Small Hydro Resource Mapping in Madagascar

SMALL HYDRO MAPPING REPORT

[ENGLISH VERSION]

April 2017

This report was prepared by SHER Ingénieurs-Conseils s.a. in association with Mhylab, under contract to The World Bank.

This is a final output from the small hydro resource mapping component of the activity "Renewable Energy Resource Mapping and Geospatial Planning – Madagascar" [Project ID: P145350]. This activity is funded and supported by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank, under a global initiative on Renewable Energy Resource Mapping. Further details on the initiative can be obtained from the ESMAP website.

The **Small Hydro Mapping Report** complements the Hydro Atlas for Madagascar and summarizes the analysis methodology and the results of the literature phase and the field phase. This is a **final output** and will be published, together with the Hydro Atlas for Madagascar, via The World Bank's main website and listed on the ESMAP website along with the other project outputs - please refer to the corresponding country page.

Washington DC 20433
Telephone: +1-202-473-1000
Internet: www.worldbank.org

Phase 3 - Production of a Validated Resource Atlas

SMALL HYDRO MAPPING REPORT

Renewable Energy Resource Mapping: Small Hydro – Madagascar [P145350]
April 2017

English version

IN ASSOCIATION WITH

FINAL OUTPUT

Correspondence Table between the terms of reference and reporting and the ESMAP phases:

ESMAP General Phasing	Correspondence with ESMAP-Small Hydro Madagascar ToR
Phase 1 Preliminary resource mapping output based on satellite and site visits	**Activity 1** - Data collection and production of Hydro Atlas, review and validation of small hydro potential **Activity 2** - Small hydro electrification planning **Activity 3** - Small hydro prioritization and workshop
Phase 2 Ground-based data collection	**Activity 4 -** Data collection and final validation (from the REVISED TERMS OF REFERENCES FOR THE ACTIVITY 4) : A - Review of previously studied small hydropower sites B - Data collection and final validation C - Pre-feasibility study of two priority sites for small hydropower development
Phase 3 Production of a validated resource atlas that combines satellite and ground-based data	D - Support to the Ministry of Energy to build capacity and take ownership of the created GIS database for hydropower E - Updated Small Hydro Mapping Report for Madagascar

SHER Ingénieurs-conseils s.a.
Rue J. Matagne, 15
5020 Namur – Belgium
Phone : +32 81 32 79 80
Fax : +32 81 32 79 89
www.sher.be

Project Manager: *Rebecca DOTET*
Référence SHER : *MAD04*
Phone : *+32 (0) 81 327 982*
Fax : *+32 (0) 81 327 989*
E-mail : *dotet@sher.be*

Rev.n°	Date	Content	Drafted	Verified
0	01/2015	Hydro Mapping Report - Interim **English version**	Gérard CHASSARD	Pierre SMITS
1	03/2015	Mapping Report - FINAL **English version**	Gérard CHASSARD	Pierre SMITS
2	04/2017	Mapping Report - FINAL (update Phase 3) **English version**	Quentin GOOR	Pierre SMITS

In case of discrepancy, the French version prevails

SHER INGÉNIEURS-CONSEILS S.A.
IS ISO 9001 CERTIFIED

Abbreviations and acronyms

ADEME	Agence de Maîtrise de l'Energie
ADER	Agence de Développement de l'Electrification Rurale (Development Agency for Rural Electrification)
AO	Appel d'Offre
DDP	Detailed Draft Project
APIPA	Autorité pour la Protection contre les Inondations de la Plaine d'Antananarivo
PDS	Proposed Draft Summary
AfDB	African Development Bank
BDHM	Banque de Données Hydro pluviométriques de Madagascar (Malagasy Data Bank of Rainfall)
EIB	European Investment Bank
WB	World Bank
BRGM	Bureau de Recherches Géologiques et Minières (Geological and Mining Research Bureau)
CIRAD	Centre International de Recherche pour l'Agriculture et Développement (International Research and Agricultural Development Centre)
DGE	Direction de l'Energie (Energy Division)
DGM	Direction Générale de la Météorologie (General Department of Meteorology)
DGRE	Direction de la Gestion des Ressources en Eau (Department of Water Ressources Managment)
EDM	Electricité de Madagascar (Malagasy Electricity)
RE	Renewable Energy
ERD	Decentralised Rural Electrification
ESF	Electriciens Sans frontières
ESMAP	Energy Sector Management Assistance Program
EU	European Union
ADF	African Development Fund
FMO	Netherlands Development Finance Company
FONDEM	Fondation Energies pour le Monde
FTM	Foiben-Taosarintanin'i Madagasikara (Malagasy Cartography Centre)
FWC	Framework Contract
GEOSIM	Logiciel de planification de l'Electrification Rurale (Rural Electrification Planning Software)
GHG	Greenhouse Gas
GIS	Geographical Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (German Society for International Cooperation)
GRDC	Global Runoff Data Centre
GRET	Groupe de Recherche et d'Echanges Technologiques (Group for Research and Technological Exchanges)
GTE	Groupe de Travail Energie (Energy Working Group)
GTZ/GIZ	Deutsche Gesellschaft für Technische / Internationale Zusammenarbeit GmbH (German Society for Technical / International Cooperation)
GVEP	Global Village Energy Partnership
GWh	Giga Watt hour, Billions of kWh or Millions of MWh
HFF	Henri Fraise & Fils (société) (Henri Fraise and Sons company)

IED	Innovation Energie Développement (Energy Development Innovation)
IEPF	Institut de l'Energie et de l'Environnement de la Francophonie (Institute of Energy and Francophone Environment)
INSTAT	Institut National de la Statistique (National Statistics Institute)
IPP's	Independent Power Producer's
IRENA	International Renewable Energy Agency
JICA	Japan International Cooperation Agency
JIRAMA	Jiro sy Rano Malagasy (Malagasy Electricity and Water Board)
kW	kilo Watt
kWh	kilo Watt hour
LCOE	Levelized Cost Of Electricity
MAP	Madagascar Action Plan
MoE	Ministry of Energy
MDE	Maîtrise De l'Energie (Energy Control)
MGA	Malagasy Ariary
MIGA	Multilateral Investment Guarantee Agency
DTM	Digital Terrain Model
MW	Mega Watt
MWh	Mega Watt hour
NEPAD	NEw Partnership for Africa's Development
NOAA	National Oceanic and Atmospheric Administration
ONE	Office National de l'Environnement
NGO	Non-Governmental Organisation
OER	Office of Electricity Regulation
ORSTOM	Office de la recherche scientifique et technique outre-mer (Overseas Office Of Scientific and Technical Research)
PADR	Plan d'Action pour le Développement Rural (Action Plan for Rural Development)
PIC	Projet Pôles Intégrés de Croissance (Integrated Poles Project of Growth)
UNDP	United Nations Development Programme
PPP	Public-Private Partnership
PV	Solar Photovoltaics
RFE	Rainfall estimates
RIAED	Réseau International d'Accès aux Energies Renouvelables (International Network for Access to Renewable Energy)
RTA	Rio Tinto Alcan
ES	Electrical System
SFI	International Finance Corporaion
GIS	Geographic Information System
SNAT	Stratégie Nationale d'Aménagement du Territoire (National Territorial Strategy Planning)
TWh	Tera Watt hour
WB	World Bank
WWF	World Wildlife Fund

Table of Content

List of Figures

List of Tables

1 Introduction

1.1 GENERAL CONTEXT OF THE ESMAP – FWC PROJECT

ESMAP (Energy Sector Management Assistance Program) is a technical assistance program administered by the World Bank and supported by 11 bilateral donors. In January 2013, ESMAP has launched an initiative that will support country-driven efforts to improve awareness about renewable energy resources (RE), implement appropriate policy frameworks for RE development, and provide 'open access' to resources and geospatial mapping data. This initiative will also support the IRENA-Global Atlas by improving the data availability and quality that can be consulted through the interactive Atlas.

The present study "Renewable Energy Resource Mapping: Small Hydro Madagascar", is part of a technical assistance project, funded by ESMAP, implemented by the World Bank in Madagascar (the "Client"), which aims at supporting the mapping resources and the geospatial planning for small hydropower. It is conducted in close coordination with the Ministère de l'Energie et des Hydrocarbures, the Office de Régulation de l'Electricité (ORE), the Agence de Développement de l'Electrification Rurale (ADER) and JIRAMA.

1.2 FRAMEWORK OF THE SMALL HYDRO MAPPING REPORT IN MADAGASCAR

The Hydro Mapping Report is the result of the consolidation of the results of the study. It was written in interaction with the Hydro Planning Report and complements the HydroAtlas. It includes the analysis methodology and the results of the literature phase and the field phase. This report presents all the activities carried out in the frame of the study and the relations between them.

1.3 OBJECTIVES, RESULTS AND ACTIVITIES OF THE STUDY

The objectives of the study are:

1. The improvement of the quality and availability of information about the hydropower resources in Madagascar;
2. A detailed review and update of small hydro potential (1-20 MW), and
3. Recommendations about the implementation of the small hydropower in the framework of the energy sector planning.

Expected results from the study are:

1. Assembled data in a geographical database (GIS);
2. A thematic atlas on hydropower in Madagascar with a particular emphasis on small hydro, and
3. Recommendations to develop the small hydropower sector in Madagascar.

The 3 phases of the ESMAP study are :

- **PHASE 1 :** Preliminiary mapping of the resources based on spatial analysis and site visits
- **PHASE 2 :** Field data collection campaign
- **PHASE 3 :** Production of a validated Atlas of the resources combining spatial data and field measurements

The activities of the study are:

- **Activity 1:** Data collection and production of HydroAtlas / Review and validation of small hydropower potential
- **Activity 2:** Integration of small hydro development in the electrification planning (rural and interconnected) in Madagascar
- **Activity 3:** Priorisation of small hydro, site visits and validation of the workshop
- **Activity 4:** Field data collection and final validation: (update HydroAtlas / campaign of hydrological measurements / additional studies in geology and environment)

An analysis and priorisation process was put forward, discussed and approved by the Malagasy party during activity 1 of the project. This process, presented in Figure 1 below enables us to understand the interaction between the different study phases.

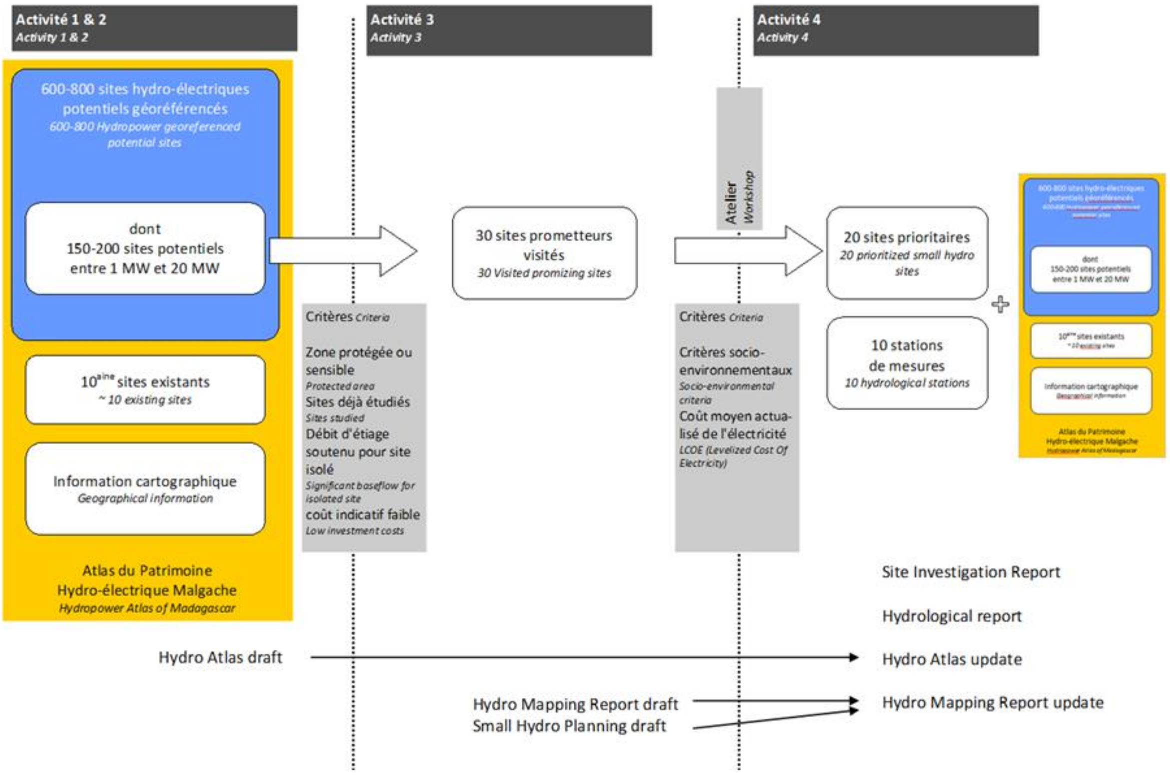


Figure 1. Analysis and priorisation process

2 Physical characteristics of Madagascar

2.1 GEOGRAPHY

The island of Madagascar is located in the southwest Indian Ocean, near East Africa, from which it is separated by the 400 km wide Mozambique Channel. Following a general direction NNE-SSW, it extends over a length of 1600 km, from Cap d'Ambre to the Cap Sainte-Marie, between 11°57' and 25°39' south. In its longest length, Madagascar is about 570 km. The meridian 47° east of Greenwich shares the island into two roughly equal parts. Its area is around 590,000 km² which is equivalent to France, Belgium and the Netherlands combined.

Antananarivo, the capital, is about 2,000 km from the equator and 8,000 km from the South Pole. Small "neighboring" islands of the Antarctic (Crozet, Kerguelen, etc.) are at 4000 km further south. The island is crossed by the Tropic of Capricorn, a little above the latitude of Toliara, that is to say, its southern part is at the same latitude of the African deserts of the southern hemisphere. This results in a moderate arid climate in this area, which is however moderated by the proximity of the sea. Madagascar is almost entirely within the tropics. But the influence of the relief, latitude and exposure creates a great climate diversity causing an extreme complexity of the hydrological regimes.

2.2 GEOMORPHOLOGY

What is immediately visible when considering a physical map of Madagascar, is the asymmetry of the island on its major axis. The western slope gently spreads to the Mozambique Channel, while the slope of the eastern side is very steep; the water divide is always less than 100 km on average from the Indian Ocean.

This characteristic of the relief has a direct impact on the drainage patterns: the longest rivers will be those of the western side while on the eastern side, the shortest rivers have a very pronounced profile with many falls and rapids.

A more detailed analysis of the relief of Madagascar will show certain characteristics that will influence more or less directly the surface water flow.

Madagascar can be divided into three main orographic units: the central highlands, the eastern side, the sedimentary area of northern west, west and south.

2.3 HYDROLOGY

The main rivers drain approximately 335 405 km² watershed, or 57% of the total area of the country. The surface water resources are estimated at 332 km³/year and groundwater resources at 55 km³/year. The 13 most important reservoirs have a total estimated capacity of 493 million m3, 108 million of which are for irrigation and 385 million for hydropower.

The effects of climate change are difficult to quantify in Madagascar. Detecting changes in annual rainfall is difficult because changes during the year may offset, and it is mainly the distribution of rainfall during the year that varies. The overall effect during the period which is of interest for small hydro investments (20-25 years) is likely to be small. The future investments projects should consider future studies on climate change.

On hydrological regimes, phenomena are cited as "capture" between two rivers Mahajamba and Kamoro currently evolving towards Mahajamba. There is also a decrease in the level and siltation of Lake Alaotra. For the last 25 years, the average annual number and intensity of cyclones affecting Madagascar have increased (50 cyclones category 4-5 between 1990 and 2004 against 23 between 1975 and 1989).

All these events disrupt enormously the crop calendar resulting in yield losses and also causing devastation of crops by flooding and silting of plots. Within the specific measures to fight against these events, the priority measure is the rehabilitation of weather stations, gauging stations in large reservoirs and rivers for the monitoring of river systems and also for lakes to better understand the importance and changing variations.

Note that only the rivers around the city of Antananarivo have gauges as part of a flood warning system and the protection of the city in case of flooding.

