy of local operators;
- Robust construction and manoeuvring solutions.

Design criteria for future stages

We suggest building up on MTC and GLM's studies, as follows:

- Provide submersion-resistance solutions for both the dam, the headworks (to accommodate hydrological uncertainty regarding extreme floods), including as much as possible for the powerhouse foundation and access;
- Provide a debris management solution (e.g. flap gate);
- Provide mechanical drives (e.g. manual drive, manual electrical command);
- Avoid the use of a trashrack cleaner (e.g. overflow intakes);

- Use redundant solutions for entrapped sediment management (i.e. primary flushing, secondary flushing);
- The main dam gate should be slot-free (radial or flap);
- Provide long-longevity gate sealing elements;
- Provide fixation system for gate sealing elements that allow local adjustment (slide fittings) to compensate for poor compliance with construction tolerances on the civil works;
- Provide fixing systems that can be handled with locally available tools (e.g. basic set of a truck repair workshop);
- Use wood or mixed wood-steel construction stoplogs;
- Limit the number of multiple gate lifting/manoeuvring equipment;
- Limit the weight and size of all steel (or mixed) structures, for manoeuvring by means of a single robust gantry crane installed on robust permanent structures (concrete /masonry /steel beams).
- Design/reinforce the access road from Monrovia to allow for future (occasional) use of a mobile crane, as a means of redundancy in case of failure of local manoeuvring equipment.

## 8 ACTION PLAN FOR HYDROLOGICAL DATA

### 8.1 Introduction

**Scope** There was no detailed scope for this activity apart from the general goals. Therefore, our approach was to analyse as much information as possible, including testimonies, with the aim of proposing a stepped roadmap for the improvement of hydrological studies, founded on the available skills and equipment in the country, on RREA's priorities and on international standards of good practice in small hydropower projects.

### 8.2 Methodology

**Approach** The work leading to the establishment of the action plan consisted on data and document review (see above chapters) and interviews with several entities. Further to the meetings held with the Kaiha 2 project team from RREA, we have met and discussed this issue with LHS's Director and technical staff, as well as with Senior staff of the Ministry of Lands, Mines and Energy (see Mission report in Appendix 2).

### 8.3 Results

**Access road** The present access road to site is a dirt road until Madloma. South from Voinjama and until the last village, the road crosses several rivers or creeks with unsafe unstable provisional bridges made of few wood trunks places side-by-side (as shown in photos from Mr. Gregory Morris's mission to site in May 2017). The final 5 km to the river site are presently done on foot, on the hill slopes, with no need for bridge or pontoon crossings.

Paving a dirt road to site should be a priority, allowing easier access for hydrometric data collection and geological and topographical investigations and surveys. Also, for the simple reason of facilitating access to potential bidders and suppliers.

Securing river crossings from Voinjama to Madloma is, likely, out of the scope of RREA but not out of reach, should the appropriate Stage Agencies be mobilized.

**Gauging station** There are no direct reading on the project site. The sooner LHS installs one station on site the better.

**Low flows** Detailed knowledge of low flows is paramount for ESIA acceptance and in particular to confirm the Operator's production in low flow seasons (firm power, minimum daily energy, minimum turbine discharge target, etc.) as well as ecological habitat safeguard during such sensitive periods. Specific action for low flow measurement should be taken.

**LWD** Presently there is absolutely no data available on Large Wood Debris on site. This reality should be documented.

**Regional floods** Nor LHS nor RREA nor Liberian Universities have compiled information or a consolidated overview on regional floods, as far as it was possible to assess.

## 8.4 Recommendations

|                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| LHS mission till 2020 | <p>LHS was staffed and organized with the support of a first programme by the Norwegian Water Resources and Energy Directorate between 2011 and June 2016. A second phase is presently ongoing and will last until July 2020, focusing on:</p> <ul style="list-style-type: none"> <li>• Improving the system for collecting data and data management</li> <li>• Maintaining the existing 10 hydrometric stations and provide all of them with automatic water level loggers;</li> <li>• Maintain the automatic weather station and the rain fall stations;</li> <li>• Expand the hydrometric network with 4 stations.</li> </ul> <p>The abovementioned objectives apply for the whole country and are not specific of the Kaiha 2 project nor reflect the best interest of RREA, although being in line with these.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| RREA's priorities     | <p>For Kaiha 2 SHP, RREA's priorities should be on:</p> <ul style="list-style-type: none"> <li>• Improving the accuracy and representativeness of water availability estimates, in view of improving the energy production assessment of the project;</li> <li>• Obtaining fair estimates of flood events, in view of improving the hydro-economic assessment of the project safety.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| Action Plan           | <p>A specific action plan is proposed in eight steps:</p> <ol style="list-style-type: none"> <li>I. Install new gauging station at the project site, to complement the operation of the Kolba City (Kolahun, MA001) gauging station.</li> <li>II. Provide provisional access to site, for hydrometric as well as geological and ESIA investigations.</li> <li>III. Install a specific station at project site for measurement of low flows (see below and a conceptual design in Appendix 3).</li> <li>IV. Generate a long time series of daily discharges of Kaiha 2 for energy and economic studies by means of a preliminary rainfall-runoff model of the Kaiha 2 catchment, using weighted rainfall data from Lisco camp, Voinjama and Kolahun stations, and the available 3-year short record of streamflows at Kolahun, to be updated as more data become available. In parallel a similar analysis can be conducted in a carefully selected analogous catchment in the region for which longer records are already available.</li> <li>V. For extreme flood events, carry out a comprehensive hydrological study, starting from the analysis of historical rainfall events in the region, including in neighbouring Guinea and Sierra Leone, to assist event-based rainfall-runoff modelling and analysis.</li> <li>VI. For extreme flood events, liaise with the hydrological services of neighbouring countries to establish a database including, ad minima:             <ol style="list-style-type: none"> <li>a. Annual river discharge maxima from regional rivers (daily values);</li> <li>b. Annual rainfall maxima (24 hours cumulated values).</li> </ol> </li> <li>VII. Make regular observations of large drifting wood (LWD) including log-counting and sizing, focusing on flood events and on deforestation seasons.</li> </ol> |

- VIII. Provide robust and redundant data filing, storage and back-up, as well as easy access to data to project stakeholders.

The third point is addressed hereafter in further detail.

Priority low  
flow logging

The two permanent gauging station Kolahun (MA001) and Sambahun (MA002) are located at more than 36 km upstream from the Kahia 2 project site. Low flows measurements directly on site are recommended to improve the estimation of energy production during the dry season or provide a sound quantitative basis for the definition of the minimum discharge that should be releases downstream for ecological safeguard purposes.

We recommend providing the new gauging station at Kahia 2 site with a dedicated channel for low flows, equipped with a calibrated weir and stage gauge. This channel can be done in one of the existing gullies at the onset of the rocky water fall.

To measure low streamflows during the dry season, a thin-plate weir is suitable. The choice of the weir's opening geometry (V-notch or rectangular) depends on the targeted flow range. The lowest flows recorded upstream are in the range of 500 l/s. At Kaiha 2 project site low flows are estimated around 850 l/s during the dry season and therefore a V-notch seems justified since it allow more accurate measurement of water discharges up to few dozen litres per second. For flows up to 1000 l/s a rectangular weir would be more suitable. For a maximum flow  $Q = 800$  l/s the following weir opening dimensions would be required:

- V-notch (angle 90°): width  $L = 1.59$  m, V height ( $H_{max}$ ) = 0.80 m;
- Rectangular: width  $L = 1.13$  m, height ( $H_{max}$ ) = 0.38 m.

Weir plates are made of reinforced steel or wooden planks. Installation should be easy to remove before wet season (or otherwise disposable). Installation should allow for easy cleaning of sand deposits or debris (e.g. by lifting, by shovel, by orifice).

A stage gauge is installed upstream of the weir to meet permanent (steady-state) and uniform flow: minimum distance is  $D_{min} > 2.39$  m (V-notch) and  $D_{min} > 1.13$  m (rectangular). A scaled ruler should be fixed to a pole strongly anchored to the riverbed. The water level is measured daily (manually) and reported on a log book.

Ideally the gauging station should be operated and maintained for a minimum of 3 dry seasons. More design details and schemes are in Appendix 3.

## 9 CONCLUSIONS

|          |                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Contents | <p>This final report presents our detailed appreciation of the documents received and of the impressions and testimonies collected in Liberia.</p> <p>Review activities on hydrological data (chapter 5) and design standards (chapter 6) focus on the most critical issues at such early design stage. These reviews should be extended and further detailed in subsequent design stages, in parallel with progress in design, as justified.</p> |
| Outlook  | <p>The report includes a list of recommendations to RREA, organized per task, for further action. The improvement of the estimates of water availability and of extreme floods is paramount to consolidate the project's feasibility, secure project funding and mobilize international suppliers and insurances.</p>                                                                                                                             |
| Schedule | <p>The review effectively commenced on June 6, 2017. A mission to Liberia was carried out in the end of August, which is described in the mission report presented as Appendix 2. The final report includes also the outcome of follow-up exchanges with RREA's staff after the mission.</p>                                                                                                                                                      |

The undersigned hereby warrants that the Work is original and exclusive for RREA,



Dr Pedro Manso  
Director & Principal Engineer PMIC

(the documents in grey are contractual and were given priority in the review analysis, namely Nos. 5008, 5009 and 5015)