3 Implementation of the geographical database

All the elements concerning the hydropower sector in Madagascar with a geographical reference are introduced in a Geographical Information System (GIS) and presented in the following sections.

3.1 CONTEXTUAL GEOGRAPHICAL DATA

There are two types of geographical data:

- **Raster Data**: these data represent the information by a cell grid with a uniform size to which values are given. Each cell covers a geographical area considered uniform (attribute value).
- **Vector Data**: these are graphical data given as points, lines, or polygons to which attributes are assigned.

The geographical data collected during Activity 1 and contributing to the Geographical Information System (GIS), their main characteristics as well as their sources, are given in the following table:

THEMATIC	FORMAT	MAIN CHARACTERISTICS	SOURCES
Administrative limits	Vector	Countries / Provinces / Regions / Districts / Town	Institut Géographique et Hydrographique de Madagascar (FTM) FTM BD500, FTM BD200
Main towns	Vector	32 cites and towns	Open Street Map, 2014
Topographic maps	Raster	1:1,000,000	FTM
	Raster	1:500,000	FTM
	Raster	1:100,000 complete cover of the country	FTM
	Raster	1:50,000 partial cover of the country	IGN France / FTM
Digital Terrain Model (DTM)	Raster	SRTM v4.1 Spatial resolution ~ 90m	NASA, 2014 http://www2.jpl.nasa.gov/srtm/
	Raster	ASTER GDEM v2 Spatial resolution ~ 30m (experimental)	http://www.jspacesystems.or.jp/en_/
Land use	Vector	11 classes of land use	Schéma National d'Aménagement du Territoire (SNAT)
Protected areas	Vector	SAPM / prioritized sites/ potential sites	Atlas numérique du système des aires protégées de Madagascar (SAPM) http://atlas.rebioma.net/
Geology	Raster	1:1,000,000	Schéma National d'Aménagement du Territoire (SNAT)
	Vector	Digitising boards to 1 :500,000	Geological service 1969
Soil maps	Raster	1:1,000,000	ISRIC-WISE, 2006
Land degradation	Raster	1:1,000,000	ISRIC-GLASOD, 1991
Pedology	Raster	1:1,000,000	Schéma National d'Aménagement du Territoire (SNAT)
	Raster	1:10,000,000	
Geomorphology	Raster	1:1,000,000	Schéma National d'Aménagement du Territoire (SNAT)

THEMATIC	FORMAT	MAIN CHARACTERISTICS	SOURCES
Mining concessions	Vector	-	Bureau Du Cadastre Miniers de Madagascar (BCMM)
Satellite image	Raster	Landsat Image 1999	Google Earth
	Raster	Landsat Image 2005	Google Earth
Population density	Raster	Landscan Image Resolution ~1km (average over 24h)	Oak Ridge National Laboratory, 2012
Poles of development	Vector	Areas benefiting from specific support actions from the government	Schéma National d'Aménagement du Territoire (SNAT)
Lakes	Vector	Inland water bodies in Africa	FAO, 2000 http://www.fao.org/geonetwork
Hydrography	Vector	River "flow accumulation" network from the HYDRO1k for Africa	FAO, 2006 http://www.fao.org/geonetwork
Gauging stations	Vector	Location of stations	GRDC, Direction Générale de la Météorologie de Madagascar, ouvrage « Fleuves et Rivières de Madagascar, 1992 »
Average monthly precipitation and temperature	Raster	Spatial resolution ~ 1km	WorldClim, v1.4 http://www.worldclim.org/
Roads	Vector	National roads, main roads and tracks	FTM BD500, FTM BD200
Interconnected networks (RI)	Vector	Reconstructed from several files and different origins	JIRAMA, ORE, SHER
Existing electricity production and distribution centres	Vector	Made from the document « Diagnostic du Secteur Energie, 2012 »	JIRAMA, 2012
Existing hydropower plants	Vector	Compilation from different origins	JIRAMA, ORE, MoE, SHER
Potential hydropower sites	Vector	Compilation from different origins	JIRAMA, ORE, World Bank, MoE, ADER, SHER

Table 1. Collected geographical data (GIS)

3.2 EXISTING ELECTRICITY PRODUCTION SITES

According to statistics on the plants of Concessionaires and Permissionnaires published on the ORE website in June 2014[1], Madagascar has an installed capacity of electricity production of 552MW, 162MW and 389MW of which are respectively produced by hydropower and thermal power. The rest is produced by other sources of renewable energy such as wind, solar and biomass. Out of this installed capacity of 552MW, only 303MW are actually available (June 2014), which corresponds to 54.9%.

1 www.ore.mg

REGION	HYDROPOWER		THERMAL		OTHER RE	
	Nominal (kW)	Available (kW)	Nominal (kW)	Available (kW)	Nominal (kW)	Available (kW)
Alaotra Mangoro	24160	20150	6085	3203	130	-
Amoron'i Mania	213	130	4359	1958	-	-
Analamanga	14280	12358	132562	75312	6	6
Analanjirofo	2576	1000	6499	2630	-	-
Androy	-	-	1498	667	19	19
Anosy	-	-	5198	4195	305	5
Atsimo Andrefana	95	5	24151	7699	7	4
Atsimo Atsinanana	-	-	2364	1269	-	-
Atsinanana	97960	66420	51794	17636	-	-
Betsiboka	85	80	1414	624	-	-
Boeny	-	-	29758	16522	104	104
Bongolava	-	-	1452	977	-	-
Diana	-	-	61064	32227	82	82
Haute Matsiatra	6050	3840	6856	4190	1	-
Ihorombe	20	15	3632	1270	81	80
Itasy	30	-	-	-	3	3
Melaky	-	-	1307	670	-	-
Menabe	-	-	5515	2935	-	-
SAVA	-	-	15878	5581	-	-
Sofia	-	-	6037	2852	-	-
Vakinankaratra	16720	10890	16308	3082	6	-
Vatovavy Fitovinany	60	50	5237	2134	-	-
TOTAL (MW)	**162.2**	**114.94**	**388.97**	**187.63**	**0.74**	**0.30**
Percentage of the total	**29.4%**	**37.9%**	**70.5%**	**62.0%**	**0.1%**	**0.1%**

Table 2. Existing power plants in June 2014 (Source: ORE website)

The distribution of installed capacity (nominal capacity) and availabality by source and by region is given in Table 2 and illustrated in Figure 2. It shows that thermal power dominates the available energy mix in most regions of Madagascar except for the regions of Alaotra-Mangoro, Atsinanana and Vakinankaratra where the country's main hydropower plants are located. The other sources of renewable energy are marginal, except the region of Itasy where only one solar power generator of 3kW is currently operational.

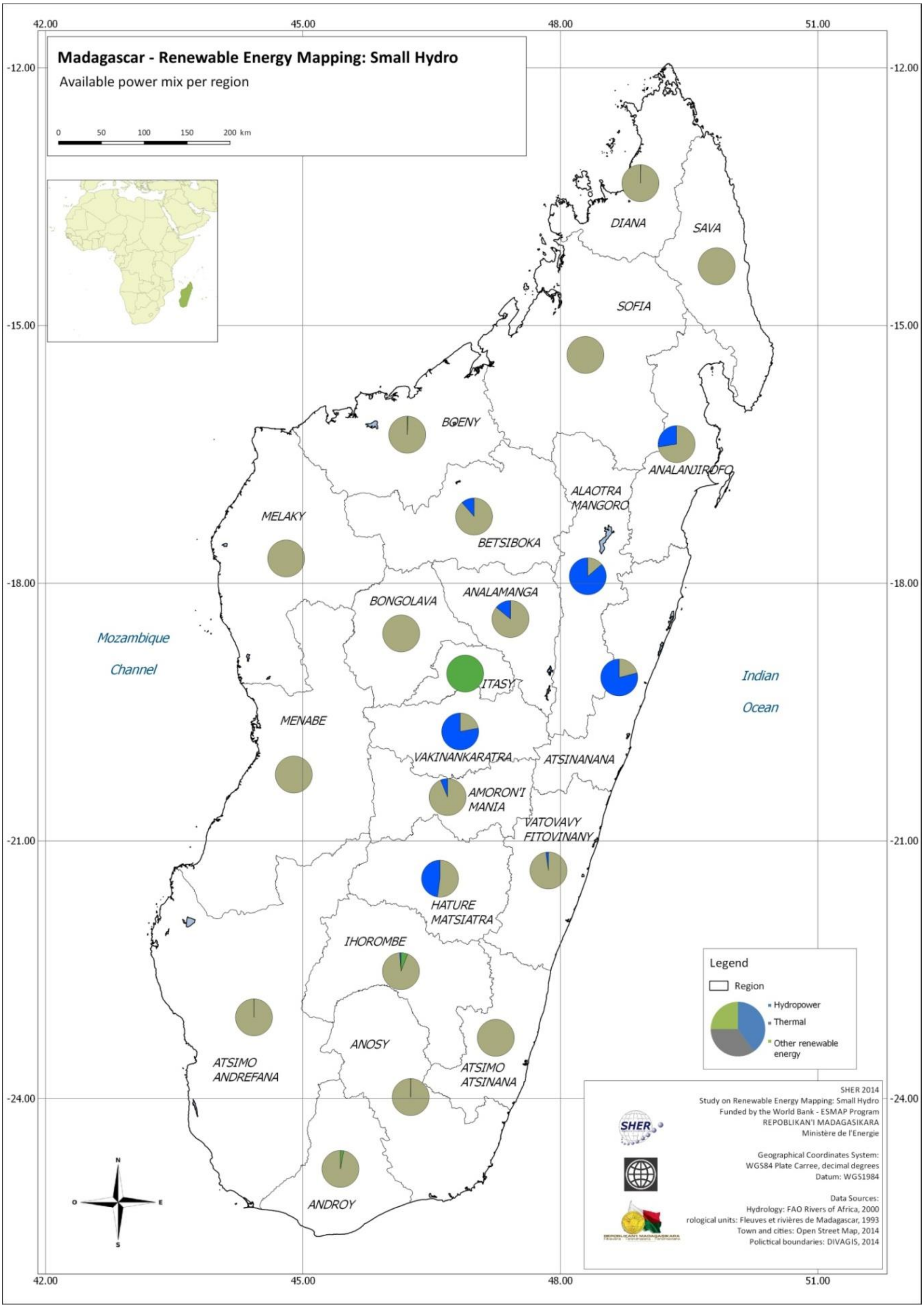


Figure 2. Available capacity by type by region. The diagram portions represent the contribution of different energy sources to the total available capacity percentage in each region.

In June 2014, Madagascar had an installed capacity of 162.25MM coming from hydropower. The latter was distributed between 11 major hydropower plants of which the installed capacity varies between 0.45MW in Manandray in the province of Fianarantsoa and 91MW in Andekaleka in the province of Toamasina. The characteristics of the 9 main power plants connected to different interconnected networks are shown in Figure 3.

Name	Owner	Type		Capacity Installed (MW)	Capacity Firm (MW)	Average energy annual (GWh)	Commis-sioned	Network
Manandona	JIRAMA	Run-of-the-river	Total	**1.6**	1.0	5		RIA
			Gr. 1	0.5			1930	
			Gr. 2	0.5			1930	
			Gr. 3	0.6			1960	
Antelomita 1	JIRAMA	Reservoir	Total	**4.1**	4.0	21		RIA
			Gr. 1	1.4			1930	
			Gr. 2	1.4			1930	
			Gr. 3	1.4			1952	
Antelomita 2	JIRAMA	Reservoir	Total	**4.1**	4.0	20		RIA
			Gr. 1	1.4			1952	
			Gr. 2	1.4			1953	
			Gr. 3	1.4			1953	
Mandraka	JIRAMA	Reservoir	Total	**24.0**	20.0	60		RIA
			Gr. 1	6.0			1956	
			Gr. 2	6.0			1956	
			Gr. 3	6.0			1966	
			Gr. 4	6.0			1972	
Andekaleka	JIRAMA	Run-of-the-river	Total	**91.0**	56.0	538		RIA
			Gr. 1	29.0			1982	
			Gr. 2	29.0			1982	
			Gr. 3	33.0			2012	
Sahanivotry	IPP (HYDELEC)	Run-of-the-river	Total	**15.0**	5.0	80		RIA
			Gr. 1	5.0			2008	
			Gr. 2	5.0			2008	
			Gr. 3	5.0			2008	
Tsiazompaniry	IPP (HFF)	Run-of-the-river	Total	**5.2**	2.0	21		RIA
			Gr. 1	2.6			2010	
			Gr. 2	2.6			2010	
Namorona	JIRAMA	Run-of-the-river	Total	**5.6**	3.5	42		RIF
			Gr. 1	2.80			1980	
			Gr. 2	2.80			1980	
Manandray	JIRAMA	Run-of-the-river	Total	**0.5**	0.4	2		RIF
			Gr. 1	0.14			1932	
			Gr. 2	0.14			1932	
			Gr. 3	0.17			1963	
Volobe	JIRAMA	Run-of-the-river	Total	**6.8**	6.0	42		RIT
			Gr. 1	1.5			1931	
			Gr. 2	1.5			1931	
			Gr. 3	1.5			1955	
			Gr. 4	2.2			1977	
			TOTAL	**157.8**	**101.9**	**830.6**		

Table 3. Key characteristics of the main existing hydropower plants connected to a RI

The operation of these plants is characterised by 125.6MW (79.6%) for run-of-the-river and only 32.2MW (20.4%) with a regulation capacity (reservoir).

In terms of management, 20.2MW (12.8%) belongs to independent producers (Hydelec and HFF) and 137.6 MW (82.2%) are managed by JIRAMA. All these plants are connected to the interconnected networks but most of the produced capacity is injected to the Interconnected Network of Antananarivo: 145 MW (91.8%) are injected to the Interconnected Network of Antananarivo (RIA), 6.1 MW (3.9%) to the Interconnected Network of Fianarantsoa (RIF) and 6.8 MW (4.3%) to the Interconnected Network of Toamasina (RIT). We also realise that the parc is relatively old, with plants commissioned in the 1930s for the oldest. In 2012, a new generator of 33MW was added to the hydropower plant of Andekaleka giving it a total installed capacity of 91MW.

The location of these existing hydropower plants is shown in the Figure 3.

Figure 3. Main existing hydropower plants

3.3 POTENTIAL HYDROPOWER SITES

3.3.1 Data sources

The database of the potential hydropower sites in Madagascar is made up of two main information sources described in the following paragraphs: (i) literature coming from various studies and lists and (ii) a spatial analysis software enabling the identification of river stretches with high hydropower potential based on the rainfall and topography. This software is a tool developed by SHER Ingénieurs-Conseils.

3.3.1.1 Existing literature

A synthesis of the existing literature was carried out through the analysis of many technical studies, strategic documents, master plans and lists of sites.

A summary of the analysed documents can be found in the HydroAtlas Report (draft) as well as the five lists of potential sites that were given to the Consultant, given in Annex 3 of this report. Table 4 below summarises the distribution of potential sites according to the information source.

Source	Number of sites
Collective list from energy sector[2]	501
List from the Ministère de l'Energie	80
List from ADER	780
List from ORE (sites shared with other lists)	67
Diverse studies/ literature	109
TOTAL	1537

Table 4. Potential hydropower sites by information source.

These lists, which include common sites, have geographical coordinates and some technical information such as the installed capacity, gross head or a flow rate.

It is important to remember that the lists are mostly summaries of several documents. Most of the time, the latter are not or are no longer available. Very often, there are significant errors in the location or the technical parameters, and it is impossible to find the source of the data neither to correct them. There is also a large incertitude on the technical parameters, when they are mentioned, because we generally don't have information on the hypotheses that helped in determining them.

2 List from the World Bank archives

3.3.1.2 SiteFinder contribution: detection tool for hydropower sites

The aim of SiteFinder software is to detect natural waterfalls or steep river stretches, associated with a flow, to show the favourable parts for hydropower development. The program is mainly based on a Digital Elevation Model (DEM) and on a certain number of climatic/ hydrological data.

The basic principle of the program is to detect waterfalls associated to a watershed. The size of the watershed can be fixed according the requirements of the study. The rivers' mean flow is estimated from the size of the watershed and/or average annual rainfall distribution data. The software computes the specific capacity for each river stretch. These results, shown on the screen, enable the identification of potential sites. An example of a result (potential site SF038), on top of the topographical map, is shown in Figure 4.

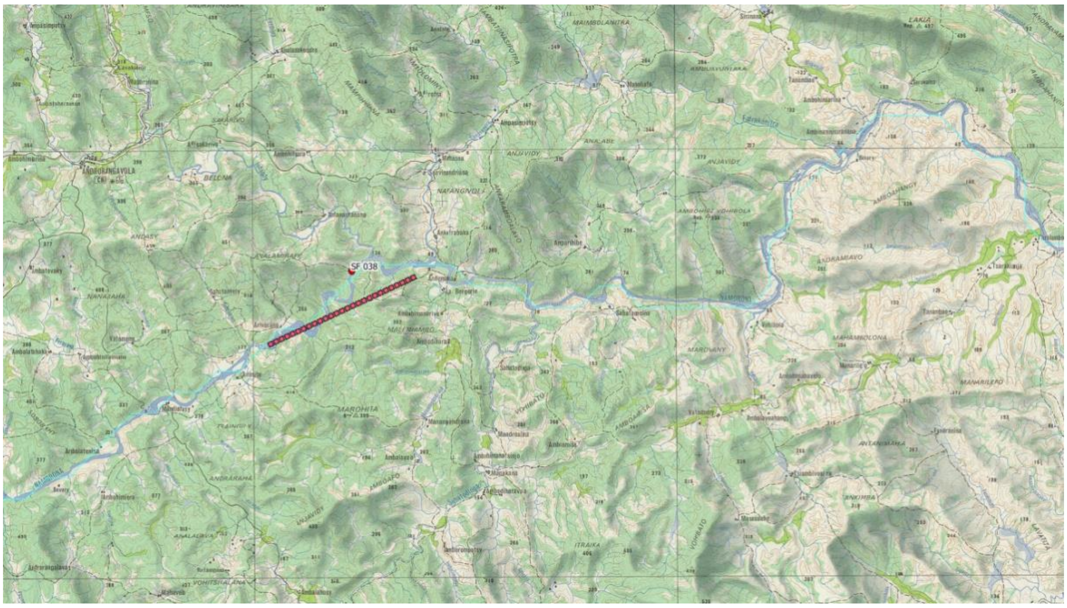


Figure 4. SiteFinder - stretch of interest indicated by red dots (example for the site SF038)

A complete analysis of the implementation of SiteFinder for Madagascar is detailed in Annex 13.

A total of 575 sites have been detected. These have been illustrated in Figure 5.

Source	Number of new sites
SiteFinder	575 (amongst which 412 have no equivalence with potential sites from the lists)

Table 5. Potential hydropower sites detected by SiteFinder

Amongst these 575 sites detected, 163 sites had already been discussed in existing documents, 109 of which were classified in ADER's list of potential sites. SiteFinder has therefore **included a total of 412 new sites** to the database of potential hydropower sites.

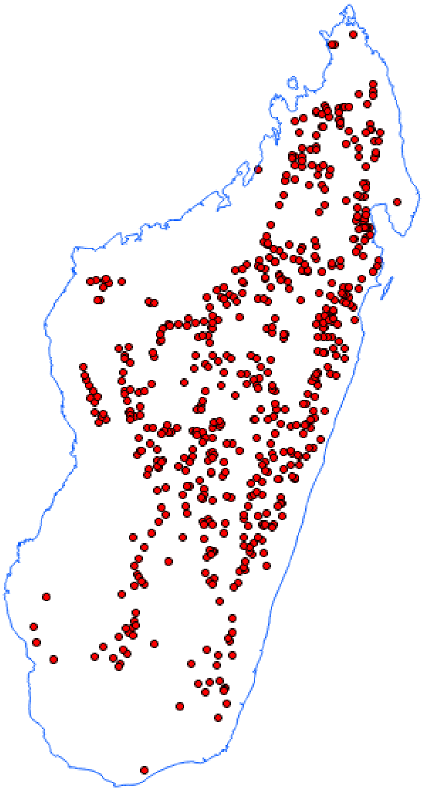


Figure 5. Geographical distribution of the 575 sites detected by SiteFinder

3.3.2 Set-up of the geographical database of potential sites

The set-up of the database of potential hydropower sites in Madagascar is the result of a long and detailed consolidation process of collected information through the different sources mentioned above. The following sections give in detail the stages of this consolidation process as well as the intermediate results.

The database was consolidated based on lists of potential sites:

- The collective list from the energy sector: 501 sites, most of them with geographical coordinates and some technical information;
- The Ministère de l'Energie: 84 sites, with geographical coordinates;
- ADER: 780 sites with geographical coordinates for most of the sites. Nevertheless, the technical parameters are not always complete;
- ORE: 67 sites without geographical references. Nevertheless, these sites are found in other studies and have been taken into account.

3.3.2.1 Format of the database

After analyzing the documents and site lists, the following parameters, if they exist, have been recorded in a geographical database (GIS):

- Location: name of the site, Province, Region, District, Town;
- Name of the river on which the site is located;
- Geographical coordinates of the structure that crosses the water;
- Watershed delineated by the DEM;
- Type of system (run-of-the-river, with storage reservoir);
- Gross head (checked on topographical maps and/or on DTM);
- Hydrology: Annual mean flow, design flow;
- Design capacity;
- Average annual capacity;
- Destination of production: load centres susceptible to be supplied (grid, towns, villages and hamlets);
- Other studies carried out: study levels, consultant and years of achievement;
- Other information.

3.3.2.2 Integration

The raw database coming from the integration of information from different sources contains 2045 potential hydropower sites (1470 coming from the literature and 575 identified by SiteFinder).

3.3.2.3 Cleaning and inventory of the database (first screening) of the potential hydropower sites

The database was manually cleaned up by removing 744 duplicates and sites without any data on the gross head, on the discharge and on the capacity. The **RAW DATABASE** includes **1301 potential identified sites**. Note that many sites could still be found with duplicates given the errors of geographical coordinates and place names. Data collected don't give any indication to the source of information and the author of the study.

A summary table of data sources is given below.

Origin	Number of sites	Missing information
Collective list from energy sector	501	12 sites don't have indicated capacity 448 sites don't have gross head 442 sites don't have indicated design flow
List of the MoE	80	No design flow data No gross head data
List of ADER	780	593 sites don't have indicated capacity 317 sites don't have gross head 777 don't have indicated design flow
Identified by SiteFinder	575	Gross head measured on 1 :100,000 topographical map, flow calculated from the DTM and simplified hydrology
List of OER (sites in common with other lists)	67	These sites, which don't have coordinates, are found in other lists
Results from various studies	109	18 sites don't have any indicated capacity 4 sites don't have gross head 14 don't have any indicated design flow
Intermediate total	2045	
Duplicates and sites without data	(-) 744	
Gross database of potential sites	**1301**	

3.4 CREATION OF THE FINAL DATABASE

All 1301 sites identified from the sources described above, were analyzed using satellite imagery, topographical and geological maps and a regional hydrological study in order to assess whether each site is favorable or not for hydropower development.

This analysis allowed the evaluation/confirmation of the available gross head, the size of the watershed drained by the site, obvious development constraints due to the presence of villages, protected areas, military sites, etc.

The geological maps gave a first indication on the nature of the rocks, the possible tectonic events and the presence of geological faults which could make the implementation of a hydropower project more complex.

The result is a consolidated database containing 403 potential hydropower sites, distributed over the country.

Based on these elements, the potential power of each of the sites has been estimated, considering a design flow corresponding to the median interannual flow, estimated based on the regional hydrological study.

All elements with a geographical component related to the hydropower sector in Madagascar are grouped in a Geographical Information System (GIS) with the reference coordination system GCS_WGS_1984 (Datum: D_WGS_1984; Prime Meridian: Greenwich; Angular Unit: Degree).

The geographical information system was set up to meet the conditions of compatibility and standardisation defined in the terms of reference so that geographical data can easily be published on the GIS platform of the World Bank. Furthermore, the consultant used the geographical information system software QuantumGIS, free to use, to process and publish the geographical data, which enables its broadcasting and free transfer at the end of the study.

The database contains the spatial vector data given in the Table 6.

below. This database has been developed using international standard formats (ESRI shapefiles and georeferenced TIFF images). A QuantumGIS[3] project has been created to group all spatial data in a geographical information system (GIS), using an explicite symbology which is similar for all maps produced in HydroAtlas. An illustration of he database in the GIS software is given in Figure 6.

An Excel file with the attribute information of the layers has also been given. This file contains all the metadata relative to the different attribute fields of the layers.

Moreover, the main elements are also available in KML format (Keyhole Markup Language) usable in Google Earth[4] to facilitate the use and dissmination of information for a less specialised public.

---

[3] Quantum GIS is a powerful, free and open source GIS software. (www.qgis.org).

[4] https://www.google.com/earth/

Thematic	Format	Main characteristics	Sources	Attributes
Administrative limits: Country	ESRI Shapefile	-	Institut Géographique et Hydrographique de Madagascar (FTM) - BD500 and BD200	**PAYS=**Name of the country
Administrative limits: Provinces	ESRI Shapefile	6 provinces	Institut Géographique et Hydrographique de Madagascar (FTM) - BD500 and BD201	**PAYS**=Name of the country **PROVINCE**=Name of the province
Administrative limits Regions	ESRI Shapefile	22 regions	Institut Géographique et Hydrographique de Madagascar (FTM) - BD500 et BD202	**PAYS**=Name of the country **PROVINCE**=Name of the province **REGION**= Name of the region
Administrative limits Districts	ESRI Shapefile	110 districts	Institut Géographique et Hydrographique de Madagascar (FTM) - BD500 et BD203	**PAYS**=Name of the country **PROVINCE**=Name of the province **REGION**= Name of the region **DISTRICT**= Name of the district
Administrative limits Municipalities	ESRI Shapefile	1433 municipalities	Institut Géographique et Hydrographique de Madagascar (FTM) - BD500 and BD204	**PAYS**=Name of the country **PROVINCE**=Name of the province **REGION**= Name of the region **DISTRICT**= Name of the district **COMMUNE**= Name of the municipality
Existing hydropower sites	ESRI Shapefile	11 main sites	Compilation of JIRAMA and ORE data	**SITE**=Name of the site **PUISS_MW**=Installed capacity [MW] **OPERATEUR**= Name of the operator **LON_DD**=Longitude [Decimal degrees] **LAT_DD**=Latitude [Decimal degrees]
Thermal power stations	ESRI Shapefile	171 main thermal groups	Created based on document « Diagnostic du Secteur Energie, JIRAMA, 2012"	**NOM**=Name of the site **REGION**=Name of the region **LOCALITE**=Name of the served village **CONCESSION**=Name of the distributor **CARBURANT**=type of fuel **PUISS_kW**= Installed capacity [kW]
Main towns	ESRI Shapefile	32 main towns	Open Street Map, 2014	**NOM**=Name of the main town
Sites of the Système d'Aires Protégées de Madagascar (SAPM)	ESRI Shapefile	Shapefile of the SAPM sites - Arrêté interministériel n°9874/2013 modifiant certaines dispositions de l'arrêté n°52005/2010 (version April 2011)	Digital atlas of the Système d'Aires Protégées de Madagascar (SAPM) - http://atlas.rebioma.net/	
Digital Elevation Model (DEM)	GeoTiff	Spatial resolution of ~90m	NASA, 2014 - http://www2.jpl.nasa.gov/srtm/	Altitude [m]
Road network	ESRI Shapefile	National roads, main roads and tracks	Institut Géographique et Hydrographique de Madagascar (FTM) - BD500 and BD200	**TYPE**='rnc'=Unclassified road ; 'rn'=National road ; 'rip'=Provincial road ; 'cip'=Provincial track ; 'autre'=Other **Numéro**=Number of the road
Interconnected electrical networks (RI)	ESRI Shapefile	RIA (Interconnected network of Antananarivo) - RIT	Compilation of JIRAMA and ORE data	**RI**=Name of the interconnected network (RI) **VOLTAGE_kV**=Line voltage (if information available) **NOM**=Name of the line (if information

Thematic	Format	Main characteristics	Sources	Attributes
		(Interconnected network of Toamasina - RIF (Interconnected network of Fianarantsoa)		available) **CREATION**=In-service date of the line (if information available)
Satellite image of Madagascar	GeoTiff	Landsat image (2005)	Google Earth	-
Land use	ESRI Shapefile	8 land use classes: - Culture - Forest - Thicket - Mangrove - Swamp - Water body - Savannah - Reforested area	Schéma National d'Aménagement du Territoire (SNAT)	**CLASSE**=Land use class **NATURE**=Land use subclass **HA**= Area [hectares]
Potential hydropower sites	ESRI Shapefile	33 promising potential hydropower sites in capacity range ~ 1-20MW	SHER, 2015	**CODE**=Code HydroAtlas **NOM**=Name of site **LAT_DD**= Latitude [Decimal degrees] **LON_DD**=Longitude [Decimal degrees] **PROVINCE**=Province **REGION**=Region **DISTRICT**=District **COMMUNE**=Municipality **IGN**= Topographic map sheet **RIVIERE**=River name **BASSIN_KM2** = Area of the watershed at the site [km²] **Q95** = Guaranteed flow - 95% of the time [m³ / s] **Q70** = Guaranteed flow - 70% of the time [m³ / s] **Q50** = Guaranteed flow - 50% of the time [m³ / s] **Q20** = Guaranteed flow - 20% of the time [m³ / s] **CONFIDENCE** = Confidence index for the estimation of hydrological data **CHUTE_M** = Gross head [m] **Pgar_MW** = Firm capacity - 95% of the time [MW] **P_MW** = Installed capacity [MW] **Egar_GWh** = 95% annual guaranteed energy production [GWh] **E_GWh** = Annual energy production [GWh]

Thematic	Format	Main characteristics	Sources	Attributes
Potential hydropower sites	ESRI Shapefile	Potential hydropower sites known or studied by the Ministère de l'Energie et des Hydrocarbures and the related entities	SHER, 2015	**CODE** = HydroAtlas Code **NAME** = Site name **RIVER** = River name **LAT_DD** = Latitude [Decimal degrees] **LON_DD** = Longitude [Decimal degrees] **CHUTE_M** = Gross Head [m] **Qeq_M3S** = Equipment flow [m³ / s] **PUISS_MW** = Installed capacity [MW] **STATUS** = Study status **SOURCE** = Source of the reference study **ALT_LAYOUT** = Development variant **PROVINCE** = Province **REGION** = Region **DISTRICT** = District **COMMUNE**=Municipality **ALT_LAYOUT**=Development variant **PROVINCE**=Province **REGION**=Region **DISTRICT**=District
Potential hydropower sites	ESRI Shapefile	Raw database of 403 potential hydropower sites in Madagascar	SHER, 2017	**CODE** = HydroAtlas Code **NAME** = Site name **RIVIERE** = River name **LAT_DD** = Latitude [Decimal degrees] **LON_DD** = Longitude [Decimal degrees] **CHUTE_M** = Gross head [m] **Qeq_M3S** = Equipment flow [m³ / s] **PUISS_MW** = Installed capacity [MW]

Table 6. Extract of the database of the analysis using Quantum GIS

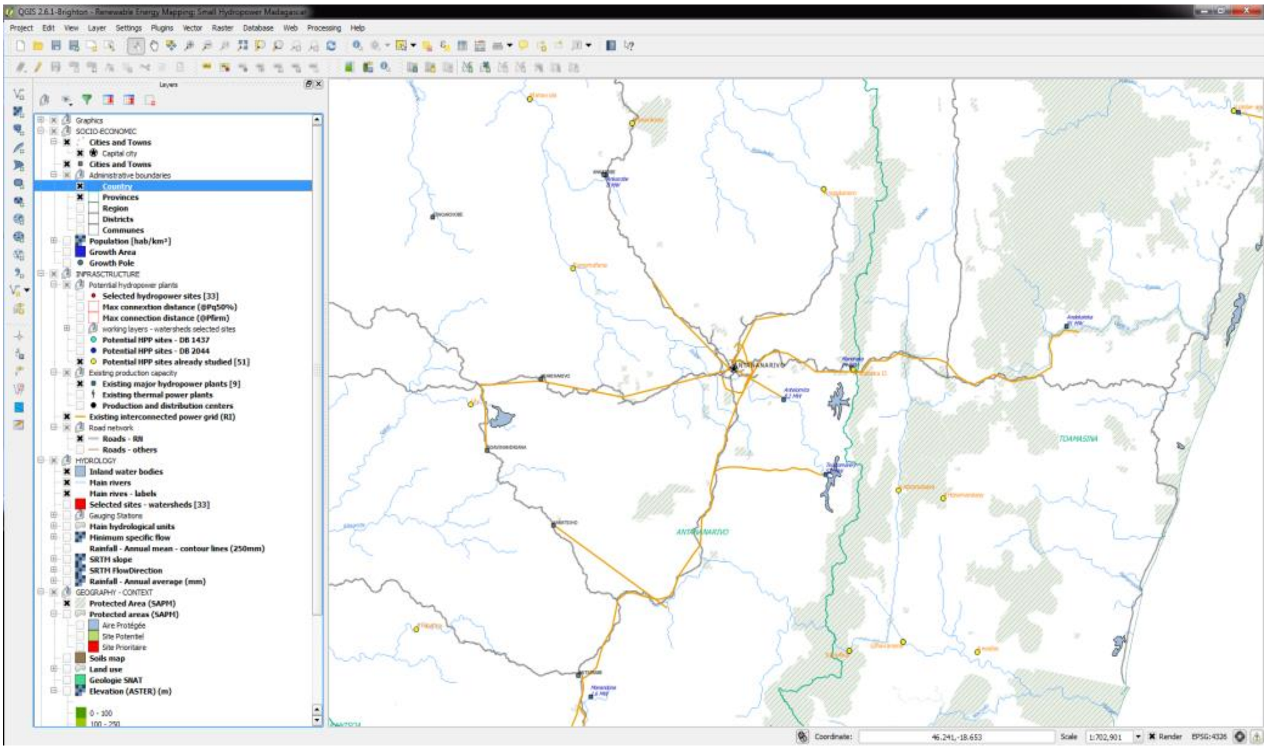


Figure 6. Information extracted from the database of the analysis using Quantum GIS.