## KAIHA 2 Small hydropower project

## RECEIVED DOCUMENTS

| No.                 | Version | External No. | Author                                                                       | Date | Concerns (or file name)                                                                                                                                          | Title                                                                           | Sub-title / Reference   | Date IN    | Surface                                      | Work Phase |
|---------------------|---------|--------------|------------------------------------------------------------------------------|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-------------------------|------------|----------------------------------------------|------------|
| 5001                |         |              | JICA                                                                         | 1975 | Kabba River station                                                                                                                                              | Discharge measurement report                                                    | 2015-2017               | 04.05.2017 | 1F0F file                                    | Review     |
| 5002                |         |              | JICA                                                                         | 1975 | 1975 JICA Hydro-Electric Power Dev. Plan 1                                                                                                                       | Report on Basic Studies of HPP development in Liberia                           |                         | 06.06.2017 | 1F0F (95 pp)                                 | Review     |
| 5003                |         |              | JICA                                                                         | 1975 | 1975 JICA Hydro-Electric Power Dev. Plan 2                                                                                                                       | Chapter II Hydro-electric power development plan                                |                         | 06.06.2017 | 1F0F (108 pp)                                | Review     |
| 5004                |         |              | Decon/KfW                                                                    | 1993 | 1993 Decon Report V2.LD                                                                                                                                          | Pre-feasibility study on the development of power in the Liberian rural areas   |                         | 06.06.2017 | 1F0F (342 pp)                                | Review     |
| 5005                |         |              | Geoscientific Eur. Dev. Fund                                                 | 1998 | 1998 Geoscientific Eur. Dev. Fund                                                                                                                                | Pre-feasibility study in Liberia                                                |                         | 06.06.2017 | 1F0F (36 pp)                                 | Review     |
| 5006                |         |              | Kingship Power/HUB PLC                                                       | 1998 | 1998 Kingship Power/HUB PLC                                                                                                                                      | Desirable supply in Liberia                                                     |                         | 06.06.2017 | 1F0F (36 pp)                                 | Review     |
| 5007                |         |              | Multiconsult II/NWRER                                                        | 2016 | 2012 HE Durgu Hydro power opportunities (I)                                                                                                                      | Desirable supply in Liberia                                                     |                         | 06.06.2017 | 1F0F (24 pp)                                 | Review     |
| 136547-RE-n-RAP-007 |         |              | Multiconsult II/NWRER                                                        | 2016 | Pre-Feasibility Studies of Selected Mini Hydro Power Sites                                                                                                       | Kahia 2 HPP Feasibility Report, final                                           | Report                  | 06.06.2017 | 1F0F (109 pp)                                | Review     |
| 136547-RE-n-RAP-007 |         |              | Multiconsult II/NWRER                                                        | 2016 | Pre-Feasibility Studies of Selected Mini Hydro Power Sites                                                                                                       | Kahia 2 HPP Feasibility Report, final                                           | Appendices              | 06.06.2017 | 1F0F (51 pp)                                 | Review     |
| 5009                |         |              | Liberia Energy Sector Support Program (LESSP)                                | 2011 | Report on Hydro Sites Identification, Final                                                                                                                      | Identification of Potential Hydropower Sites in Bong, Nimba and Lofa Counties   |                         | 06.06.2017 | 1F0F (24 pp)                                 | Review     |
| 5010                |         |              | UPS # Pula Iron Ore Mining Inc.                                              | 2012 | Pula Iron Ore Pre-feasibility Study                                                                                                                              | HYDROPOWER STUDY                                                                |                         | 06.06.2017 | 1F0F (9 pp)                                  | Review     |
| 5011                | a       |              | UPS # Pula Iron Ore Mining Inc.                                              | 2012 | Pula Iron Ore Pre-feasibility Study                                                                                                                              | HYDROPOWER STUDY                                                                |                         | 06.06.2017 | 1F0F (67 pp)                                 | Review     |
| 5012                | b       |              | SHERP, MWHR/European Union                                                   | 2013 | Via Reservior Reconnaissance Study - Overall Assessment and Project Definition                                                                                   | ST. JOHN RIVER RECONNAISSANCE STUDY                                             | Final report            | 06.06.2017 | 1F0F (59 pp)                                 | Review     |
| 5013                |         |              | RAL # European Union                                                         | 2014 | Field Survey                                                                                                                                                     | GIS Mapping for the development of a rural energy master plan.                  | Final report            | 06.06.2017 | 1F0F (165 pp)                                | Review     |
| 5014                |         |              | RPEA                                                                         | 2017 | RESMP - GIS Files (1171 files, 10 folders: base data/implementation phases/program/initial/wed-long-term/network/solar resource map/hydro resource field survey) | Field Survey and GIS Mapping for the development of a rural energy master plan. |                         | 06.06.2017 | 22.Mb                                        | Review     |
| 5015                |         |              | Liberian Institute of Statistics and Geographical Information Service # RPEA | 2013 | Draft Analytical report                                                                                                                                          | - Final report<br>- RPEA Maps<br>- RPEA field data                              |                         | 22.06.2017 | - 1F0F (81 pp)<br>- 14 files<br>- 1.XLS file | Review     |
| 5016                |         |              | G Morris LLC                                                                 | 2017 | Sedimentation report                                                                                                                                             | Kahia 2 Sedimentation report                                                    |                         | 11.08.2017 | PDF                                          |            |
| 5017                |         |              | LHS                                                                          | 2014 | Flow data                                                                                                                                                        | Flowdata, Kahia-2, Used by MultiConsult Flowdata, KOLIBA CITY                   |                         |            | EXCEL<br>ZIP                                 |            |
| 5018                |         |              | w Hakin                                                                      | 2017 | Kahia2 HPP                                                                                                                                                       | Review of pre Feasibility Report Final                                          | WDHakin signed_09242019 | 24.03.2017 | 1F0F (27 pages)                              | Review     |

## Appendix 2 – Mission report

[included hereafter]



Rural and Renewable Energy Agency (RREA)



# Small hydropower plant Kahia 2, Liberia

## Review of Hydrology & Hydraulic Works

**MISSION REPORT, 27.08.2017 – 31.08.2017**



Dr Pedro Manso

1701/2002

02.10.2017

| Date       | Contents       | Prepared by: |
|------------|----------------|--------------|
| 02.10.2017 | First issuance | PM           |
|            |                |              |

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## List of Acronyms /Abbreviations

|         |                                                          |
|---------|----------------------------------------------------------|
| EA:     | Executing Agency                                         |
| ECOWAS: | Economic Community of West African States                |
| ECREE   | ECOWAS Centre for Renewable Energy and Energy Efficiency |
| ESIA:   | Environmental and Social Impact Assessment               |
| EPC:    | Engineering Procurement & Construction                   |
| ESMP:   | Environmental and Social Management Plan                 |
| GOL:    | Government of Liberia                                    |
| GLM     | GLM Engineering SAC                                      |
| IED     | Energy consultants                                       |
| LEC:    | Liberia Electricity Corporation                          |
| MoLME:  | Ministry of Lands, Mines and Energy                      |
| MTC     | Multiconsult                                             |
| RREA:   | Rural and Renewable Energy Agency                        |
| TOR:    | Terms of Reference                                       |
| UNCED:  | United Nations Conference on Environment & Development   |
| UNMIL:  | United Nations Mission in Liberia                        |
| USAID:  | United States Agency for International Development       |
| WAPP:   | West African Power Pool                                  |

# 1 INTRODUCTION

**Background** This report is part of the service contract with RREA, initiated in April 2017, and follow acceptance of the inception report in July 2017.

**Report contents** This report presents a summary of the main activities carried out during the mission by Dr Pedro Manso to Liberia during the last week of August.

**Mission goals** The mission aimed at:

- i) Meeting the main project stakeholders (RREA, LHS, MoLME)
- ii) Assess the recent practice of LHS on hydrological data and check data sources
- iii) Collect additional data and references
- iv) Discuss preliminary views on the hydrological & hydraulic activities

**Salient features** The present salient features of the project are as follows [MTC 2016] :

|                                                              |                                                      |
|--------------------------------------------------------------|------------------------------------------------------|
| River catchment at Kahia 2 falls .....                       | 1129 km <sup>2</sup>                                 |
| Annual inflows, mean runoff .....                            | 33.9 m <sup>3</sup> /s                               |
| Low flows, 1% .....                                          | 0.34 m <sup>3</sup> /s                               |
| Dam type .....                                               | concrete overflow weir + embankment dam on left bank |
| Dam height .....                                             | 7.5 m high concrete section                          |
| Powerhouse installed capacity .....                          | 2.5 MW                                               |
| Units.....                                                   | 4 S-type units, 2 x 0.5 + 2 x 0.75 MW horizontal     |
| Installed discharge .....                                    | 23.2 m <sup>3</sup> /s                               |
| Maximum operation level (full supply) .....                  | 450.5 m asl                                          |
| Minimum operation level .....                                | N/A                                                  |
| Reservoir live (or active) volume .....                      | N/A                                                  |
| Reservoir surface at MOL .....                               | N/A                                                  |
| Gross head .....                                             | 13 m                                                 |
| Electricity, average generation .....                        | 17.5 GWh/a                                           |
| Machine hall level .....                                     | 437.50 / 442.00 m asl                                |
| Tailwater level for 1/1000 RP-flood, reference section ..... | N/A                                                  |
| Plant factor, annual average.....                            | 36% (year 1) to 74% (year 20)                        |
| Transmission line .....                                      | 115 km, 33 kV                                        |
| Access road .....                                            | 5.5 km from Mbaloma                                  |

## 2 JOURNAL

| Date                                 | Activities                                                                                                                                                                                                                                                                                                                                                                                                   |
|--------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Sunday 27 <sup>th</sup><br>August    | Transfer Pully - Geneva<br>Flight Geneva – Brussels<br>Flight Brussels – Roberts International Airport, Liberia<br>Individual work on draft report<br>Visa controls<br>Transfer to Monrovia, check-in at hotel                                                                                                                                                                                               |
| Monday 28 <sup>th</sup><br>August    | <u>Morning:</u><br>Plenary meeting with RREA project team<br>Executive meeting with RREA project manager<br><u>Afternoon:</u><br>Technical meeting with Mr. David Wyles, EISA expert<br>Technical meeting with RREA Senior Civil Engineers & Procurement Officers on standards, supplies, logistics, quarries, etc.                                                                                          |
| Tuesday 29 <sup>th</sup><br>August   | <u>Morning:</u><br>Work meetings at Liberian Hydrological Institute, with staff responsible for Mano River basin and counterparts involved in the Feasibility Study for Kahia 2. Visit of LHS warehouse. Detailed assessment of relevant rating curves and discharge estimation procedures.<br><br><u>Afternoon:</u><br>Field visit of Haindi gauging station in River St. Paul and Wakata rainfall station. |
| Wednesday<br>30 <sup>th</sup> August | <u>Morning</u><br>Meeting at Ministry of Lands, Mines and Energy<br>Introductory meeting with RREA project manager<br><br><u>Afternoon:</u><br>Meeting with Mr. Bill Hagin at Mt. Coffee HPP site<br>Transfer to Roberts International Airport.<br>Visa controls and check-in<br>Flight Roberts International Airport – Brussels                                                                             |
| Thursday 31 <sup>st</sup><br>August  | Flight Brussels- Geneva<br>Transfer by train from Geneva Airport to Pully                                                                                                                                                                                                                                                                                                                                    |

### 3 MEETINGS AT RREA

#### 3.1 Meeting with RREA executive management

Meeting#1

Participants:

Mr. Augustus Gouane, Executive Director  
Mr. Stephen Potter, Acting Program Director

Highlights and main conclusions:

1. RREA is preparing to launch a call for EPC contractors. The aim is to build the Terms of Reference directly on the available feasibility study, complemented/updated with additional expert advice. The terms of reference are due by Dec'2017.
2. RREA's team has successfully commissioned the Yandahun small hydro project (60 kW) in 2014.
3. Kahia 2 is part of an energy supply project for Lofa County combined with diesel generation, as proposed by IED (energy consultants).

#### 3.2 Meeting with RREA project team

Meeting#2

Participants (see list of attendance in Appendix 2):

Mr. David Wyles, ESIA expert  
Mr. Anthony Waylea, Pico-PV specialist  
Mr. Augustine Moore, Procurement specialist  
Mr. Varney Garpue, Civil Engineer

Highlights and main conclusions:

1. The **ESIA** studies scheduled to start in September 2017, for 3 months.
2. **Reservoir:** PM recommends assessing the reservoir footprint in detail, in terms of static backwater, dynamic backwater, spillway design implications, dam closure implications, access rehabilitation and other mitigation or compensation measures.
3. **Gauging stations:** The location of the available gauging stations was not clear, as also observed from previous reports. To be clarified at LHS.
4. **Gauging station rating curves:** the issues of station location, riverbed stability and reference level setting require further discussion with LHS.
5. **Low flows:** this issue requires specific activities.
6. **Penstocks:** PM recommends adopting simple design criteria and solutions (e.g. straight route, no bifurcations, one penstock per unit, etc.)
7. **Turbine** units: PM recommends adopting simple design criteria and solutions, for instance replacing the 2 x 2 units (total 4) by four identical units or three identical machines (e.g. 3 x 0.8 or 3 x 0.9 MW). Phased-installation can follow the evolution of demand (and grid connection), deferring capex.
8. **Project lifetime:** PM highlight the need to agree and specify a project lifetime at the earliest, which will affect all subsequent reference documents of the project as well as design and operation standards.
9. **Dam:** There is no experience in Liberia of providing clay core for embankments. PM recommends equating other solutions, preferably resistant to flood overflow.

10. **Debris management:** MTC's report is vague on this issue. PM recommends avoiding expensive and demanding trashrack cleaner. Combining sluice and flap gates likely more suitable. To be dealt with in final report.
11. **Project governance / operation:** RREA does not intend to operate the powerplant but rather to provide a concession to a private operator (as currently tried out at Mount Coffee HPP by LEC).
12. **Investment costs:** the overall MTC budget was discussed, in particular in terms of detail and available bases for the estimation of quantities / unit prices / lumped prices / contingencies / compensation & mitigation measures.
13. **Risk:** the interplay between project duration, risk exposure and design criteria for flood management was discussed, in particular the implications in terms of general layout of the scheme, specific solutions for the most relevant structures and costs.

## 4 JOINT ACTIVITIES WITH THE LIBERIAN HYDROLOGICAL SERVICE

### 4.1 Meeting at LHS

Meeting#3      Participants (see list of attendance in Appendix 2):

Mr. David Wyles, ESIA expert RREA  
Mr. Varney Garpue, Civil Engineer RREA  
Mr. Guah Kennedy, LHS technician  
Mr. Victor Toby, LHS technician  
Mr. Anthony D. Kpadeh, LHS Director

Highlights and main conclusions:

1. **Gauging station labelling:** Kolba City and Kolahun are the same location.
2. **Irrigation weir:** there is an irrigation weir at a location called Yangbealahun, which is made of stones and regularly wash out during floods. The Sambahun gauging station is located upstream from this weir. When the weir is operational the gauging station provides values affected by the weir's backwater, namely on the upper part of the rating curve.
3. **Kolahun station:** the stage gauge is installed in one of the bridge piers. The geometry of the riverbed section is, according LHS, fairly stable. In total, LHS did 25 measurements of river discharge (with transects, using the ADCP) since 2013.
4. **Long-term river discharge records:** there are no long historical records. The longest available records correspond to the Haindi station in the St. Paul River, since 2012.
5. **Natural variability:** the possible differences between the Annual Flow Duration Curves (AFDCs) and the long-term (aggregated) Flow Duration Curve (LTFDC) were discussed. In the absence of available data for Kaiha River, the natural variability of the inflows may possibly be adopted from neighbouring catchments with identical hydrological regime.
6. **Extreme events:** apart from Mount Coffee dam, presently undergoing extensive rehabilitation after major wash out in the 1990's, there are no other dams in Liberia which can provide lessons from spillway operation.
7. **Need for rainfall analysis:** hydrological studies, in particular for flood analysis, require longer discharge records than those available. One means to circumvent such difficulty is to elaborate rainfall-runoff models, starting from longer rainfall data records. Despite being very useful for spatial and time breakdown and visualization, these models require calibration to become more than exploratory tools.
8. **Long-term rainfall data records:** the longest available recording in Liberia are available in the publication "Rainfall data book of Liberia". The longest records available are those of the Firestone Cavalla station (53 years, between 1928 and 1980), followed by those of the Harbel station (45 years, between 1936 and 1980). Recent recording at higher frequency (daily) are now available for these stations, and could be used for climate-change assessment studies.
9. **Rainfall records in Kahia river catchment:** For the Kahia River catchment there are data from the Voinjama station (1953-1970, monthly values, page 17) and the Kolahun station (1953-1970, monthly values, with gaps, page 20). Recent recordings are now available at daily frequency.

10. **Evaporation and evapotranspiration:** no data is available.
11. **New station:** PM recommends installing a proper gauging station at the project site as soon as possible. LHS agrees and states that local access is the major difficulty.
12. **LHS capacity:** The LHS was staffed, equipped and trained in recent years (since 2011), with the help of Norwegian cooperation; joint field activities were carried out both in Norway and Liberia.
13. **LHS equipment:** The LHS is equipped with currentmeters, ADCP, stage gauges, GPS in quality and number. The warehouse is organized. The library is organized. The digital database is organized. A web-based platform is used for authorized personnel (hydrometcloud.com).
14. **LHS practice:** The LHS is using a raft-mounted ADCP to obtain velocity fields at selected river transects, for subsequent integration and discharge estimation.
15. **LHS operational perspectives:** the capacity-building project with Norwegian funding is extended for an additional 4-year period until 2020.

## 4.2 Field activities

Haindi

Following inspection of LHS warehouse and equipment, participants set off for Haindi to visit the first new-generation gauging station installed in Liberia under the present cooperation agreement with Norway. The gauging station is equipped with a stage gauge on the left riverbank and with two pressure-cell sensor on the right bank (Photo 1 below).

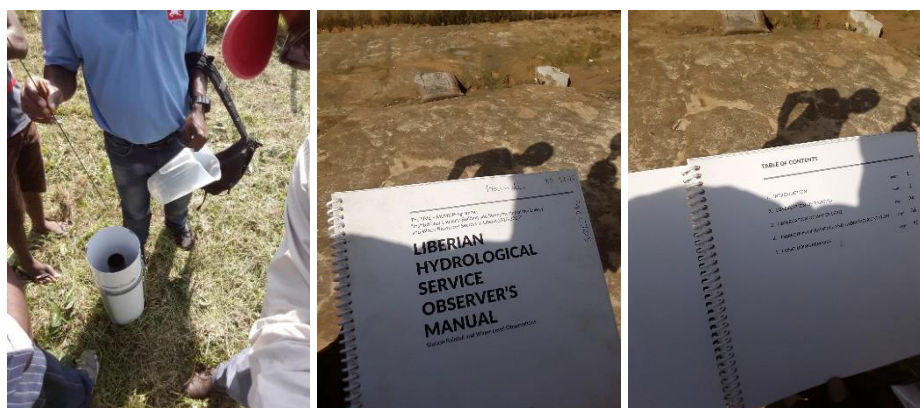


*Photo 1 – Haindi gauging station cubicle. PV panel and satellite antenna. In the background, LHS staff downloading readings from one of the two pressure-cell sensor onto a portable computer.*

The station is powered by a combination of PV solar panel and lithium batteries (encapsulated), as well as with a satellite connection. The readings are transmitted live to LHS datacentre (as well as to Mount Coffee HPP who is paying for the connection), but are also downloaded periodically in situ.

#### Wandaka

A rainfall gauging station is installed in the nearby village of Wandaka. Daily measurements of rainfall depth are carried out manually, following instructions by LHS (Photo 2 below). After a first learning periods of manual readings, LHS plans to install an automatic recording station and reduce the frequency of manual checks.



*Photo 2 – Current practice for rainfall measurements at Wandaka station: left) demonstration by LHS staff of manual procedure for volumetric measurements using calibrated bucket, ruler, plastic and steel cylinders; centre, cover of LHS manual; right, table of contents of LHS manual.*

## 5 CONTACTS WITH THIRD PARTIES

### 5.1 Meeting at the Ministry of Land, Mines and Energy

Meeting#1

Participants (see list of attendance in Appendix 2):

Mr. Sylvester M. Massaquoi, Director for Alternative Energy, Dept. Energy  
Mr. Edward M. Konneh, Assistant Director for Alternative Energy, Dept. Energy  
Mr. Nanlee Johnson  
Mr. Edouard Konnel

Highlights and main conclusions:

1. PM made a short presentation of the project, including the guidelines for an action plan on hydrology.
2. **International collaboration on hydropower:** The MoLME is member of the ECREE program (ECOWAS Centre for Renewable Energy and Energy Efficiency), with particular interest in the small plant program. However, the ministry is conscious that it will take many years to establish a national grid reaching all counties.
3. **Small hydropower inventories:** apart from the inventory carried out by JICA, there is one available inventory by the ministry itself that identified eight sites in Lofa county.
4. **Access to Kahia 2 site:** following PM's request for assistance for temporary road access to site to facilitate investigations, it was suggested that RREA contacts the Millennium Challenge Account (MCA). This entity is said to sponsor activities such as road construction to untangle specific infrastructure projects.
- 5.

### 5.2 Meeting at Mount Coffee HPP

Meeting#4

Participants:

Ms. Eunice Dahn, Project Coordinator RREA  
Mr. Bill Hakin, Mt. Coffee Project Implementation Unit / Consultant RREA in charge of preparing the Terms of Reference for the EPC call

Highlights and main conclusions:

1. **Flood discharge capacity:** Mount Coffee dam spillway is being rehabilitated for a 1/10'000 year flood return period. An emergency spillway is provided for a 1/50 return period. The PMF peak discharge considered is 17'000 cms.
2. **Reservoir aerial survey:** Mount Coffee is presently conducting LiDAR surveys using a recently custom-released airplane from ACS (African Consolidated Surveyors).
3. **Kahia Lidar survey:** BH will ask for a quotation to ACS. PM will prepare KMZ files of the reservoir and tailwater river reach potentially concerned by dam break inundation. Future surveys for the overhead transmission line and access roads will not be included yet.

## 6 OUTLOOK

|                          |                                                                                                                                                                                                                                               |
|--------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Review activities        | The mission was very useful and went smoothly. All of the objectives were attained. The review on hydrology and hydraulics can proceed. LHS is a sound partner that merits further support for its mission, including training of more staff. |
| Hydrological action plan | The bases for a hydrological action plan were discussed with LHS, RREA and MoLME and will be finalized in the Final report.                                                                                                                   |

The undersigned author hereby warrants that the Work is original and exclusive for RREA,



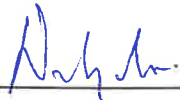
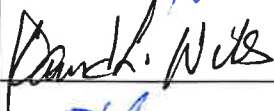
Dr Pedro Manso  
Principal consultant PMIC

## Appendix 1 – Meeting attendance lists

[separate documents to be appended]

## Meeting with Dr. Manso at RREA

August 28, 2017

| No | Name                         | Positon                              | Phone Number                                 | Signature                                                                           |
|----|------------------------------|--------------------------------------|----------------------------------------------|-------------------------------------------------------------------------------------|
| 1  | ANTHONY D. WAYLEA, JR / RREA | PICO-PV SPECIALIST                   | 0776 047690 /<br>anthonyw@rrealiberia.org    |  |
| 2  | VARNEY K. GARDIE             | CIVIL ENG                            | Vgarpue@yahoo.com<br>0776 160865 / 088644791 |  |
| 3  | Augustine Moore              | procurement specialist               | 0776 975560<br>Augustinem@rrealiberia.org    |  |
| 4  | David L. Niles               | ENVIRONMENTAL &<br>SOCIAL CONSULTANT | 0886 327484<br>0775 994039                   |  |
| 5  | PEDRO MANSO                  | CONSULTANT / EXPERT                  | +41.76.4265394                               |  |
| 6  |                              |                                      |                                              |                                                                                     |
| 7  |                              |                                      |                                              |                                                                                     |
| 8  |                              |                                      |                                              |                                                                                     |
| 9  |                              |                                      |                                              |                                                                                     |
| 10 |                              |                                      |                                              |                                                                                     |

AUGUST 29, 2017

meeting with the Liberian Hydrological Service  
ATTENDANCE

| NO. | NAME              | PHONE #                                                | E-MAIL ADDRESS                                  |
|-----|-------------------|--------------------------------------------------------|-------------------------------------------------|
| 1.  | GUAH KENNEDY      | 0777024809<br>0886665730                               | gkennedy2004@yahoo.com<br>kennedyguah@gmail.com |
| 2.  | Victor Toby       |                                                        |                                                 |
| 3.  | David L. Wilk     | 0775840363<br>0555661637<br>— 0886527484<br>0775894039 | VictorToby57@yahoo.com<br>— davidw@realizer.org |
| 4.  | PEDRO MANSO       | +41.76.4265394                                         | pedromanso@hotmail.com                          |
| 5.  | VARNEY K. GARPUE  | 0886997372                                             | vgarpue@yahoo.com                               |
| 6.  | Anthony D. Kpadeh | — 0886543884                                           | Kpadehanthony2015@gmail.com                     |

AUGUST 30, 2017

| NAME                              | INSTITUTION                                         | PHONE / E-MAIL                             | STATUS  |
|-----------------------------------|-----------------------------------------------------|--------------------------------------------|---------|
| Silvester M. S. S. A. Q. U. O. I. | Ministry of Lands, Mines, & Energy, Dept. of Energy | +231 886 522-634<br>satingzwa@yahoo.com    | Invited |
| P. Nantee Johnson                 | MLME                                                | +231 775-212233<br>nanteejohnson@yahoo.com | Invited |
| Varney K. Garpue                  | RREA                                                | 0886 997372<br>varpue@yahoo.com            | Invited |
| David L. Wiles                    | REA                                                 | 0886 527484<br>davidw@realibor.org         | Invited |
| Edward M. Konnel                  | MLME                                                | 0886-518177<br>edwardkonnel@yahoo.com      | Invited |

## Appendix 2 – Presentation for MoLME

[separate document to be appended]