4 Identification and selection process of the most promising sites

4.1 SETTING UP OF A PORTFOLIO OF THE MOST PROMISING SITES MEETING THE STUDY CRITERIA

A substantive work has been carried out to establish a portfolio of hydropower projects that meet the criteria of the study. This work was conducted in close consultation with the Ministère de l'Energie et des Hydrocarbures and related entities and in accordance with the terms of reference of the study. The criteria below were discussed and validated several times during the mission statement of the inception report and at the meetings on July 1st and July 3rd 2014.

The Government of Madagascar strongly emphasized the needs for the study to respect the least cost constraint since the early beginning of the selection process. This economic factor was included from the early stages of the process despite the constraints related to incomplete and heterogeneous data.

The diagram on the next page shows schematically the study process. It appears that the progress of the study, based on pre-determined criteria, reduces the number of sites and, in parallel, information and knowledge on potential sites increases.

Note also that the planning process is a dynamic and iterative process that is refined based on the increase of knowledge on potential sites.

- Raw and cleaned up database: **No planning is possible** because the uncertainty about the technical data and the coordinates of the sites is maximum.

For example, the Vohipary AD158 site has a capacity of 3.7 MW in the Collective list from energy sector, a capacity of 1.38 MW in the listing of the ORE, a capacity of 18.7 MW in the listing of Ministère de l'Energie and after site visit, a capacity of 38.9 MW has been calcuated.

- Portfolio of 49 potential sites that meet the study criteria: a **preliminary planning** is possible taking into account the site connection distance to either one of the three interconnected networks (Antananarivo-Antsirabe - RIA, Toamasina - RIT and Fianarantsoa - RIF) or to a remote centre already equipped with a thermal group.
- 33 visited promising sites: **indicative planning** is possible because some of the technical unknown factors about potential sites are lifted. Capacity, production and costs calculations allow to consider realistically the connection assumptions. This planning could eventually help integrate these projects in a future national electricity master plan.

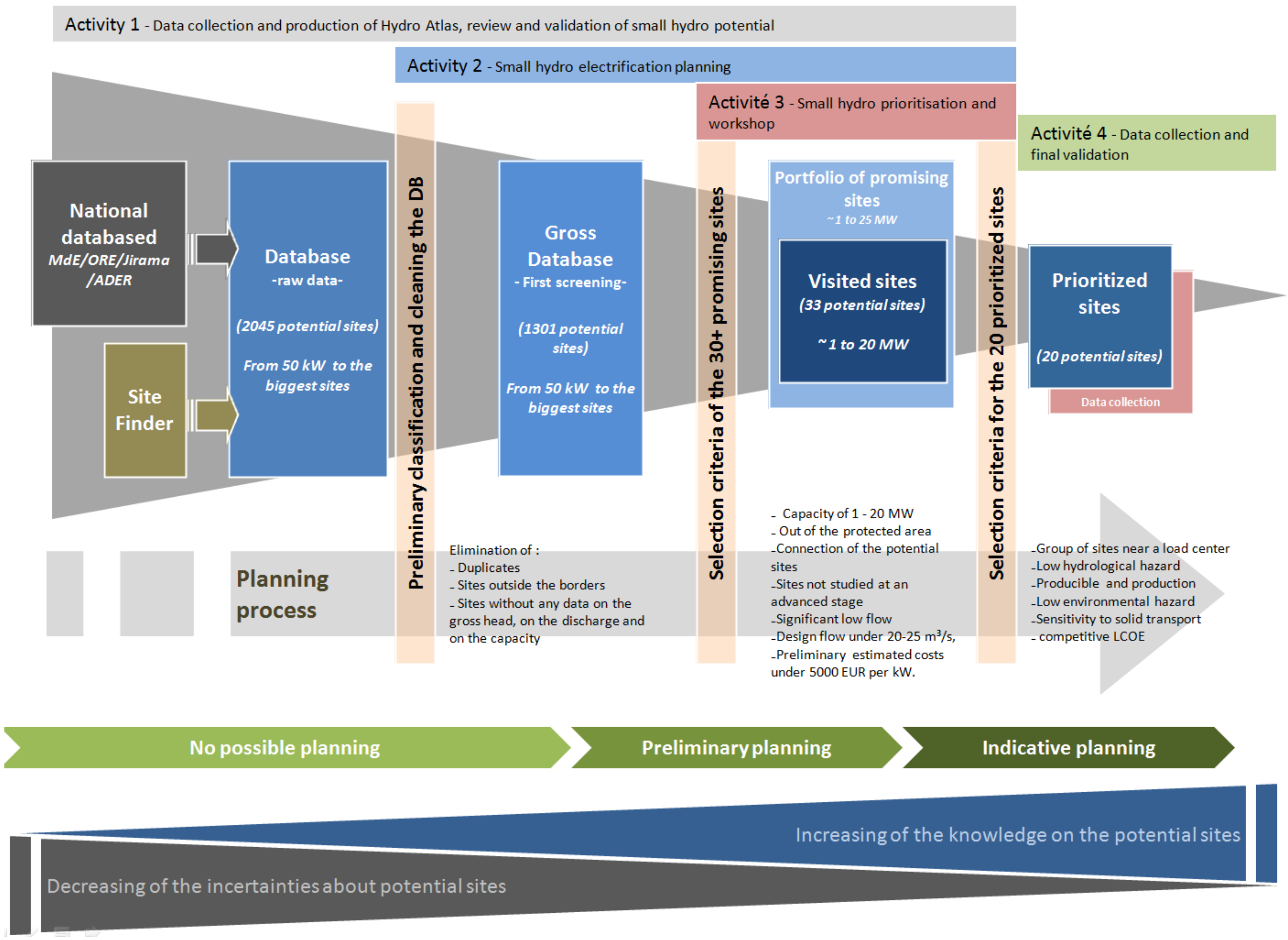


Figure 7. Selection process of the potential sites

4.2 STUDY CRITERIA

4.2.1 Energy policy and growth area

As part of the search for coherence, synergy and coordination of the development of small hydropower against the other develmopment objectives of the Malagasy government, the site selection conforms to spatial medium-term Territory Development objectives with an emphasis on growth areas as defined in the National Scheme of Territorial Planning.

The site selection is consistent with this criterion prioritising the connection of potential sites to cities located within the growth areas. The philosophy is to focus on the public and private efforts on small areas to "stimulate" the rest of the country.

4.2.2 Average interannual flow

The flow rate was taken from the information contained in the records and the studies available to the consultant and recorded in the database. When site data are complete, that rate has been used in the classification process.

4.2.3 Potential capacity

For sites without data on the capacity and the flow but with data on the gross head, the flow has been recalculated using the same method as used for the sites identified with SiteFinder (see Section 13.1.1.1.3). Base on this this value, the capacity has been calculated. These sites are selected in the following steps. Sites without information on the flow, the gross head and on the capacity, could not be considered for further analysis.

Sites with 'installed' capacity less than 800 kW and above 25MW were discarded. However, for the sites from SiteFinder, a greater tolerance was given (> 700kW and no maximal limit). This is justified by the following. The lowest sites have been underestimated due to unfavorable hydrological estimation in a first approach (this is in fact based on the minimum low flows). Higher capacity sites have been overestimated based on an early favorable topography (eg long slopes, even when they are steep, cannot be developed for a limited stretch).

4.2.4 Average annual producible

The annual average producible was taken from the information contained in the records and studies made available to the consultant and recorded in the database. It was considered risky at this stage of the study, to deal with the annual average producible for sites with very little information or sites identified by SiteFinder.

4.2.5 Low flow

An approximation of the low flow was made for all Sitefinder sites and reconstructed for potential sites that lacked flow data but had a gross head.

4.2.6 Approximative length of the access roads / tracks

Given the large number of identified sites, the approximate lengths of the access roads have been calculated in a straight line between the potential site and the nearest road. This value was then multiplied by a factor to take into account the actual sinuosity of the road / access track.

4.2.7 Connection to a network or remote site

Connecting the potential sites to a load centre was systematically evaluated based on the nearest distance to a load center or to an existing grid.

4.2.8 Determination of an estimative construction cost of a SHPP in Madagascar

The aim of the method described in this paragraph is to compare all the listed hydropower sites in Madagascar based on an indicative cost empirically determined from a set of similar priced projects. The full construction cost [C][5] of a small hydro development (SHPP) from 1 to 20 MW based on its installed capacity [P] and its gross head [H] between 5 and 300 m can be roughly estimated using he following expression with some precision:

$$C = K \cdot P^{\alpha} \cdot H^{\beta} \text{ (in Millions of Euros)}$$

In this range of gross heads and unit capacity, we can find turbines of the type of Pelton, Francis, Kaplan, Bulbe or Banki.

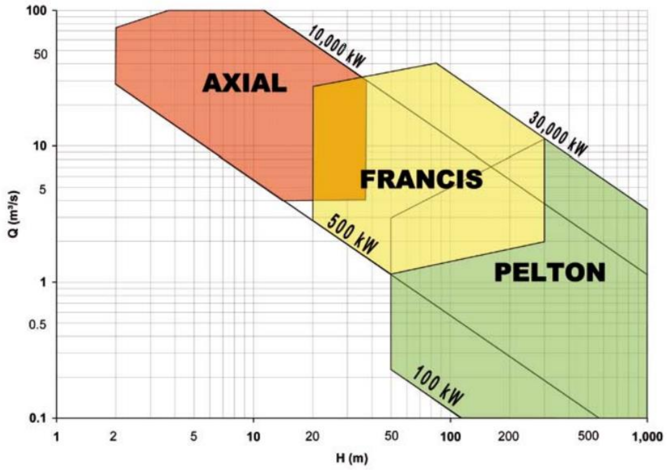


Figure 8. Source : Compact Hydro Program (ANDRITZ HYDRO)

To establish a formula on a country's specific cost, we need to have relatively recent data of projects that have been implemented or studied with as much as possible details of installation in order to evaluate the specificities of each site. In general, small hydropower projects have the simplest design and are less complex to implement but they can sometimes have penstock or a headrace which is important compared to the gross head and /or a seasonal storage capacity which will result in a huge increase of the construction cost.

For Madagascar, there is currently no good homogenous and coherent database, given the limited number of implementations and recent studies (APS/APD) during the last six years.

For the SHPP of 1 to 20 MW in Madagascar, a cost formula (**C = K P^{α} H^{β} in M €**) was established (excluding costs of access lines) after updating the prices based on the economic conditions of January 2014 and possible adjustments related to site specifications with an accuracy of +/- 30%.

[5] But not including the power evacuation line and the main access road to the plant

The suggested cost formula of SHPP between 1 and 20MW in Madagascar is as follows:

$$C = 5{,}0\ P^{0{,}97}\ H^{-0{,}12} \text{ (in Millions of Euros)}$$

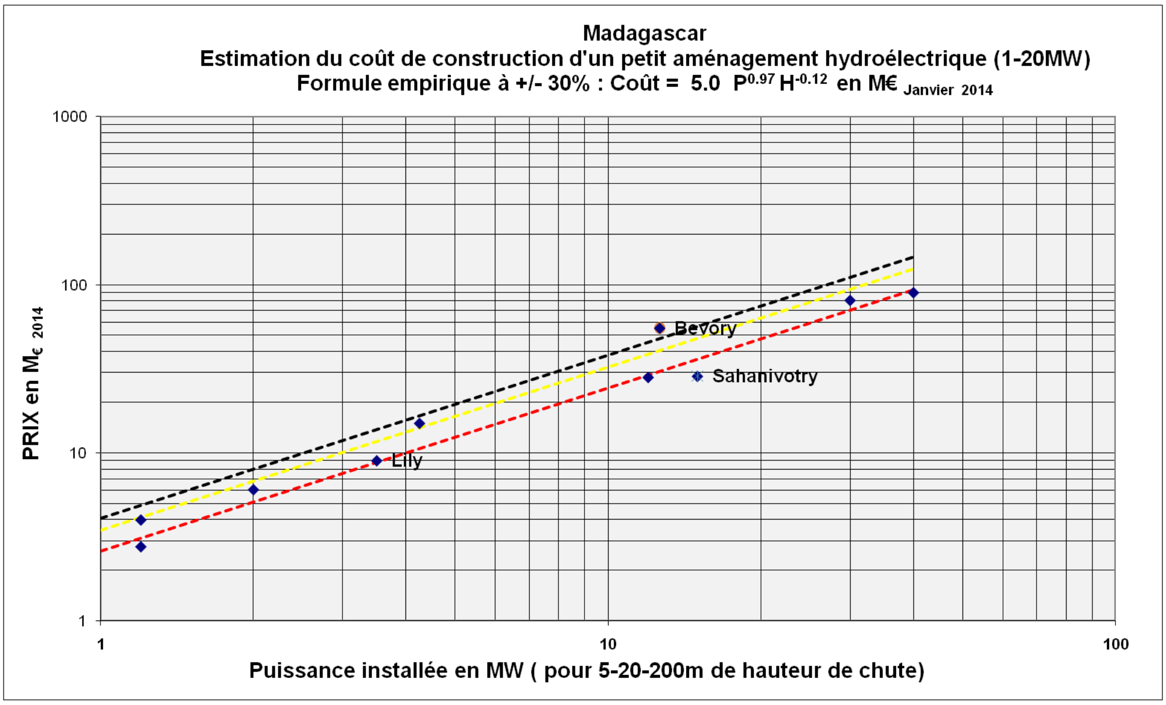
Remark : By comparison, the cost per kW for the capacity range between 1 and 20 MW decreases much less for the micro-power plants[6] lower than 1MW in Switzerland; This explains to a certain extent the coefficient obtained for the power which is 0.97 (close to 1) and greater than the coefficient for the Swiss micro-power plants of 0.91.

The list of selected projects (12) between 0.5 and 40 MW to establish the given cost function is:

Projects	Capacity
Sahanivotry	15 MW
Maroantsetra-Vodiriana	1.2 MW
Beandrarezona	0.5 MW
Farahanstana-Mahisty	12 MW
Ampandriambazana	30 MW
Ambodiroka	40 MW
Ampitabepoky	1.2 MW
Bevory-Andriamanjavona	13 MW
Lokoho aval	2.0 MW
Lily	3.5 MW
Tsiafampiana 3	4.3 MW
Tazonana aval 2	0.6 MW

A graphical representation of the log-log SHPP identified based on the installed capacity and the gross head is given below.