# Kaiha 2 small hydropower project, Liberia

Presentation for Ministry of Lands, Mines and Energy

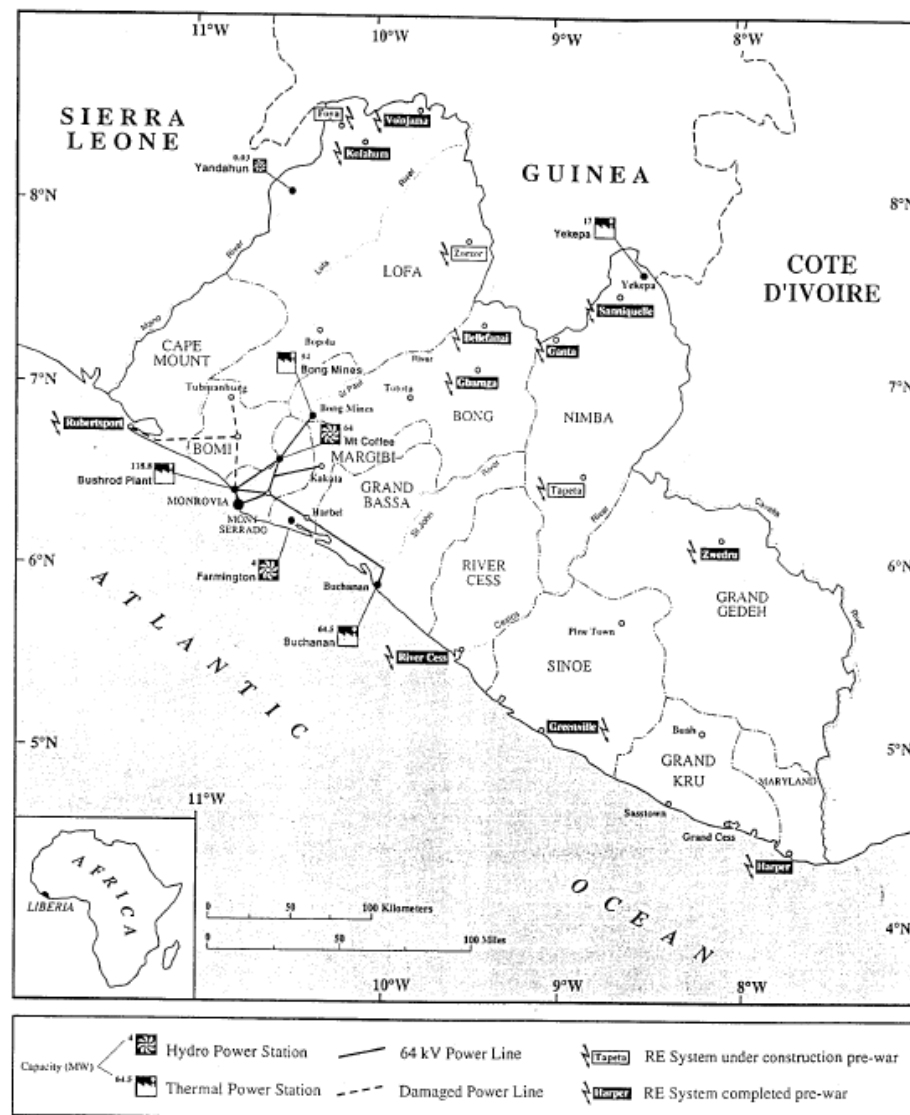
Dr Pedro Manso, PMIC Sàrl (Switzerland)



Project Context

30.08.2017

# Inventory maps



Source: JICA (ref. 5005)

# Location

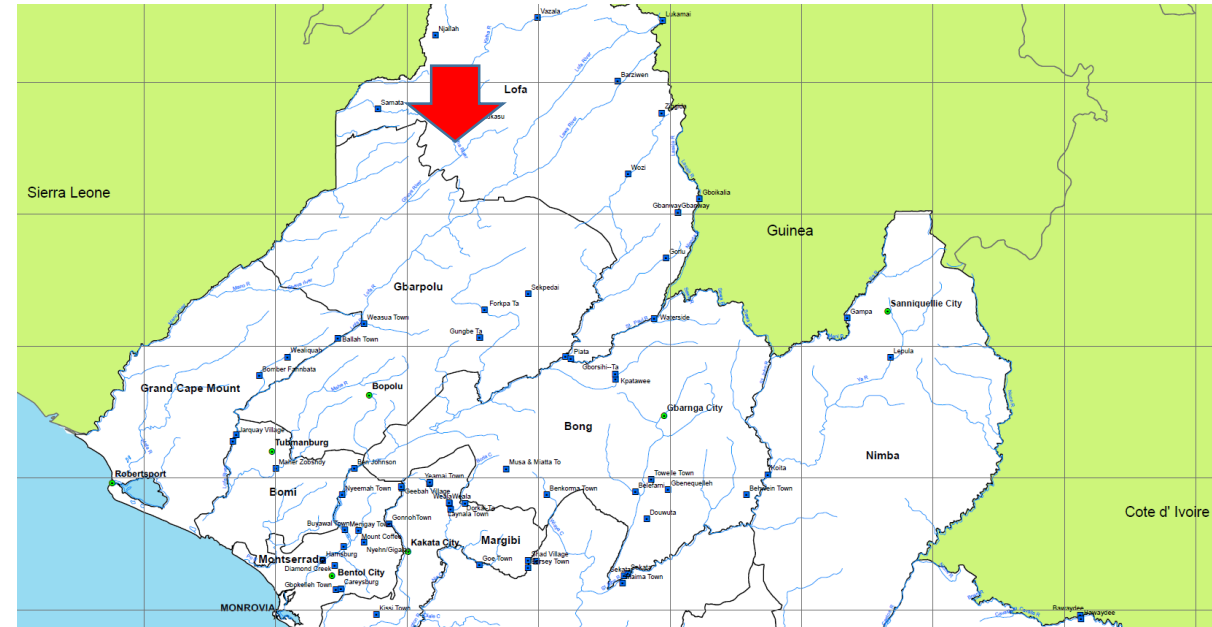
Lofa county

Road access via Voinjama

Approx. 500 km from Monrovia

Remote location

Best site for hydropower in the  
Upper Mano River basin



# Hydrological concerns

- Water availability
  - Availability for production
  - Low flows for ecological safeguard
  - Climate change
- Safety against water-related Extreme events
  - Flood
  - Droughts
  - Climate change

**BANKABILITY**

**INSURANCES**

**SOVEREIGN GUARANTEES**

**ATTRACT INTERNATIONAL  
SUPPLIERS**

# Hydrological action plan

- 1 • Provisional road access to site for investigations & ESIA
- 2 • New river discharge measurement station directly on site
- 3 • Integrate on new station a specific facility for low flows
- 4 • Hydrological study of extreme events (floods and droughts)
- 5 • Regional international collaboration for database on floods
- 6 • Hydrological study on sediment, driftwood and other debris

## Appendix 3

### Liberian watersheds and hydrological-stations Map

[external document to be appended]



## Appendix 4

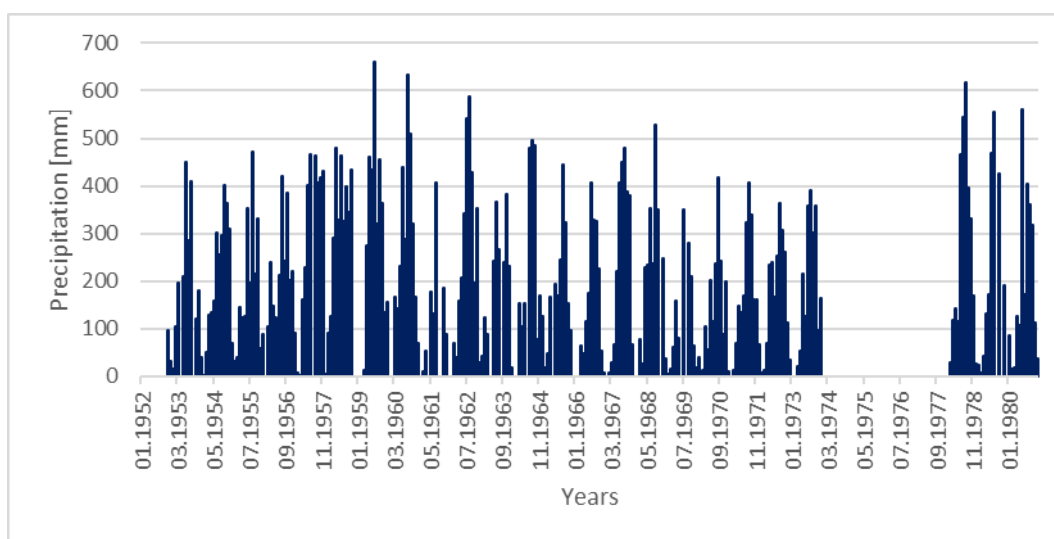
### Mano River, 3 rainfall stations, Voinjama, Kolahun & LISCO Camp: Recorded periods

Complete data  
 Partial data  
 M Monthly data  
 D Daily data

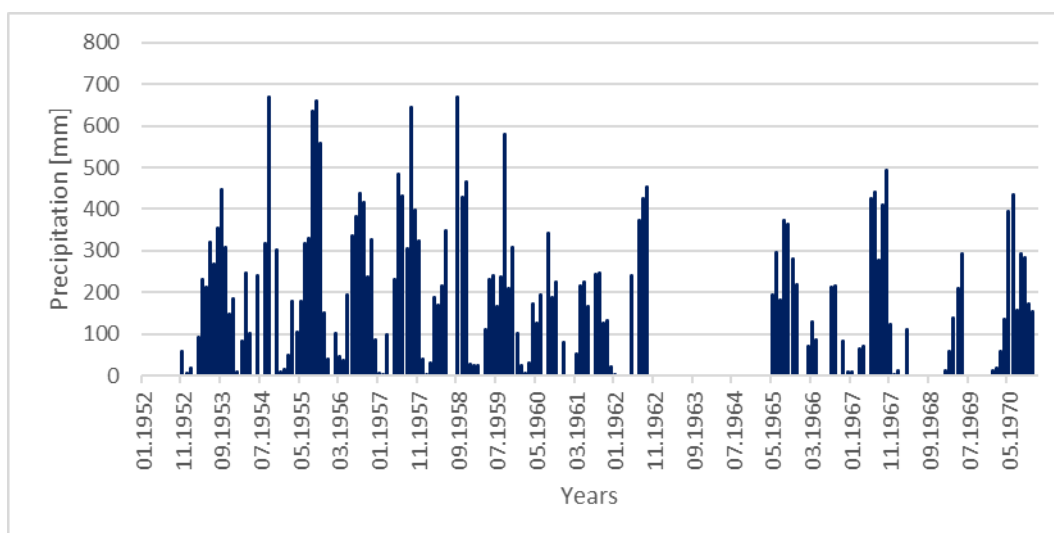
|                                  | Recorded period         | Total years | Percentage of Missing data |
|----------------------------------|-------------------------|-------------|----------------------------|
| Mano River at Voinjama           | [1953-1973] [1978-1980] | 21+3        | 6                          |
| Mano River LISCO Camp (Wologisi) | 1969-1977               | 9           | 6                          |
| Mano River at Kolahun            | 1953-1970               | 18          | 36                         |
| Mano River at Kongo              | 2016                    | 1           |                            |
| Lofa River at Lofa Bridge        | 2013-2016               | 4           |                            |
| Via River at Piatta              | 2013-2016               | 4           |                            |
| St. Paul River at Haindi         | 2013-2016               | 4           |                            |
| LHS                              | [2007-2010] [2013-2016] | 4+4         |                            |
| St. John River at Mt. Finlay     | 2013-2016               | 4           |                            |



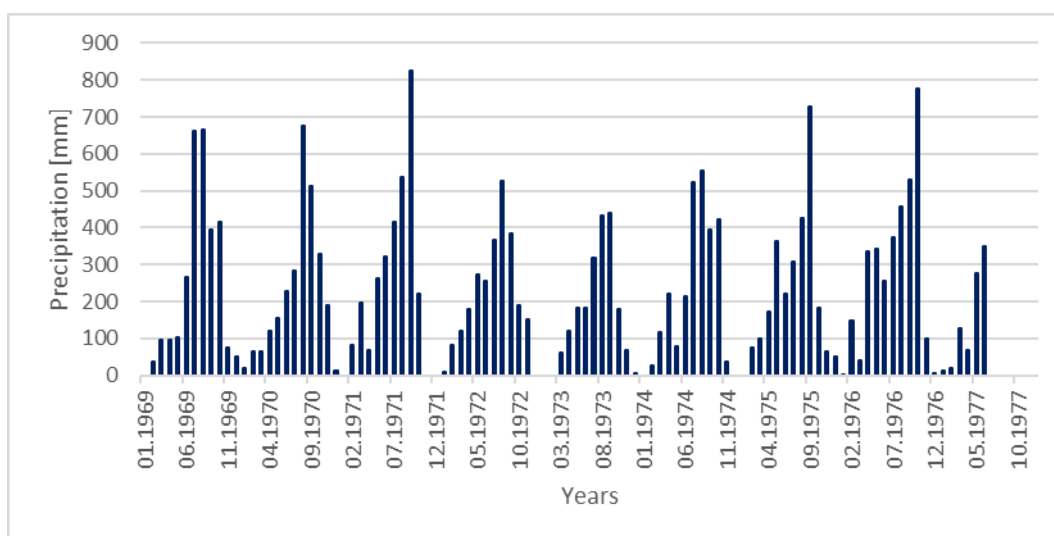
### Time series of rainfall measurements