6 *For small hydropower plants in Switzerland of less than 1MW, MHyLab established a cost formula in Swiss francs in June 2000:* ***C*** *=* $34{,}12 + 16{,}99 \times P^{0{,}91} \times H^{-0{,}14}$ *en 1000* FRS_{2000}*, but including an additional cost coefficient for the installations with a length (L) of the hydraulic circuit 3 times greater than the gross head (H). This coefficient* $\boldsymbol{\alpha}$ *is equal to* $1 + 0{,}006 \times H^{-0{,}8} \times (L - 3H)$ *; It is indicative for a gross head of 100m of 1.1 for a gallery of 1km and 1.4 for a gallery of 3km, and for a gross head of 200m, it goes from 1.09 to 1.2 for a gallery respectively from 1km to 3km*



An increase (m) or a reduction (m) of 10 to 50% should be applied for hydropower projects with a more complex design such as the development of Bévory project that includes a 4 km tunnel, or the existing development of Sahanivrotry for which the installation cost was very low thanks to the relatively low equipment prices compared to the world prices.

The adapted formula cost becomes like this:

$$C = (1+m)\, 5{,}0\ P^{0{,}97}\ H^{-0{,}12} \quad \text{(m = 0 for less complex work)}$$

Construction costs in € / kW by the formula cost (without any complexity adjustment) for the selected projects are the following:

Small hydropower project	Gross head (m)	Capacity (MW)	Flow (m3/s)	Ratio (in €/kW)
Sahanivotry	210	15	9	**2 376**
Maroantsetra-Vodiriana	91.5	1.2	3.5	**2 840**
Beandrarezona	35.8	0.5	2	**3 281**
Farahanstana-Mahisty	29	12	57	**3 056**
Ampandriambazana	268	30	16	**2 258**
Ambodiroka	72	40	72	**2 634**
Ampitabepoky	20	1.2	9	**3 429**
Bevory-Andriamanjavona	89	13	19	**2 656**
Lokoho downstream	60	2.0	5	**2 947**
Lily	75	3.5	6	**2 819**
Tsiafampiana 3	38	4.3	15	**3 049**
Tazonana downstreaml 2	98.8	0.6	1	**2 875**

The construction cost of a less complex project varies between 2,300 and 3,500 € / kW but with adjustments the cost can vary between 1,600 and 5,000 € / kW.

In case the head is not given, the following approximation is made:

$C = 3{,}95\ P^{0{,}87}$

The cost estimates of the energy line and access road to the site are generally proportional to the distance except for bridges and stations. For lines, the voltage levels for SHPP in Madagascar are mainly 35kV for smaller projects (less than 4/5 MW) and 63kV for projects less than 20MW. The 138kV voltage level is more specific for projects wth a capacity higher than 20MW.

The cost of the transmission line of a SHPP is calculated based on its length and its voltage level (35 or 63kV) and the cost of access to the site is on average depending on the distance between the site and the station.

The proposed cost grid in € million / km is the following:

Costs for lines and roads	in $M€_{1/1/2014}$
Simple line in :	
- **35 kV** (in 75mm²)	**0,08 M€/km**
- **63 kV (**in 148mm²)	**0,175 M€/km**
Access roads :	**0,2 M€/km**

Example: for Bévory-Andriamanjavona hydropower project with an installed capacity of 13MW, having a 4km long headrace tunnel and located approximately at 30 / 40km from the station:

Bevory-Andriamanjavona	Characteristics & estimated costs
Capacity	13 MW
Gross head	89 m
Flow	19 m³/s
Estimated development costs with the formula cost	34,6 M€ (2660 €/kW)
Headrace	4 km
Adjusted development cost with m= 0,4 **(i)**	48 M€
Line	35 km
Line cost **(ii)**	6 M€
Road	40 km
Access road cost **(iii)**	8 M€

The maximum threshold for which a site is not retained was set at € 5,000 / kW.

4.2.9 Environmental impacts

The protected areas are coming from the Système d'Aires Protégées de Madagascar (SAPM). This describes the situation and regional distribution of the different areas mentioned in the Interministerial Article No. 18633/2008 / MEFT / MEM of 17 October 2008 on setting global temporary protection of sites covered by the Interministerial Article No. 17914/2006 / MEFT / MEM of 18 October 2006

The sites located within protected areas have been excluded. The sites bordering protected areas without critical impact have been kept.

Figure 9. Location of a potential site in a protected area

4.3 RESULTS OF THE SELECTION AND PORTFOLIO OF 1-20 MW HYDROPOWER PROJECTS

The following table lists the criteria that were applied in the process for the selection of promising sites.

Study criteria	Number of selected potential sites
Raw database of potential hydropower sites of Madagascar	1301 sites
- 168 sites with missing capacity or flow or zero gross head	1133 sites
- 5 existing sites	1128 sites
- 36 sites of capacity > 25 MW	1092 sites
- 673 sites of capacity < 800 kW (ou < 700 kW for the the sites identified by SiteFinder)	446 sites
- 80 sites in protected areas	366 sites
- 305 sites with a construction cost per installed kW estimated at > 5000 EUR/kW	61 sites
- 12 sites have been removed after a quality assurance review by an experienced hydropower engineer, based on desk study including detailed map studies. These sites present no interest for hydropower development.	49 sites

Table 7. Count of the 49 sites meeting the study criteria

After the selection process, a portfolio of the 49 sites has been identified as the MOST PROMISING sites. Fact sheets were developed and presented in the HydroAtlas. These 49 sites have not been studied in detail or even not at all or the information has been lost (case of Tsinjoarivo). Within the portfolio of 49 sites, 24 sites were identified by SiteFinder and are therefore brand new sites for Madagascar. The next step was to select from this portfolio of 49 sites the best potential sites to be visited during activity 3.

4.4 SUMMARY PLANNING

At this stage of the study, given the lack of visits and measurements to confirm the technical parameters of the sites, it is not possible to draw technical conclusions for the 49 sites. The data are very incomplete and imprecise. However, there has been enough evidence to allow us to say that they have a potential hydropower in the context of the study and deserve a field visit.

The consultant considered the possibilities of connection either to the grid or to the nearest isolated thermal centre as well as the site accessibility. A particular attention was given to sites that can be developed in the short term by private investors. These will probably be the key stakeholders for the future productive investments in the hydropower sector.

9 sites of the 49 have very difficult access and/or a grid connection in mismatch with their capacity. These sites are located either at more than a day of walking distance from a track or their connection to the first approximation is greater than 40 km away. In the medium term, it is considered that these sites will not be visited until a reasonable access will be constructed, or will be excluded from future prioritisations: closer projects or an extension of an existing grid will be preferred.

7 sites among these 49 are located in red areas from a security point of view. For obvious safety reasons, these sites were not visited during the study period. However, they maintain their intrinsic interest and may be subject to investigation in future studies, when the level of security is again favourable.

The final list of sites to visit includes 33 promising sites for site visits:

Code	Site name
AD158	Vohipary
AD160	Ilengy
AD337	Tsaravao
AD411	Ambodimanga
AD465	Marianina
AD481	Tsinjoarivo
AD544	Analamanaha
AD601	Antaralava
AD620	Behingitika
AD631	Antanjona
AD644	Antaninaren
AD652	Tambohorano
AD653	Vohinaomby

Code	Site name
AD691	Ambatosada
G191	Andriamanjavona
G407	Fanovana
SF011	SF011
SF015	SF015
SF019	SF019
SF020	SF020
SF022	SF022
SF023	SF023
SF038	SF038
SF079	SF079
SF080	SF080
SF118	SF118
SF147	SF147
SF148	SF148
SF195	SF195
SF196	SF196
SF204	SF204
SF420	SF420
SF533	SF533

Table 8. List of the 33 promising potential sites to visit

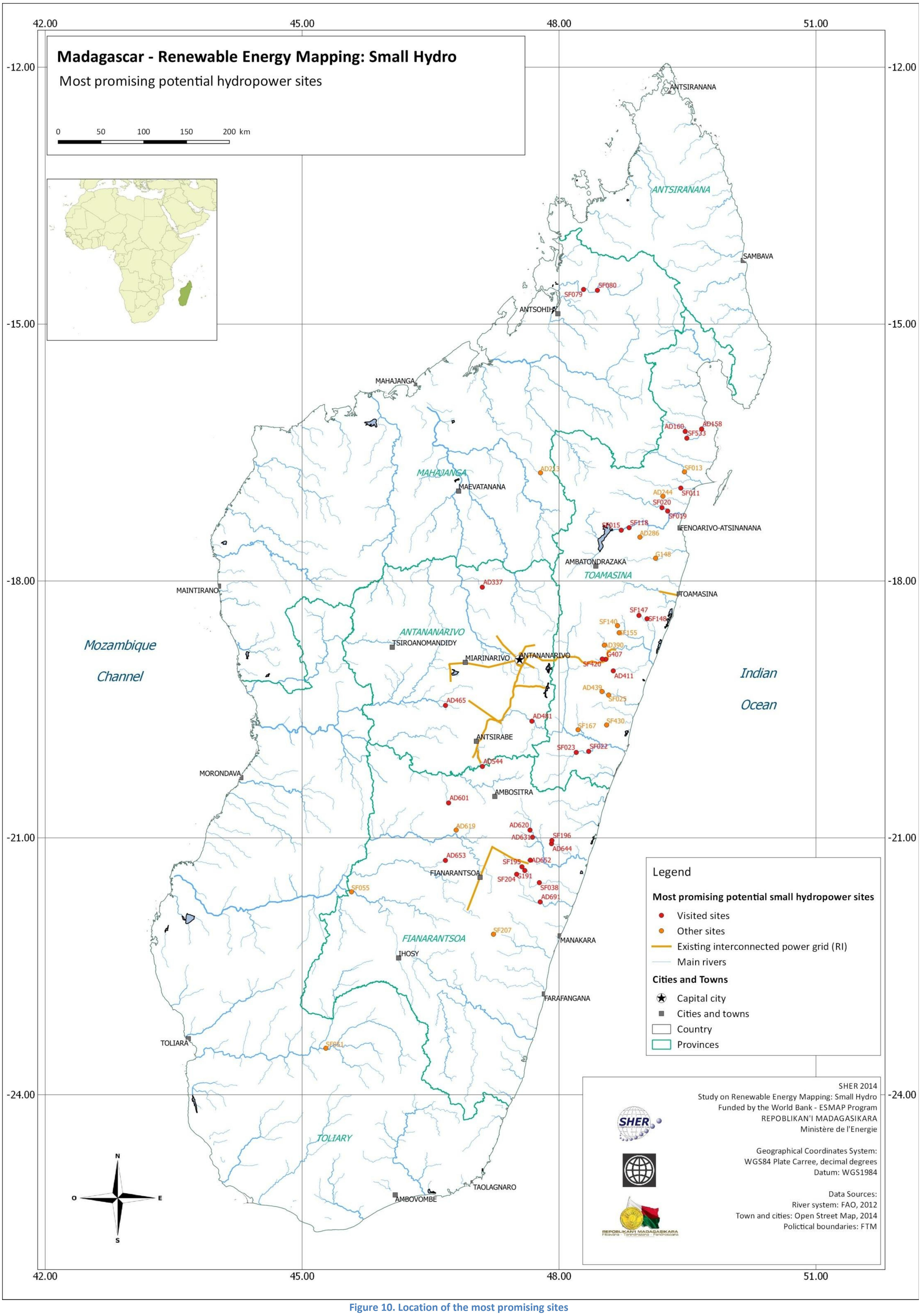


Figure 10. Location of the most promising sites

5 Most promising sites for short-term investments

5.1 ORGANISATION OF VISITS TO THE MOST PROMISING SITES

Following the selection process, the field visits allowed to collect the data needed to assess the hydropower potential of the different sites and to determine their preliminary cost, in addition of a better appreciation of the site.

The visits took place between late September 2014 and late November 2014, a period of 2 months. The reconnaissance work was conducted by several teams of experts. Teams of the Ministère de l'Energie and related entities accompanied the Consultant's experts to the field during the week of 27 September 2014.

The data for each site can be classified into primary data (measured on site) and secondary data (derived from the primary data).

Six (6) categories of data can be defined:

- The **Administrative** data, allowing to validate the site name (or void if any);
- The **Point** data, obtained using a GPS/altimeter, set by their three-dimensional coordinates (longitude, latitude, altitude);
- The **Vector** data deduced from point data type allowing to obtain the length of the different linear structures;
- The **Measured** data performed on site using a decametre for length measurements, a turbidity meter for turbidity measurements, or a flow meter for flow measurements;
- The **Appreciation** data to describe textually particular elements at the site;
- **Photos**, giving a better perception of the site. The photos are georeferenced and oriented.

The table below summarizes the different data collected by type. The material used to collect these data and the class to which these data are also specified.

DATA TYPE	COLLECTED DATA	MATERIAL OR TOOL	CLASS 1AIRE	CLASS 2AIRE
Administrative	River name	Questioning the locals	×	
	Name of the nearest village to the site	Questioning the locals	×	
Point	along the river	GPS / altimeter	×	
	at the intake site	GPS / altimeter	×	
	at the surge chamber site	GPS / altimeter	×	
	At the plant site	GPS / altimeter	×	
	At any point remark identified on the site (head, tributary, bridge, ford ...) .	GPS / altimeter	×	
Vector	Field visit tracking	GPS / altimeter	×	
	Channel or tunnel	GIS software		×
	Penstock	GIS software		×
	The power line to create	IS software		×
	Access road to create	GIS software		×
	The road section to be rehabilitated to allow access to the site	GPS / altimeter	×	
Measurement	Width of the floodplain of the river	Measuring tape	×	
	Estimated width of the dam	Measuring tape	×	
	Estimated height of the dam	Topographic map		×
	Turbidity	Turbidity measurement	×	
	Flow	Flow measurement	×	
	Slope of the sides of the valley	Topographic map		×
	Original waterfall	GPS / altimeter	×	
Appreciation	General description of the planned scheme	Observation	×	
	Shape of the valley	Observation	×	
	Type of the considered dam	Observation	×	
	Type of the considered project	Observation	×	
	Type of the considered connection	Observation		×
	Network to which the project will be connected	Programme GIS		×
	General geology of the site	Observation	×	
	Availability of raw materials near the site	Observation	×	
	Sediment transport	Observation	×	
	Potential impact of the project	Observation and discussion with the locals	×	
	Accessibility to the site	Observation	×	
	Existing infrastructures	Observation and discussion with the locals	×	
	Future infrastructures	Observation and discussion with the locals	×	
Photos			×	

5.2 TARGETED HYDROLOGICAL STUDY FOR THE MOST PROMISING SITES

5.2.1 Objectives and limitations of the hydrological study on the promising sites

The objective of this hydrological study is to determine the statistical characteristics of the flow time series at the 33 hydropower sites previously identified as the most promising for the objectives of this study. More precisely, it is necessary to determine the flow duration curve (statistical distribution of the flows) as well as to estimate the flood flows for different periods of return (probabilities of occurrence).

These statistical characteristics have a major role for the estimation of the technical and economic parameters of the potential hydropower projects as well as for their development planning and connection type for the evacuation of the produced energy.

For the majority of the potential hydropower sites in this study, there is little or no specific information on their hydrological regime. Therefore, we have developed a methodology to obtain an estimate of the statistical characteristics of the flow time series at the sites of interest, based on data available at other flow gauging stations located on the territory of Madagascar. This methodology of regionalisation, the available data and the results are described in the following sections.

The rating curves (relationship between the measured water heights and the corresponding flows) as well as any other information related to the quality of the measurements, have not been made available to us. In addition, only monthly flow data were made available to us by the different sources. Therefore, the analysis of these data will provide only limited information for the identification of extreme flows during periods of low flow and floods.

The temporal and spatial resolutions of the available information on river flows in Madagascar, which have an interest in the frame of this study, as well as the analysis methodology that follows, allow having an indicative estimate of the hydrological characteristics at the sites of interest. Therefore, these data may under no circumstances be used for infrastructure design without additional hydrological studies.