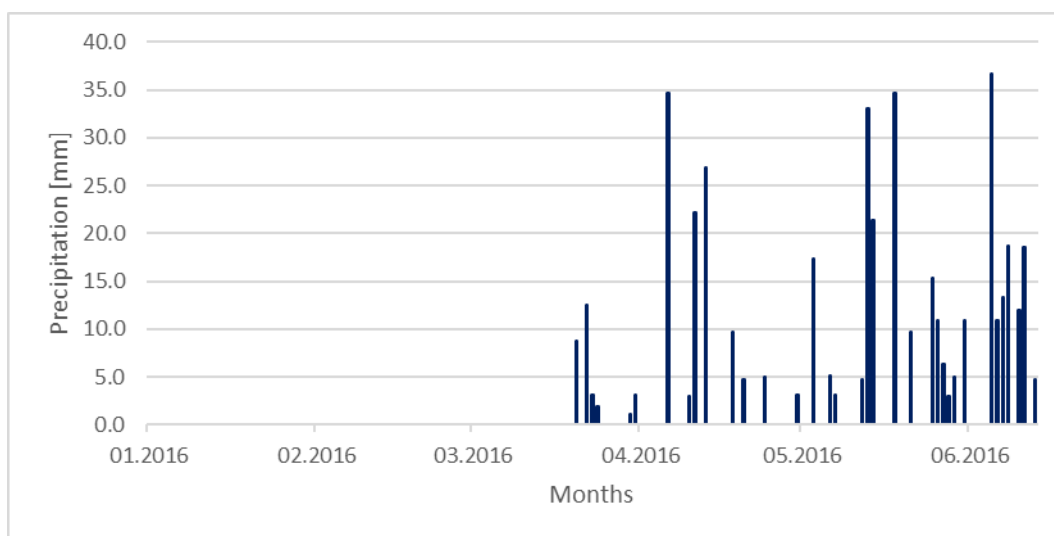
*Time series of rainfall measurements on Mano River at Voinjama rainfall station (1952-1980)*



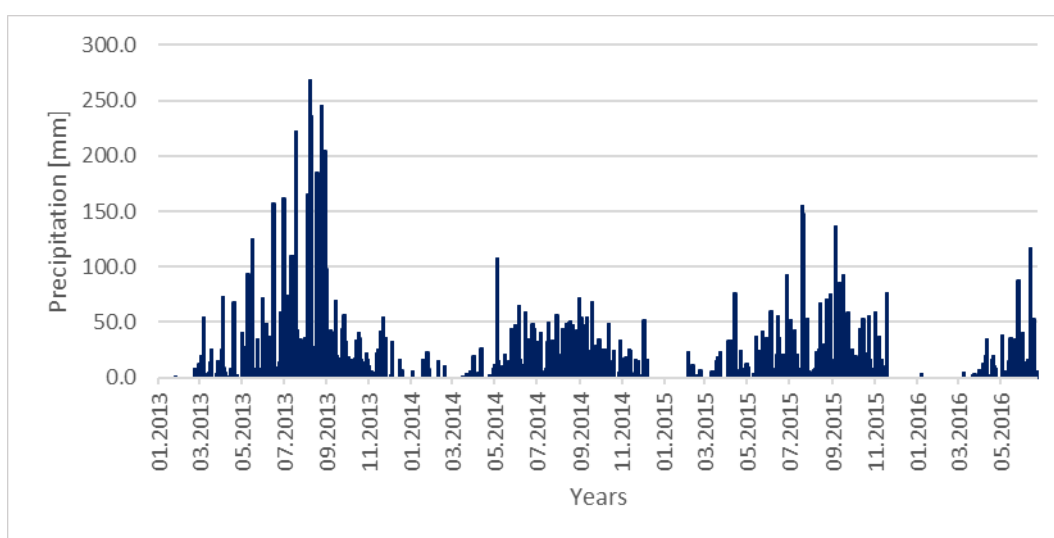
*Time series of rainfall measurements on Mano River at Kolahun rainfall station (1952-1970)*



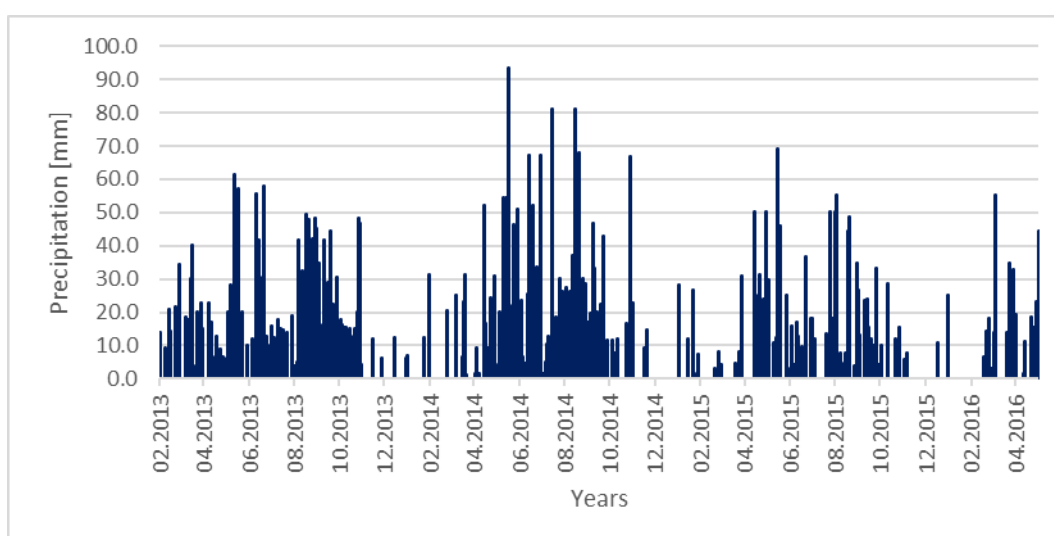
*Time series of rainfall measurements on Mano River at LISCO Camp rainfall station (1969-1977)*



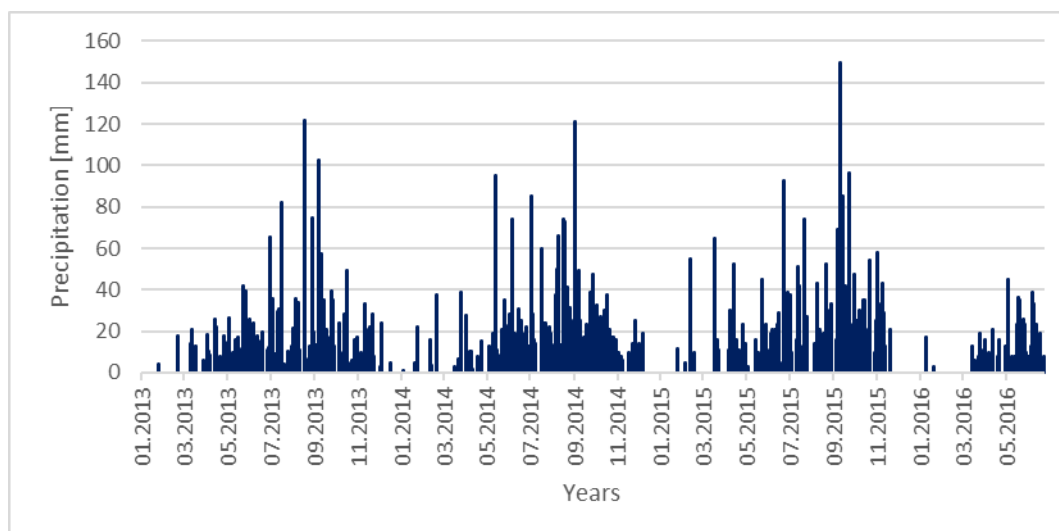
*Time series of rainfall measurements on Mano River at Kongo rainfall station 2016*



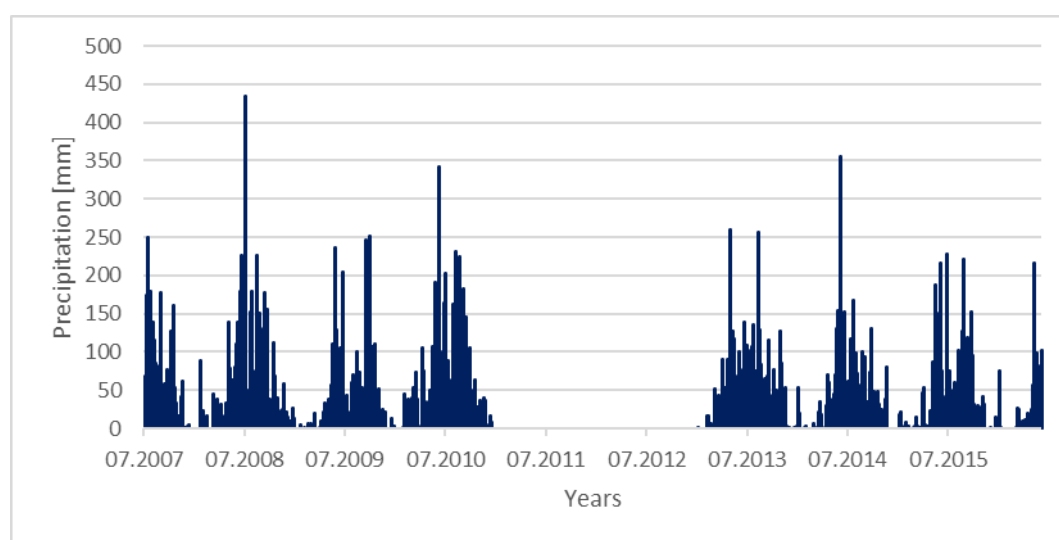
*Time series of rainfall measurements on Lofa River at Lofa Bridge rainfall station (2013-2016)*



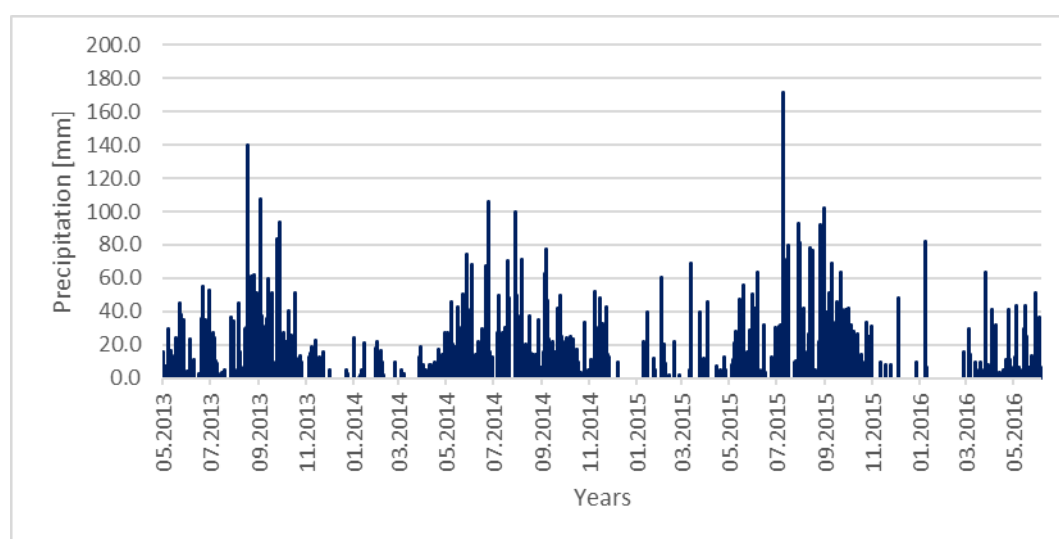
*Time series of rainfall measurements on Via River at Piatta rainfall station (2013-2016)*