5.2.2 Hydrometeorological database

5.2.2.1 Available data and sources

Hydrological data: The historical flows data have been obtained from three sources: (i) the book "Fleuves et Rivières de Madagascar" published by ORSTOM in 1993 (FR)[7], (ii) the database of the Global Runoff Data Center (GRDC)[8] and (iii) the General Department of Meteorology of Madagascar (DGMET). The format in which the data was received is described and their geographical location is illustrated in Table 9.

[7] Caperon P., Danloux J. et Ferry L., Fleuves et Rivières de Madagascar, ORSTOM Editions, Paris, 1993.

[8] http://www.bafg.de/GRDC/EN/Home/homepage_node.html

Rainfall Data: The rainfall data of the WORLDCLIM[9] database (version 1.4) were compiled in our spatial database. These data are available for the whole of Madagascar on a monthly time step and a spatial resolution of about 1km. These data are freely available from the internet.

Digital Elevation Model: The Digital Elevation Model (DEM) used for the hydrological study is the "Shuttle Radar Topography Mission (SRTM v3). These data were acquired by the American Space Agency (NASA) through radar measurements from a space shuttle in February 2013 and have a spatial resolution of 3 arc-second (about 30m at the equator). This set of data is particularly well suited for the identification of river watersheds, the identification of river systems and for the calculation of the slopes. In addition, these data have the advantage of being freely available on the internet. The DEM of Madagascar is shown in Figure 11.

5.2.2.2 Compilation and consolidation of hydrological data

The historical flow measurements in Madagascar were obtained from three sources: (i) the book "Fleuves et Rivières de Madagascar" published by ORSTOM in 1993 (FR)[10], (ii) the database of Global Runoff Data Center (GRDC)[11] and (iii) the General Direction of Meteorology of Madagascar (DGMET).

All of the data described above have been compiled into a single hydrological database with 149 flow gauging stations. A consolidation of the database according to the different information sources was made based on the geographical coordinates of the stations, the names of the stations and rivers on which the stations are located and the size of the watersheds gauged by those stations. Finally, a visual validation has been done for each of the 149 stations, using the maps and satellite images within the GIS developed in the frame of this study. At the end of this exercise, 87 different stations have been identified, out of the 149 stations. A unique code, starting with the letter "M" and followed by two digits (M01 to M87) has been attributed to these 87 stations. The distribution of the 149 stations, according to their source, is illustrated in the table below:

Table 9. Distribution of gauging stations according to data sources

Data source	Received data format	Number of stations	Time step	Data coverage:		
				1 station	2 stations	3 stations
GRDC	Digital : *.dat files*	34	Monthly	3	13	18
FR	Paper	43	Monthly	7	18	18
DGMET	Digital : *.xls files*	72	Monthly	33	21	18
	Total	***149***	**-**	***43***	***26***	***18***

The temporal coverage of each of the 149 stations is illustrated by a chronogram in Table 10. It was noted that the oldest measurements in our possession started in in 1947 and the most recent are from 2001. It clearly appears that most of the time series are characterised by a low percentage of

9 http://www.worldclim.org/

10 Caperon P., Danloux J. et Ferry L., Fleuves et Rivières de Madagascar, ORSTOM Editions, Paris, 1993.

11 http://www.bafg.de/GRDC/EN/Home/homepage_node.html

completeness from 0% to rarely more than 80%. On this basis, it is therefore not possible to establish a common timeframe which would be long enough for a detailed spatio-temporal analysis of the data from the different stations.

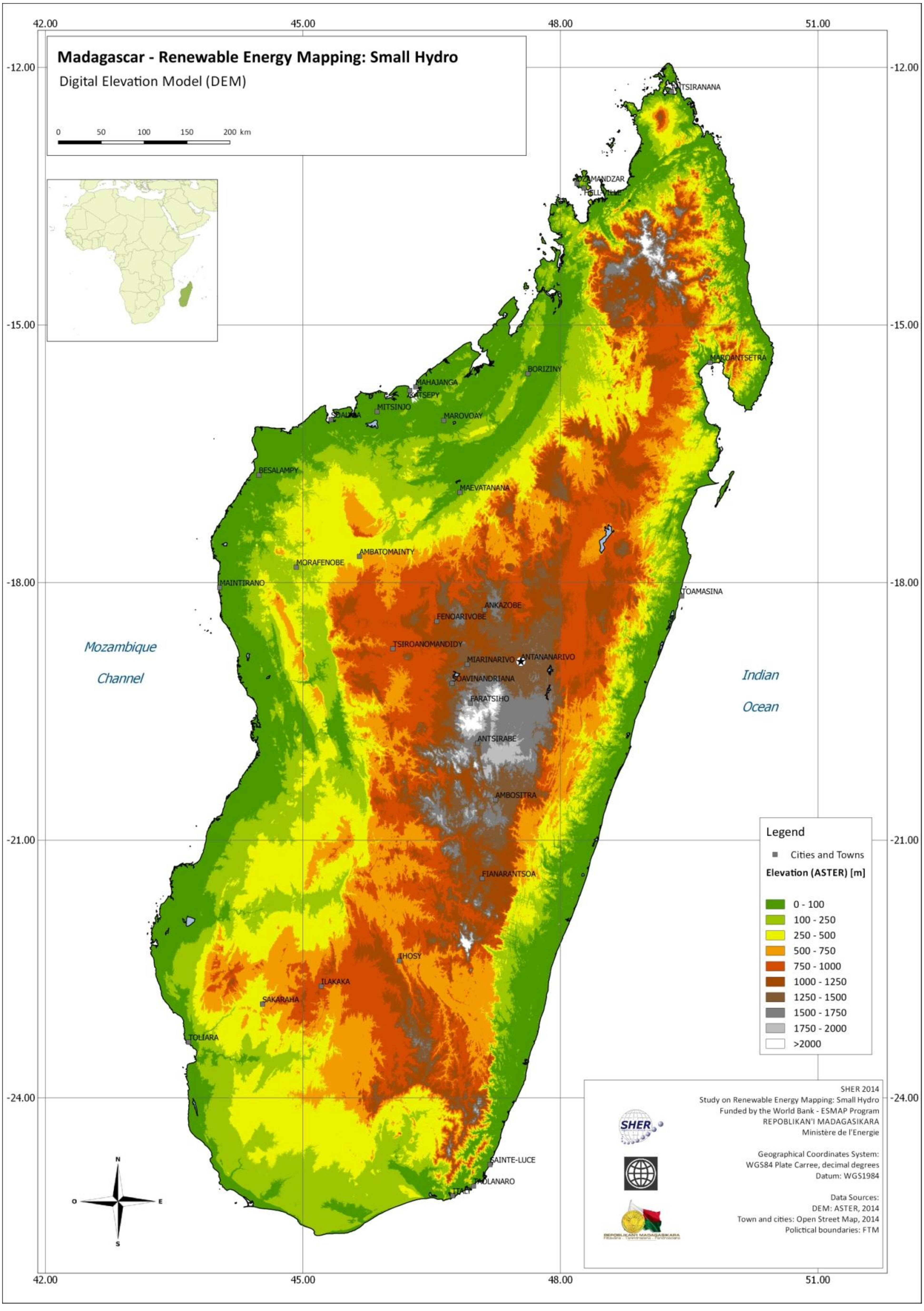
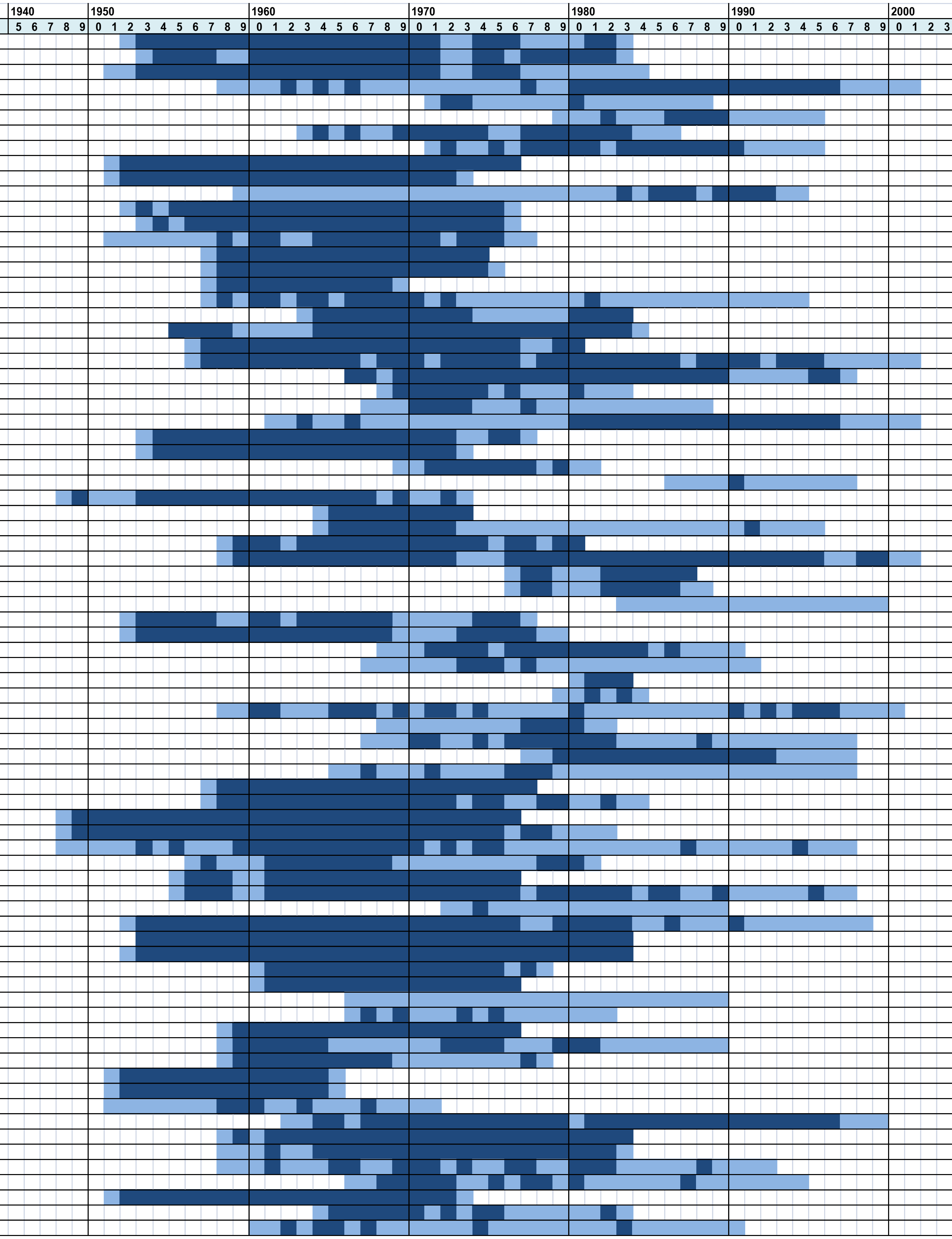


Figure 11. Digital elevation model of Madagascar



CODE	SOURCE	RIVER	STATION	MAJORE RIVER BASIN	First Y	Last Y	Length	complètes	Nbre data	Data type*
M01	FR	SAMBIRANO	AMBANJA	SAMBIRANO	1952	1983	32	75%	308	M
M01	GRDC	SAMBIRANO	AMBANJA	SAMBIRANO	1953	1983	31	77%	329	M
M01	DGMET	SAMBIRANO	AMBANJA	SAMBIRANO	1951	1984	34	65%	308	M
M02	DGMET	SISAONY	AMBATOFOTSY AU P.K. 22	BETSIBOKA	1958	2001	44	48%	435	M
M03	GRDC	MANAMBOLO	AMBATOLAHY	TSIRIBIHINA	1971	1988	18	17%	116	M
M03	DGMET	MANAMBOLO	AMBATOLAHY	TSIRIBIHINA	1979	1995	17	29%	115	M
M04	GRDC	MAHAVAVY	AMBILOBE	MAHAVAVY NORD	1963	1986	24	63%	235	M
M04	DGMET	MAHAVAVY - NORD	AMBILOBE PONT NOUV. ECHELLE ORANGE	MAHAVAVY NORD	1971	1995	25	60%	238	M
M05	FR	MANDRARE	AMBOASARY	EFAHO	1951	1977	27	96%	0	M
M05	GRDC	MANDRARE	AMBOASARY	EFAHO	1951	1973	23	91%	264	M
M06	DGMET	BESALY	AMBOASARY - EST	MANDRARE	1959	1994	36	22%	172	M
M07	FR	RAMENA	AMBODIMANGA	SAMBIRANO	1953	1976	24	88%	272	M
M07	GRDC	RAMENA	AMBODIMANGA	SAMBIRANO	1953	1976	24	88%	270	M
M07	DGMET	RAMENA	AMBODIMANGA	SAMBIRANO	1951	1977	27	52%	275	M
M08	FR	ISINKO	AMBODIROKA	BETSIBOKA	1957	1974	18	94%	204	M
M09	FR	BETSIBOKA	AMBODIROKA	BETSIBOKA	1957	1975	19	89%	209	M
M09	GRDC	BETSIBOKA	AMBODIROKA	BETSIBOKA	1957	1969	13	85%	144	M
M09	DGMET	BETSIBOKA	AMBODIROKA AMONT	BETSIBOKA	1956	1994	39	32%	248	M
M10	GRDC	MAEVARANO	AMBODIVOHITRA	MAEVARANO	1963	1983	21	67%	180	M
M10	FR	MAEVARANO	AMBODIVOHYTRA	MAEVARANO	1955	1983	29	80%	308	M
M11	FR	IKOPA	AMBOHIMANAMBOLA	BETSIBOKA	1956	1980	25	88%	262	M
M11	DGMET	IKOPA	AMBOHIMANAMBOLA	BETSIBOKA	1955	2001	47	74%	495	M
M12	DGMET	IHAZOLAVA	AMBOHIMANDROSO RN 7 (P.K. 85)	MANGORO	1966	1997	32	78%	342	M
M13	GRDC	BEMARIVO	AMPASIMATERA	SOFIA	1968	1983	16	50%	150	M
M13	DGMET	BEMARIVO	AMPASIMATERA	SOFIA	1967	1988	22	23%	135	M
M14	DGMET	SISAONY	AMPITATAFIKA	BETSIBOKA	1961	2001	41	46%	312	M
M15	FR	MANDRARE	ANDABOLAVA	MAEVARANO	1953	1977	25	84%	0	M
M15	GRDC	MANDRARE	ANDABOLAVA	MAEVARANO	1953	1973	21	90%	240	M
M16	DGMET	SALOHY	ANDAMPIHELY	SOFIA	1969	1981	13	62%	117	M
M17	DGMET	LOKOHO	ANDAPA (JIRAMA)	LOKOHO	1986	1997	12	8%	62	M
M18	GRDC	VOHITRA	ANDEKALEKA	RIANILA	1948	1973	26	69%	252	M
M19	FR	VOHITRA	ANDEKALEKA AVAL	RIANILA	1951	1979	29	90%	105	M
M19	DGMET	VOHITRA	ANDEKALEKA AVAL	RIANILA	1963	1995	33	28%	160	M
M20	FR	SISAONY	ANDRAMASINA	BETSIBOKA	1957	1980	24	83%	245	M
M20	DGMET	SISAONY	ANDRAMASINA	BETSIBOKA	1957	2001	45	82%	494	M
M21	FR	MANIGORY	ANDROMBA	MANINGORY	1945	1979	35	67%	135	M
M21	DGMET	MANINGORY	ANDROMBA	MANINGORY	1975	1988	14	54%	135	M
M22	DGMET	MANANARA	ANJOZOROBE	BETSIBOKA	1983	1999	17	0%	62	M
M23	FR	ZOMANDAO	ANKARAMENA	MANGOKY	1952	1976	25	62%	237	M
M23	GRDC	ZOMANDAO	ANKARAMENA	MANGOKY	1952	1979	28	75%	308	M
M24	DGMET	SISAONY	ANKAZOBE	BETSIBOKA	1968	1990	23	61%	224	M
M25	DGMET	TSINJOMORONA	ANKOBAKOBAKA	TSINJOMORONA	1967	1991	25	16%	184	M
M26	GRDC	MANIA	ANKOTROFOTSY	TSIRIBIHINA	1980	1983	4	75%	40	M
M26	DGMET	MANIA	ANKOTROFOTSY	TSIRIBIHINA	1979	1984	6	33%	38	M
M27	DGMET	IKOPA	ANOSIZATO	BETSIBOKA	1958	2000	43	35%	393	M
M28	GRDC	SOFIA	ANTAFIANTSALANA	SOFIA	1968	1982	15	27%	82	M
M28	DGMET	SOFIA	ANTAFIATSALANA (PONT RN 32)	SOFIA	1967	1997	31	35%	214	M
M29	DGMET	LILY	ANTAFOFO CHUTES AVAL	TSIRIBIHINA	1977	1997	21	67%	191	M
M30	DGMET	ANDROMBA	ANTSAHALAVA	BETSIBOKA	1965	1997	33	15%	250	M
M31	FR	AMBOROMPOTSY	ANTSAMPANDRANO	MANGORO	1956	1979	24	95%	244	M
M31	DGMET	AMBOROMPOTSY	ANTSAMPANDRANO	MANGORO	1956	1984	29	71%	290	M
M32	FR	IKOPA	ANTSATRANA	BETSIBOKA	1948	1976	29	97%	328	M
M32	GRDC	IKOPA	ANTSATRANA	BETSIBOKA	1948	1982	35	83%	392	M
M32	DGMET	IKOPA	ANTSATRANA (AMPOTAKA)	BETSIBOKA	1948	1997	50	38%	400	M
M33	GRDC	MANANJARI	ANTSINDRA	MANANJARY	1956	1981	26	46%	175	M
M33	FR	MANANJARY	ANTSINDRA	MANANJARY	1955	1976	22	86%	226	M
M33	DGMET	MANANJARY	ANTSINDRA	MANANJARY	1954	1997	44	67%	443	M
M34	DGMET	MANAMPATRANA	AU BAC DE MAZAVALALA AMONT (MAHAZOA)	MANAMPATRANA	1972	1989	18	6%	116	M
M35	DGMET	IVONDRO	AU BAC DE RINGARINGA	IVONDRO	1951	1998	48	66%	433	M
M35	GRDC	IVONDRO	RINGARINGA	IVONDRO	1953	1983	31	100%	372	M
M35	FR	IVONGORO	RINGA-RINGAA	IVONDRO	1952	1983	32	97%	377	M
M36	DGMET	FARAONY	AU BAC DE VOHILAVA	FARAONY	1959	1978	20	84%	207	M
M36	FR	FARAONY	VOHILAVA	FARAONY	1960	1976	17	94%	186	M
M37	DGMET	MANAMPANIHY	AU BAC D'ELANARY	MANAMPANIHY	1966	1989	24	0%	127	M
M38	GRDC	IAROKA	BAC AMPITABE	RIANILA	1966	1982	17	24%	172	M
M39	FR	IKOPA	BAC DE FIADANANA	BETSIBOKA	1958	1976	19	95%	216	M
M39	DGMET	IKOPA	BAC DE FIADANANA	BETSIBOKA	1957	1989	33	41%	287	M
M39	GRDC	IKOPA	BAC FIADANANA	BETSIBOKA	1958	1978	21	52%	156	M
M40	FR	MANGOKY	BANIAN	MANGOKY	1951	1984	34	87%	0	M
M40	GRDC	MANGOKY	BANIAN	MANGOKY	1951	1965	15	87%	168	M
M40	DGMET	MANGOKY	VONDROVE	MANGOKY	1950	1971	22	24%	191	M
M41	DGMET	ANDROMBA	BEHENJY	BETSIBOKA	1962	1999	38	82%	406	M
M42	FR	TSIRIBIHINA	BETOMBA	TSIRIBIHINA	1957	1983	27	92%	298	M
M42	GRDC	TSIRIBIHINA	BETOMBA	TSIRIBIHINA	1958	1983	26	77%	291	M
M42	DGMET	TSIRIBIHINA	BETOMBA	TSIRIBIHINA	1957	1992	36	37%	340	M
M43	DGMET	MANGOKY	BETROKA	ONILAHY	1966	1994	29	34%	203	M
M44	FR	MANANARA	BEVIA	MAEVARANO	1951	1973	23	91%	0	M
M45	GRDC	MANGOKY	BEVOAY	MANGOKY	1964	1983	20	50%	156	M
M45	DGMET	MANGOKY	BEVOAY RIVIERE	MANGOKY	1960	1990	31	19%	207	M

CODE	SOURCE	RIVER	STATION	MAJORE RIVER BASIN	First Y	Last Y	Length	complètes	Nbre data	Data type*
M46	FR	IKOPA	BEVOMANGA	BETSIBOKA	1947	1972	26	96%	290	M
M46	GRDC	IKOPA	BEVOMANGA	BETSIBOKA	1949	1979	31	94%	360	M
M46	DGMET	IKOPA	BEVOMANGA AVAL	BETSIBOKA	1947	1999	53	52%	373	M
M47	DGMET	IKOPA	BEVOMANGA AMONT	BETSIBOKA	1965	1991	27	70%	282	M
M48	FR	RIANILA	BRICKAVILLE	RIANILA	1951	1969	19	84%	206	M
M48	DGMET	RIANILA	BRICKAVILLE (VOHIBINANY)	RIANILA	1950	1999	50	4%	216	M
M49	FR	MORONDAVA	DABARA	MORONDAVA	1951	1984	34	0%	0	M
M49	GRDC	MORONDAVA	DABARA	MORONDAVA	1951	1984	34	32%	178	M
M49	DGMET	MORONDAVA	DABARA (PONT)	MORONDAVA	1967	1973	7	71%	60	M
M50	GRDC	LINTA	EJEDA	LINTA	1976	1982	7	43%	70	M
M51	FR	EFAHO	FANJIHIRA	EFAHO	1962	1975	14	93%	148	M
M52	DGMET	MATSIATRA	FANORO	MANGOKY	1969	1989	21	33%	122	M
M53	FR	MANIA	FASIMENA	TSIRIBIHINA	1955	1983	29	97%	338	M
M53	GRDC	MANIA	FASIMENA	TSIRIBIHINA	1956	1988	33	58%	348	M
M53	DGMET	MANIA	FASIMENA	TSIRIBIHINA	1954	1990	37	6%	315	M
M54	FR	IVOHANANA	FATIHITA	MANANJARY	1955	1976	22	95%	239	M
M54	DGMET	IVOANANA	FATIHITA	MANANJARY	1955	1988	34	52%	267	M
M55	FR	RIANILA	FETRAOMBY	RIANILA	1963	1973	11	80%	105	M
M56	DGMET	MANGOKY	IANAKAFY	ONILAHY	1966	1972	7	14%	45	M
M57	DGMET	KOTOMBOLO	IFANJA	TSIRIBIHINA	1979	1984	6	33%	42	M
M58	DGMET	MANDRARE	IFOTAKA (AMPAIPAIKA)	MANDRARE	1952	1988	37	0%	214	M
M59	FR	IHOSY	IHOSY	MANGOKY	1952	1976	25	92%	0	M
M59	GRDC	IHOSY	IHOSY	MANGOKY	1953	1969	17	82%	195	M
M59	DGMET	IHOSY	IHOSY	MANGOKY	1952	1995	44	43%	328	M
M60	GRDC	MATSIATRA	IKIBO	MANGOKY	1971	1981	11	73%	109	M
M60	DGMET	MATSIATRA	IKIBO	MANGOKY	1970	1988	19	37%	131	M
M61	DGMET	ONIVE	ILEMPONA	MANGORO	1965	1999	35	46%	307	M
M62	DGMET	ILEMPONA	ILEMPONA	MANGORO	1965	1999	35	34%	280	M
M63	DGMET	SANDRANGITA	KALANDY	SOFIA	1967	2001	35	71%	354	M
M64	FR	MATSIATRA	MALAKIALINA	MANGOKY	1952	1963	12	83%	132	M
M65	GRDC	MANGORO	MANGORO	MANGORO	1960	1982	23	70%	255	M
M65	FR	MANGORO	MANGORO GARE	MANGORO	1956	1979	24	79%	249	M
M65	DGMET	MANGORO	MANGORO GARE	MANGORO	1955	1998	44	35%	262	M
M66	FR	MANANARA SUD	MARANGATY	MANANARA	1955	1976	22	100%	248	M
M66	GRDC	MANANARA	MAROANGATY	MANANARA	1960	1978	19	74%	192	M
M67	DGMET	KITSAMBY	MAROFAHITRA	TSIRIBIHINA	1965	1995	31	10%	118	M
M68	DGMET	MENARAHAKA	MENARAHAKA (RN27)	MANANARA SUD	1969	1981	13	31%	111	M
M69	GRDC	MAHAJILO	MIANDRIVAZO	TSIRIBIHINA	1981	1983	3	33%	24	M
M69	DGMET	MAHAJILO	MIANDRIVAZO	TSIRIBIHINA	1968	1990	23	13%	120	M
M70	DGMET	KATSAOKA	NIAKOTSORANO (PONT TSARATANANA)	BETSIBOKA	1965	1990	26	0%	165	M
M71	DGMET	FIHERENANA	NOSIARIVO (PONT ROUTE ANKAZOABO)	FIHERENANA	1980	2001	22	14%	80	M
M72	DGMET	SAHANIVOTRY	P.K 197.5	TSIRIBIHINA	1962	1999	38	41%	276	M
M72	FR	SAHANIVOTRY	PK 197	TSIRIBIHINA	1983	1980	-2	83%	199	M
M73	FR	IKOPA	PONT DE MAHITSY	BETSIBOKA	1947	1975	29	97%	329	M
M74	DGMET	ANDROMBA	PONT RTE D'ARIVONIMAMO	BETSIBOKA	1962	1999	38	29%	338	M
M75	GRDC	VOHITRA	ROGEZ	RIANILA	1952	1979	28	93%	330	M
M75	DGMET	VOHITRA	ROGEZ	RIANILA	1959	1988	30	63%	280	M
M75	FR	VOHITRA	ROGEZ (ANDEKALEKA)	RIANILA	1951	1980	30	93%	330	M
M76	DGMET	MAMBA	SABOTSY-PONT GIROD	BETSIBOKA	1962	1991	30	7%	152	M
M77	DGMET	SAHAMBANO	SAHAMBANO (RADIER RN 27) AMONT	MANANARA SUD	1966	1988	23	39%	164	M
M78	FR	MANANDONA	SAHANIVOTRY	TSIRIBIHINA	1963	1980	18	94%	204	M
M78	GRDC	MANANDONA	SAHANIVOTRY	TSIRIBIHINA	1964	1988	25	80%	293	M
M78	DGMET	MANANDONA	SAHANIVOTRY	TSIRIBIHINA	1962	1999	38	59%	339	M
M79	DGMET	SANDRANDAHY	SANDRANDAHY	TSIRIBIHINA	1979	1984	6	50%	46	M
M80	DGMET	MAHAVAVY - SUD	SITAMPIKY	MAHAVAVY SUD	1953	1970	18	67%	183	M
M81	FR	ONILAHY	TONGOBORY	ONILAHY	1951	1974	24	75%	0	M
M81	DGMET	ONILAHY	TONGOBORY	ONILAHY	1950	2001	52	31%	336	M
M82	FR	MENARANDRA	TRANOROA	MENARANDRA	1951	1983	33	85%	0	M
M82	GRDC	MENARANDRA	TRANOROA	MENARANDRA	1951	1983	33	82%	357	M
M82	DGMET	MENARANDRA	TRANOROA	MENARANDRA	1951	1997	47	26%	348	M
M83	FR	MANOMBOVO	TSIHOMBE	MANAMBOVO	1956	1976	21	81%	0	M
M83	DGMET	MANAMBOVO	TSIHOMBE	MANAMBOVO	1955	1997	43	57%	356	M
M84	FR	ONIVE	TSINJOARIVO	MANGORO	1963	1980	18	94%	202	M
M84	GRDC	ONIVE	TSINJOARIVO	MANGORO	1963	1982	20	85%	218	M
M84	DGMET	ONIVE	TSINJOARIVO	MANGORO	1962	1997	36	69%	364	M
M85	FR	AMDROMBA	TSINJONY	BETSIBOKA	1953	1980	28	100%	314	M
M85	DGMET	ANDROMBA	TSINJONY	BETSIBOKA	1953	1972	20	85%	213	M
M86	FR	MANANANTANANA	TSITONDROINA	MANGOKY	1952	1969	18	89%	204	M
M87	FR	NAMORONA	VOHIPARARA	NAMORONA	1951	1979	29	97%	338	M
M87	DGMET	NAMORONA	VOHIPARARA	NAMORONA	1950	1990	41	75%	419	M

Table 10. Timetable of the available gauging stations

Given the importance of the hydrological data for the assessment of the technical and economical parameters of the potential hydropower projects, their development and connection type, we have given to each of the 149 stations a confidence index (“High”, “Medium” or “Low”) according to the data quality. This confidence index is based upon the following criteria:

- For stations with several data sources (FR, GRDC ou DGMET), the comparison, according to the data sources, of the monthly and annual statistics calculated for each of the 149 gauging stations;
- The length of the time series;
- The percentage of gaps in the time series (degree of completeness);
- The data consistency with the area of the watershed related to the gauging station and the rainfall measurements ;
- Availability of literature (documentation) related to the measures at the gauging station (existing statistical processing).

According to these criteria, 43 flow gauging stations have been selected. The main statistical characteristics of these stations are presented in Table 12 and their spatial coverage is shown on Figure 13. Note that the stations are distributed as follows: 47% on the West side of the country, 33% on the East side, 14% on the South side and 7% on the side of Tsaratanana. This breakdown by major watersheds is explained in Table 11.

HYDROLOGICAL REGIONS	WATERSHED	STATION NUMBER
Tsaratanana side		**3**
	Maevarano	1
	Sambirano	2
East side		**14**
	Mananara	1
	Rianila	1
	Faraony	1
	Ivondro	1
	Mananjary	2
	Mangoro	3
	Maningory	1
	Namorona	1
	Rianila	3
West side		**20**
	Betsiboka	9
	Mangoky	5
	Morondava	1
	Onilahy	1
	Tsiribihina	4
South side		**6**
	Efaho	2
	Maevarano	2
	Manambovo	1
	Menarandra	1

Table 11. Distribution of selected gauging stations

These 43 selected stations cover a measurement period from 1945 to 1989 as shown on Figure 12 and their main characteristics are detailed in Table 12.