*Time series of rainfall measurements on St. Paul River at Haindi rainfall station (2013-2016)*

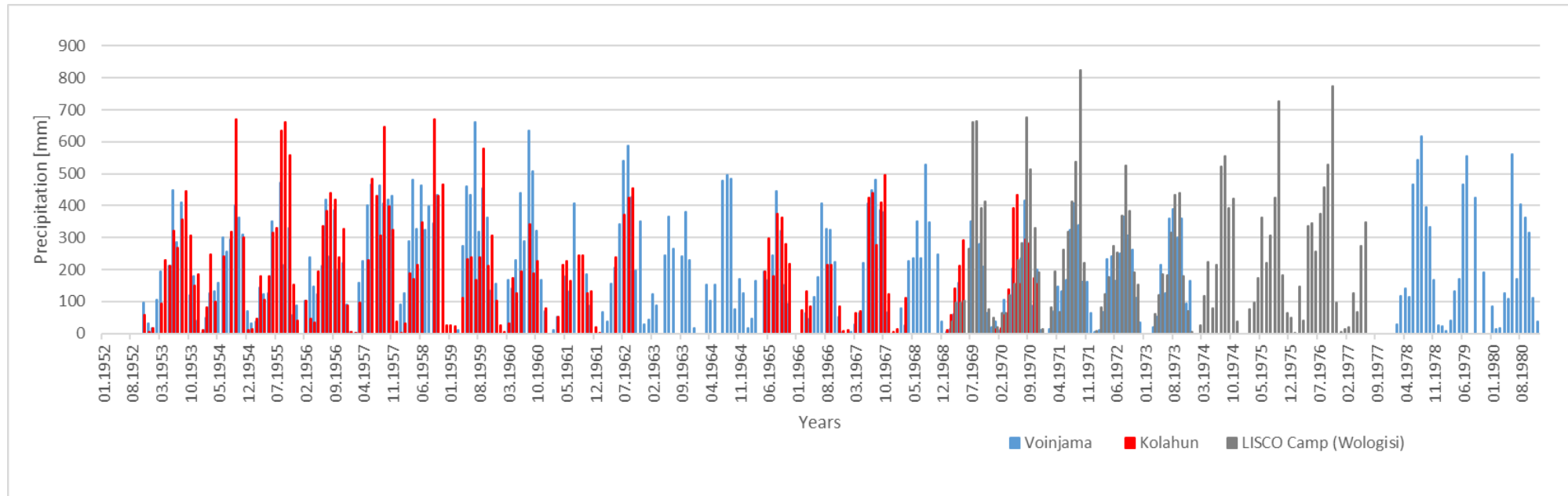


*Time series of rainfall measurements on LHS rainfall station (2007-2016)*



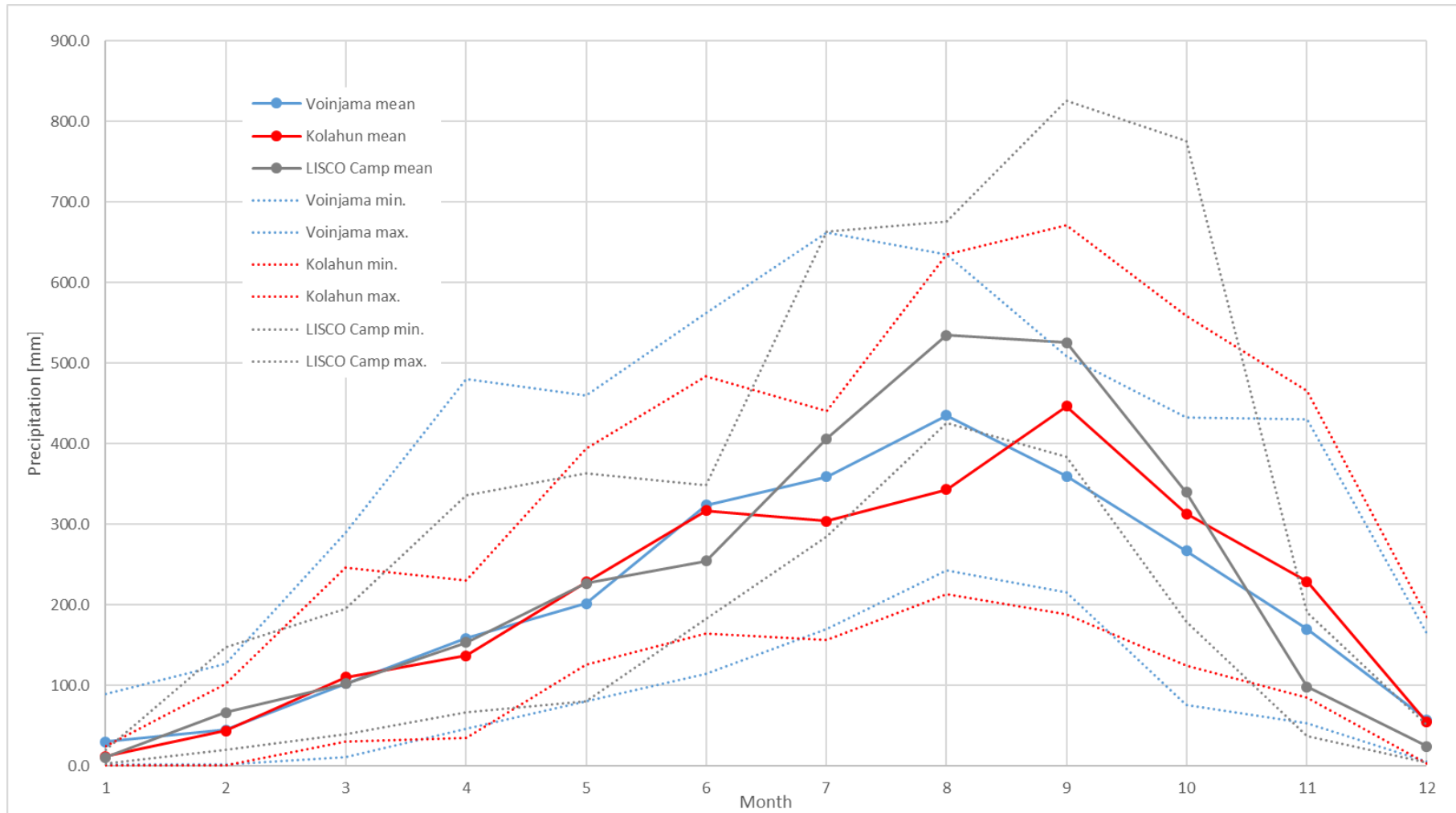
*Time series of rainfall measurements on St. John River at Mt. Finlay rainfall station (2013-2016)*

### Mano river, 3 rainfall stations, Voinjama, Kolahun & LISCO Camp: Time series of rainfall measurements



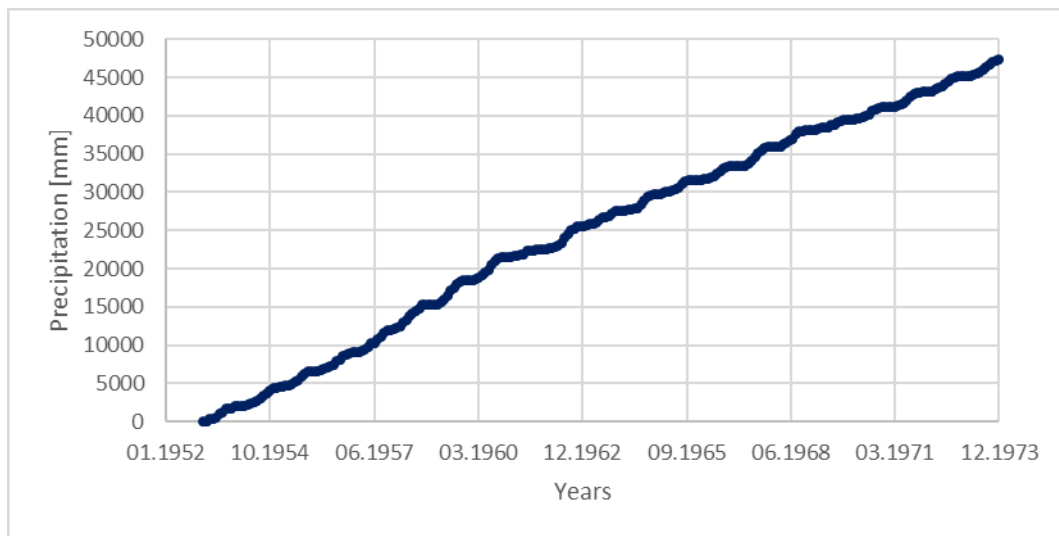
Time series of rainfall measurements on Mano River (3 stations)

**Mano river, 3 rainfall stations, Voinjama, Kolahun & LISCO Camp: Rainfall statistic data**

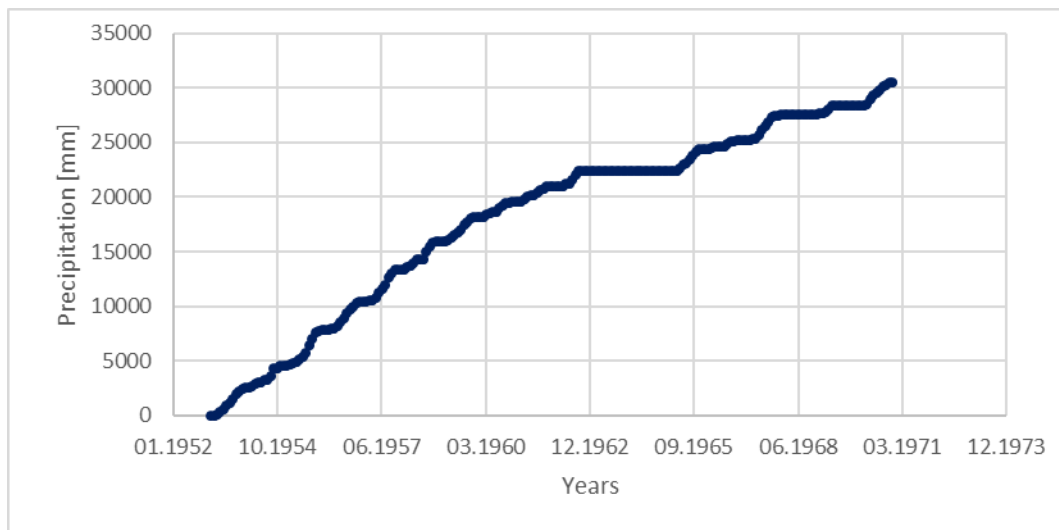


*Rainfall variability*

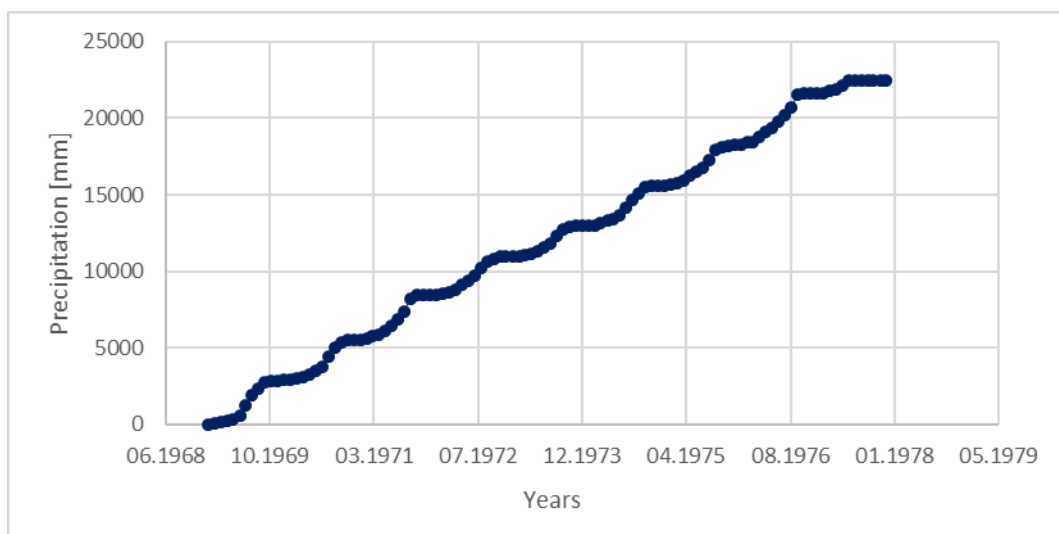
### Mano river, 3 rainfall stations, Voinjama, Kolahun & LISCO Camp: Single mass plot



*Voinjama single mass plot (1953-1973)*

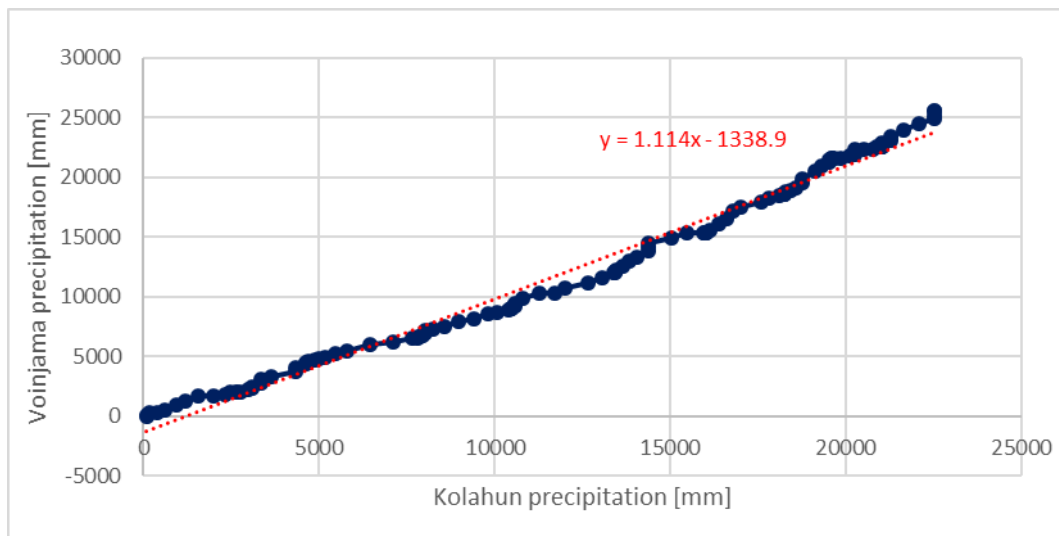


*Kolahun single mass plot, (1953-1970)*

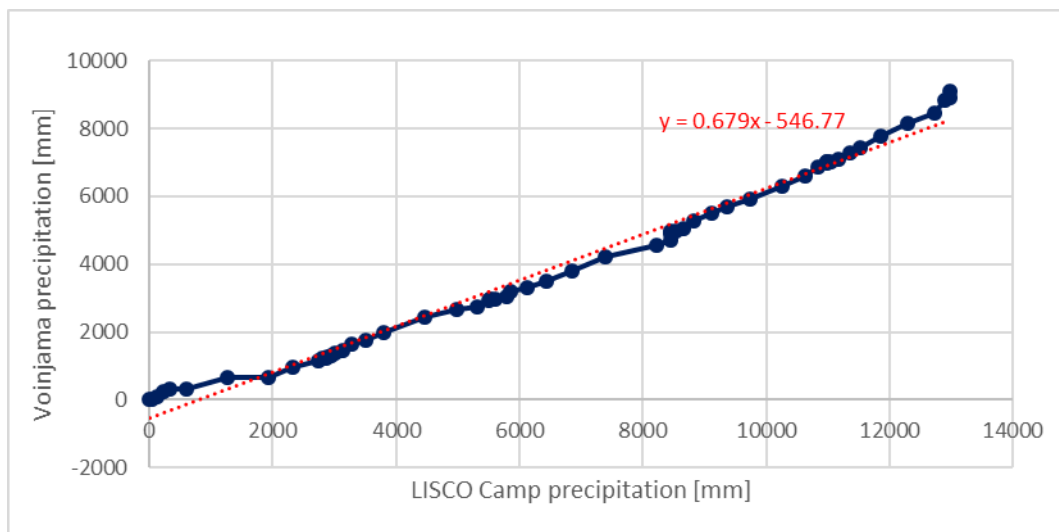


*LISCO Camp single mass plot, (1969-1977)*

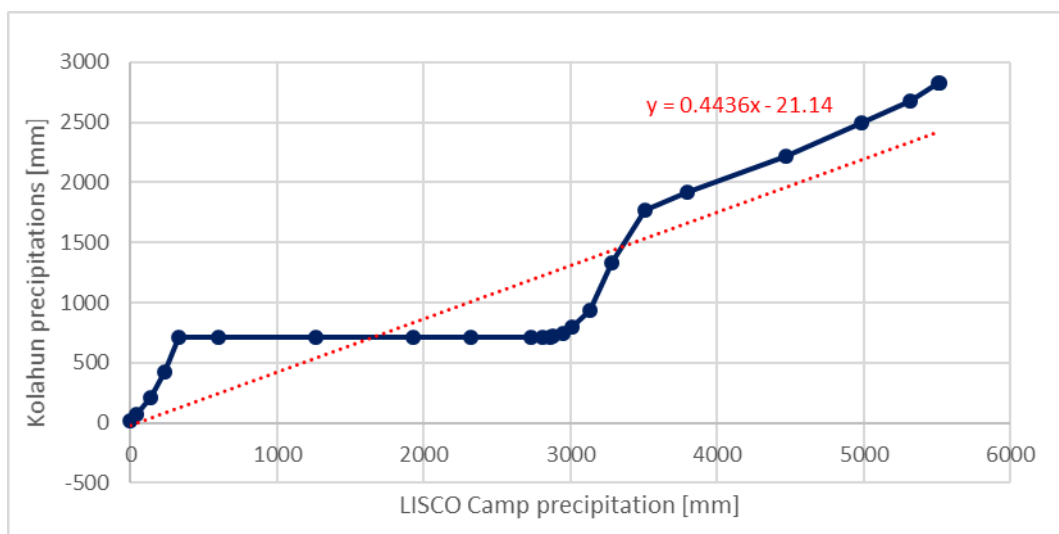
### Mano river, 3 rainfall stations, Voinjama, Kolahun & LISCO Camp: Double mass plot



Double mass plot Rainfall data analysis comparison: X= Kolahun, Y=Voinjama, (1953-1962), 10 years



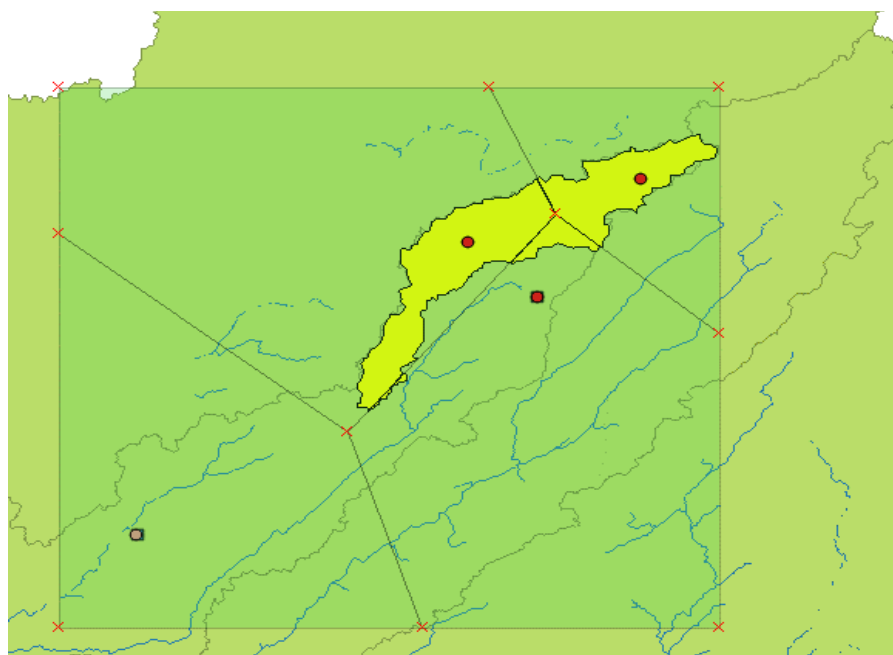
Double mass plot Rainfall data analysis comparison: X= LISCO Camp, Y=Voinjama, (1969-1973), 5 years



Double mass plot Rainfall data analysis comparison: X= LISCO Camp, Y=Kolahun, (1969-1970), 2 years

| NAME                      | BASIN      | EUTM   | NUTM   | X       | Y     | Altitude<br>[m asl] |
|---------------------------|------------|--------|--------|---------|-------|---------------------|
| National Iron Ore Company | Mano River | 266330 | 811149 | -11.117 | 7.333 |                     |
| Voinjama                  | Mano River | 417434 | 930441 | -9.750  | 8.417 | 545.00              |
| Kolahun                   | Mano River | 380695 | 915784 | -10.083 | 8.283 | 483.00              |
| Zoi                       | Mano River | 310647 | 847826 | -10.717 | 7.667 | 472.00              |
| LISCO Camp (Wologisi)     | Mano River | 395349 | 902846 | -9.950  | 8.167 | 581.00              |
| Mano River Kongo          | Mano River | 264498 | 813002 | -11.133 | 7.350 |                     |

*Available rainfall stations in the Mano River Basin*



*Specific weight of independent rainfall stations for definition of catchment rainfall over the Kaiha 2 watershed according Thiessen polygon analysis: Voinjama (35%, El. 545), Lisco Camp (7%, El. 581) and Kolahun (58%, El. 483). Elevations obtained from Google Earth (public access).*

## Appendix 5

### New gauging station: low flows control and measurements

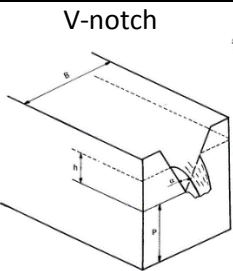
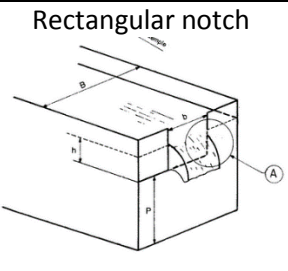
This document introduces a first design of a gauging station composed by a thin-plate weir and staff gage for measurement of low flows at the Kaiha 2 project site. Water level  $h$  [m] is measured with a staff gage upstream the weir. Rating curve known from weir design (geometry) gives an estimation of flow in function of observed water level using the relationship  $Q[m^3/s] = f(h[m])$ .

#### WEIR DESIGN

##### Weir type

There are many methods to measure streamflow. In natural rivers, a suitable solution is to design an artificial control section (weirs) to generate critical flow. Choice of thin-plate weir shapes depends on the target flow range and measurement accuracy. The two main shapes are shown in Table 3. Trapezoidal weir is removed from analysis because of its complex geometry.

Table 3 - Comparison between V-notch and rectangular notch thin plate weir  
(source: G. REMENIERAS, Hydrology for Engineers)

| Design                  | V-notch                                                                            | Rectangular notch                                                                   |
|-------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|                         |  |  |
| Flow range <sup>3</sup> | $1 \text{ l/s} < Q < 1000 \text{ l/s}$                                             | $10 \text{ l/s} < Q < 5000 \text{ l/s}$                                             |

The lowest measured flow discharge available is 510 l/s, measured in March 2016 at Kolahun gauge (01MA001) for which a 3-year long record is available. The corresponding flow at Kaiha 2 project site is estimated around 850 l/s based on a linear surface ration between the Kolahun gauge section catchment area (673 km<sup>2</sup>) and project catchment area (1129 km<sup>2</sup>). For such maximum discharge in the dry season, a V-notch weir would be suitable. However, for somewhat higher discharges of up to 1000 l/s a rectangular weir should be preferred (see Figure 7).

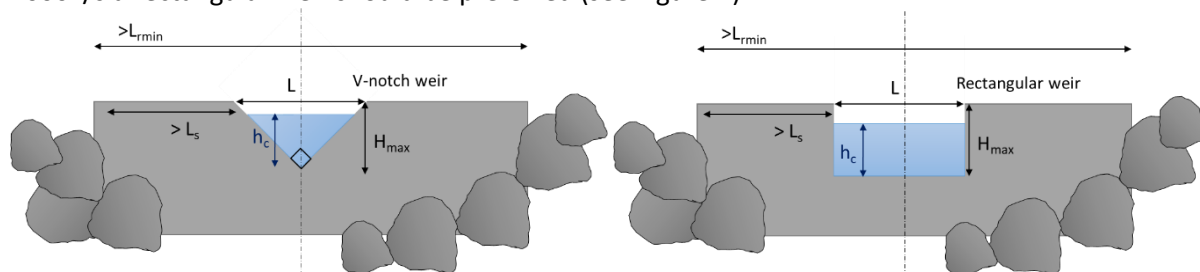


Figure 7 Weir shapes and dimensions,  $h_c$  is the critical water level occurring at the control section.

<sup>3</sup> MhyLab déversoir (2007) citing Benoist and Birgand, « Les dispositifs de mesure des débits dans les bassins versants agricoles », IRSTEA 2002. <http://medhycos.mpl.ird.fr/fr/data/hyd/Drobot/5C.htm> (online access 11.10.2017).

### Weir dimensions

Weir dimensions are estimated in Table 4 for both V-notch and rectangular options for three maximum flows: 800 l/s, 1000 l/s and 3000 l/s. Some river requirements are also given.

Table 4 - Weir dimensions

|                                           |          | V-notch weir |       |       | Rectangular weir |       |       |
|-------------------------------------------|----------|--------------|-------|-------|------------------|-------|-------|
| Maximum flow                              | Qmax l/s | 800          | 1 000 | 3 000 | 800              | 1 000 | 3 000 |
| Maximum water level on weir crest         | Hmax m   | 0.80         | 0.87  | 1.35  | 0.38             | 0.44  | 0.95  |
| V-notch width                             | L m      | 1.59         | 1.74  | 2.70  | 1.13             | 1.32  | 2.84  |
| Minimum river length upstream weir        | Drmin m  | 7.96         | 8.70  | 13.50 | 3.76             | 4.39  | 9.46  |
| Minimum river width upstream weir         | Lrmin m  | 2.78         | 3.04  | 4.72  | 2.63             | 3.07  | 6.62  |
| Minimum river depth upstream weir         | Hrmin m  | 1.19         | 1.30  | 2.02  | 0.75             | 0.88  | 1.89  |
| Minimum staff gage distance upstream weir | DImin m  | 2.39         | 2.61  | 4.05  | 1.13             | 1.32  | 2.84  |
| Maximum weir thickness                    | tmax mm  | 20.00        |       |       | 20.00            |       |       |
| Minimum weir thickness                    | tmin mm  | 5.00         |       |       | 5.00             |       |       |
| Weir side width                           | Ls m     | 0.60         | 0.65  | 1.01  | 2.26             | 2.63  | 5.68  |

### Other design considerations

To properly design the weir other features should be defined:

- *Installation lifetime*: one or several dry seasons, temporary or permanent installation.
- *Weir material*: depends on installation lifetime and handling. To remove it easily before wet season, a light material like wood or reinforced steel is appropriate (Figure 8). It can be conceived for manufacturing in a local workshop.
- *Foundation*: the weir should be fixed on the riverbed to ensure stability and avoid leakage.
- *Sediments*: the weir should allow for easy removal of debris and sediment (e.g. by shovel, by lifting) and may be equipped with an orifice equipped with a hand-valve. Should it be left in position during the wet season, it may be severely damaged and require full replacement.



Figure 8 Example of a V-notch weir with wood plate (<http://www.dransenergie.ch/>)

## **WATER LEVEL MEASUREMENT**

To measure water level  $h$ [m] upstream weir, a vertical staff gage (graduated ruler) is installed (Figure 9). Some set up instructions should be followed, the main ones being:

- The staff gage *needs to be able to hold up against high water or wind, but also not be too heavy to carry and set it easily* [USACE]. It is better to attach the staff gage on a permanent structure like a bridge or a dock; if there is none, a sturdy fence could be used.

- Avoid placing the staff gage in a location where the water pools or is very slow moving, because sediments will collect around the base of the staff gage and affect readings [USACE].

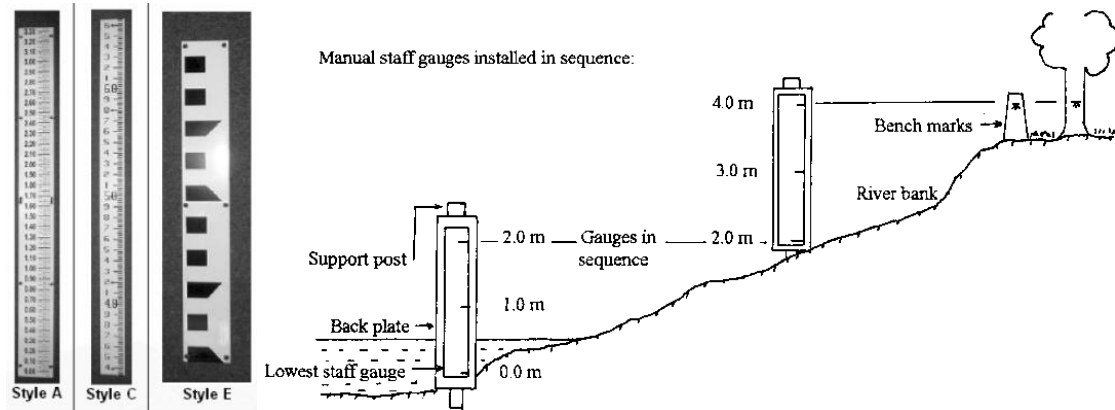


Figure 9 Photos of staff gage (USACE) and configuration  
(scheme from S. Miller, NRI, NATURAL RESOURCES INSTITUTE, Overseas Development Administration)

- The staff gage location should be far away upstream the weir to meet permanent (steady-state) and uniform flow (Figure 10).
- *Setting the staff gage level:* zero mark on ruler should be set to a topographic reference system and periodically checked/levelled.

Water level is directly read (manual visual measurement) on staff gage and daily reported on a table. One observation per day should be sufficient to obtain a rating curve.

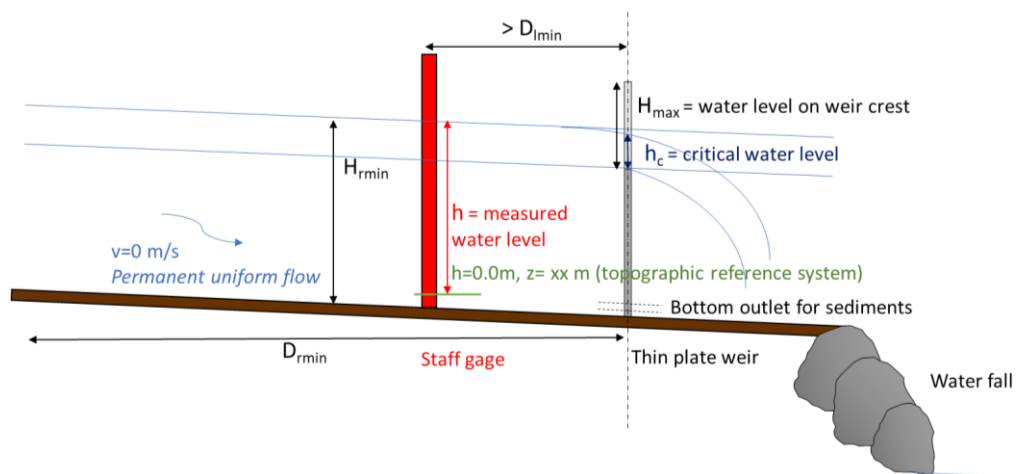


Figure 10 Longitudinal view of gauging station along idealized river bed.

## LOCATION AND CONSTRUCTION

The gauging station is installed on Kahia 2 project site upstream of the waterfall/rapids, profiting from one of the existing gullies in the rocky sill on the onset (Figure 11). The selection of a good location must satisfy the following requirements:

- The staff gage is installed in a location with stable backwater conditions (steady-state, uniform), considering the local riverbed slope, the local channel geometry (e.g. river minimum width), the minimum water depth etc.

- The river flow in dry season should be channelized into one single path. To avoid multiple water pathways, block other channels by placing rocks/structure/materials, forcing the flow to converge into the equipped channel (see on Figure 12).
- The weir structure and the staff gage should be preferably installed in dry conditions, while the river is diverted elsewhere using temporary structures (i.e. low cofferdam-like). Once the installation works are concluded, the temporary diversion is removed (or relocated and reinforced at previous diversion channel).
- The staff gage should be easily accessible from one of the river banks, by foot in dry conditions.
- An access road should be available for construction and maintenance.



Figure 11 Downstream view of waterfall on Kaiha 2 project site (Multiconsult prefeasibility studies report, 2016)

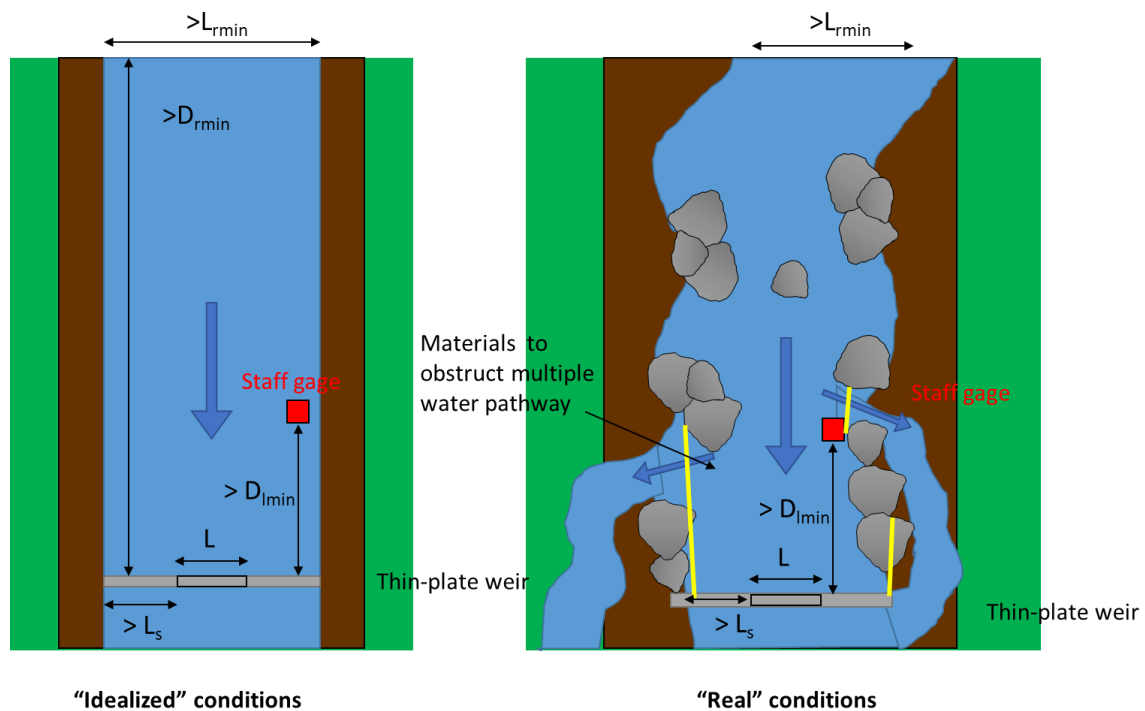


Figure 12 Choice of gauging station location: idealized vs. real conditions.