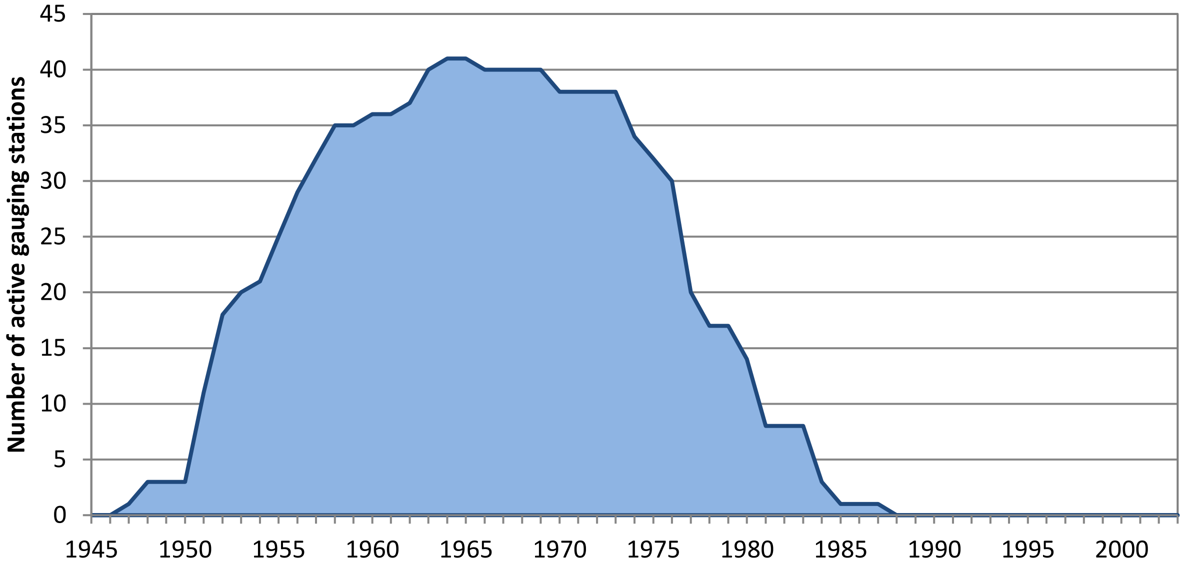


Figure 12.Number of flow gauging stations for which validated data are available as a function of time

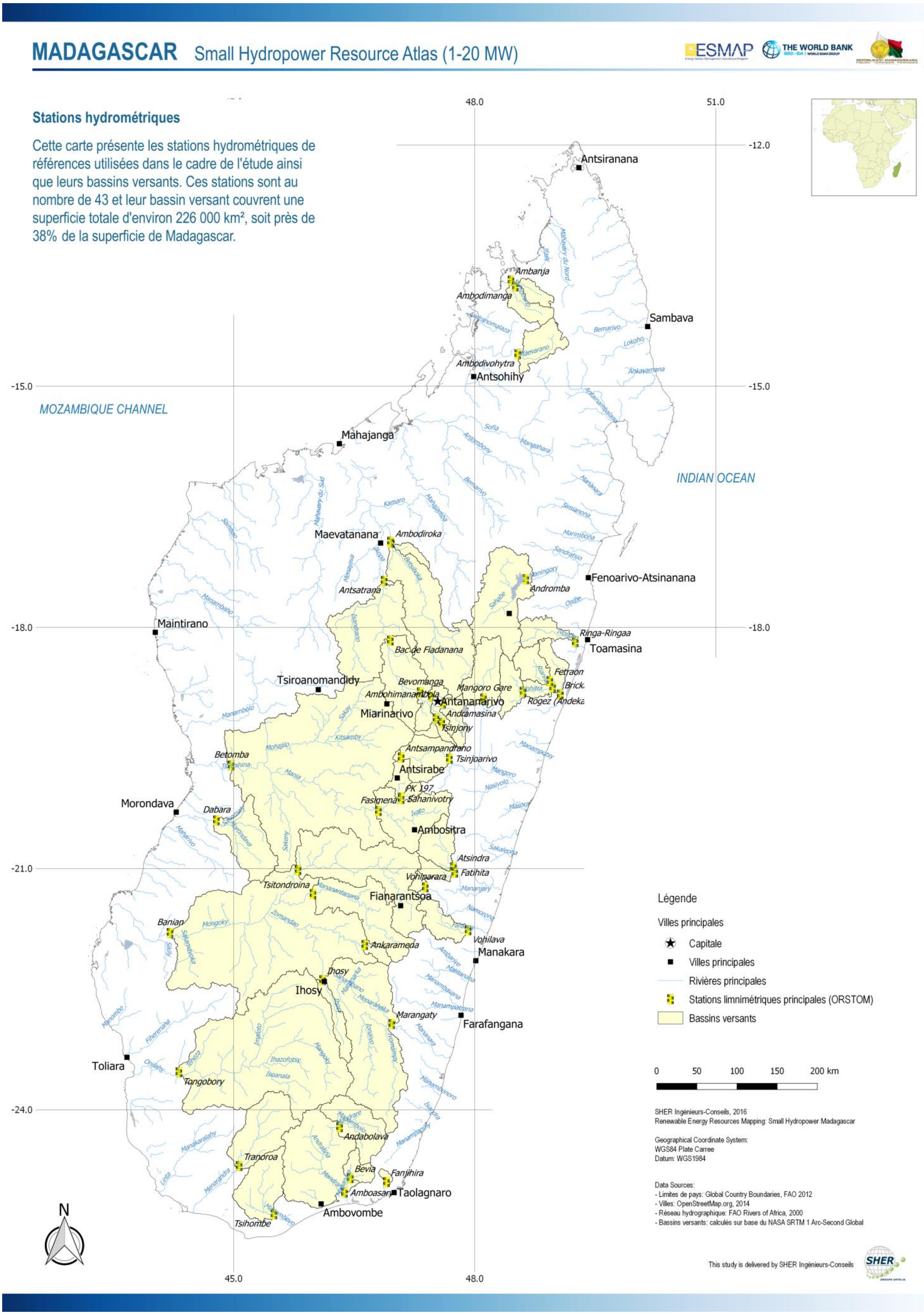


Figure 13. Location of the selected gauging stations

5.3 Modelling of the flow duration curve

5.3.1 Methodological approach

As mentioned earlier in this chapter, there is little or no information available on the hydrological regime of rivers at the selected potential hydropower sites. Therefore, we propose to obtain an estimate of the statistical characteristics of river flows at the sites of interest, based on the data available at other flow gauging stations on the territory of Madagascar.

The methodology of regionalisation includes the following 4 steps:

1) Descriptive analysis of hydrological data and selection of the statistical model ;

2) Estimation of the watersheds characteristics (for gauged and ungauged watersheds);

3) Regional comparisons;

4) Transfer of models to sites of interest and flow estimation.

These various steps are presented schematically in the figures below and are explained in the paragraphs below, with the presentation of the key results.

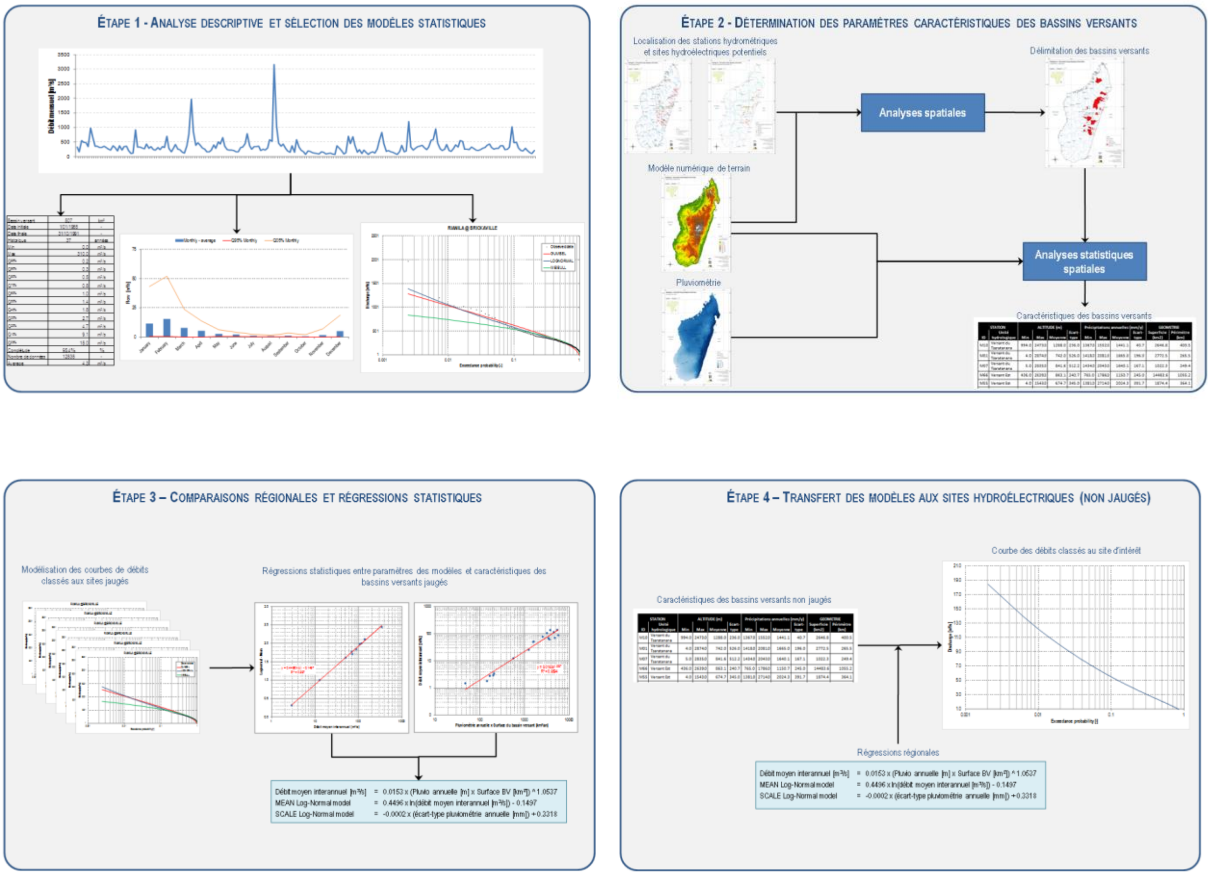


Figure 14.Modelling of flow duration curves: schematic representation of the modelling methodology

5.3.2 Descriptive analysis of hydrological data and selection of statistical model

This step is about the calculation of monthly and interannual statistics of the time series of hydrological data, the visualisation of the data and a quality control. The main characteristics of the measurement stations are shown in Table 12 below.

Table 12. Main statistical characteristics of the selected flow gauging stations

Code	River	Station name	Average monthy flow [m^3/s]												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Inter-annuel
M01	SAMBIRANO	AMBANJA	275.0	368.0	336.0	214.0	105.0	56.1	35.8	26.2	20.8	19.4	36.5	120.0	133.1
M05	MANDRARE	AMBOASARY	242.0	187.0	121.0	37.0	19.6	14.1	10.8	10.6	7.5	9.0	28.1	152.0	69.5
M07	RAMENA	AMBODIMANGA	144.0	187.0	158.0	107.0	55.2	28.6	19.3	14.9	10.7	10.7	17.0	62.6	67.2
M08	ISINKO	AMBODIROKA	51.6	65.6	58.3	21.5	9.4	7.1	5.5	4.2	3.2	2.8	12.3	26.4	22.1
M09	BETSIBOKA	AMBODIROKA	625.0	737.0	695.0	295.0	167.0	136.0	112.0	95.5	74.5	70.4	159.0	414.0	296.2
M10	MAEVARANO	AMBODIVOHYTRA	86.8	130.0	121.0	84.8	34.9	21.4	15.7	11.7	7.7	5.4	8.6	34.2	46.3
M11	IKOPA	AMBOHIMANAMBOLA	42.0	41.2	40.0	25.9	22.8	23.0	23.9	25.0	23.4	23.1	27.2	37.4	29.5
M15	MANDRARE	ANDABOLAVA	115.0	90.1	57.3	25.2	15.3	11.2	9.0	9.0	6.5	6.9	22.5	72.9	36.5
M19	VOHITRA	ANDEKALEKA AVAL	234.0	256.0	274.0	151.0	105.0	97.5	105.0	110.0	81.2	66.8	77.3	127.0	139.9
M20	SISAONY	ANDRAMASINA	12.2	12.7	10.8	5.5	3.7	3.3	3.2	3.0	2.4	2.2	3.9	9.6	6.0
M21	MANIGORY	ANDROMBA	62.6	115.0	160.0	155.0	107.0	77.7	59.5	45.9	34.0	24.3	19.2	27.2	73.6
M23	ZOMANDAO	ANKARAMENA	32.4	29.5	19.6	6.9	3.2	2.4	2.0	1.8	1.3	1.3	5.0	21.6	10.5
M31	AMBOROMPOTSY	ANTSAMPANDRANO	5.5	5.8	6.5	3.5	1.9	1.5	1.2	1.0	0.9	0.9	1.8	3.8	2.9
M32	IKOPA	ANTSATRANA	933.0	1050.0	1040.0	523.0	286.0	219.0	179.0	149.0	121.0	122.0	264.0	640.0	457.6
M33	MANANJARY	ANTSINDRA	178.0	216.0	208.0	152.0	102.0	82.1	80.5	82.5	63.7	48.6	66.0	128.0	116.8
M35	IVONGORO	RINGA-RINGAA	143.0	158.0	180.0	123.0	93.5	90.8	95.3	98.0	79.7	65.3	65.5	93.6	106.9
M36	FARAONY	VOHILAVA	183.0	261.0	224.0	140.0	99.6	77.2	79.7	83.7	58.7	48.3	62.0	124.0	119.3
M39	IKOPA	BAC DE FIADANANA	362.0	391.0	361.0	203.0	111.0	82.2	71.3	60.9	47.2	43.3	106.0	268.0	174.5
M40	MANGOKY	BANIAN	1520.0	1370.0	999.0	419.0	221.0	181.0	154.0	129.0	101.0	97.8	234.0	858.0	519.9
M42	TSIRIBIHINA	BETOMBA	2390.0	3430.0	2020.0	937.0	399.0	297.0	248.0	223.0	202.0	223.0	424.0	1200.0	985.3
M44	MANANARA	BEVIA	17.8	12.8	12.2	3.6	2.5	2.8	1.9	2.1	1.7	1.3	2.6	8.9	5.8
M46	IKOPA	BEVOMANGA	152.0	153.0	156.0	101.0	52.3	40.9	37.5	32.8	26.6	24.5	44.2	108.0	77.0
M48	RIANILA	BRICKAVILLE	465.0	508.0	720.0	382.0	291.0	284.0	294.0	279.0	221.0	179.0	222.0	299.0	344.7
M49	MORONDAVA	DABARA	144.0	151.0	95.4	21.9	16.1	19.4	12.4	10.9	9.6	9.1	18.0	106.0	50.7
M51	EFAHO	FANJIHIRA	21.3	30.9	22.7	12.8	8.7	5.8	10.2	9.9	3.7	3.3	7.2	9.3	12.0
M53	MANIA	FASIMENA	285.0	330.0	276.0	175.0	119.0	100.0	94.4	87.2	74.1	71.0	100.0	193.0	157.8
M54	IVOHANANA	FATIHITA	73.2	104.0	96.1	67.1	52.3	33.4	31.7	31.8	25.5	20.1	26.0	47.6	50.4
M55	RIANILA	FETRAOMBY	245.0	233.0	216.0	146.0	107.0	100.0	104.0	140.0	94.4	80.8	85.2	115.0	138.4
M59	IHOSY	IHOSY	50.0	42.1	28.3	13.3	7.4	5.8	4.8	4.4	3.3	3.4	5.6	24.9	16.0
M64	MATSIATRA	MALAKIALINA	652.0	531.0	431.0	166.0	92.6	77.4	64.0	58.8	47.3	39.1	90.2	680.0	243.4
M65	MANGORO	MANGORO GARE	155.0	185.0	179.0	105.0	66.6	53.8	49.1	43.1	33.4	30.0	53.1	119.0	88.9
M66	MANANARA SUD	MARANGATY	496.0	545.0	435.0	249.0	145.0	110.0	108.0	115.0	76.8	61.9	108.0	303.0	227.8
M72	SAHANIVOTRY	PK 197	18.1	21.4	18.2	12.6	8.1	6.1	5.5	4.7	3.7	4.0	8.1	13.8	10.3
M73	IKOPA	PONT DE MAHITSY	52.8	53.2	54.5	33.3	24.0	22.5	22.0	20.7	16.9	16.4	24.1	40.7	31.7
M75	VOHITRA	ROGEZ	105.0	116.0	132.0	77.4	54.9	53.2	56.8	58.6	45.8	36.2	41.3	62.1	69.7
M78	MANANDONA	SAHANIVOTRY	53.6	66.1	54.3	36.8	21.0	14.5	12.7	10.5	8.1	8.2	17.7	38.2	28.3
M81	ONILAHY	TONGOBORY	373.0	327.0	229.0	87.2	56.5	51.6	45.8	43.8	40.3	48.7	121.0	327.0	145.2
M82	MENARANDRA	TRANOROA	108.0	80.3	42.2	11.2	5.5	3.1	2.1	2.0	2.2	4.5	19.6	84.6	30.3
M83	MANOMBOVO	TSIHOMBE	15.3	14.5	6.5	1.4	0.4	0.2	0.2	0.0	0.2	0.6	3.6	12.4	4.6
M84	ONIVE	TSINJOARIVO	137.0	166.0	149.0	89.2	47.3	34.3	30.8	27.1	20.2	16.6	42.4	110.0	72.0
M85	AMDROMBA	TSINJONY	17.0	18.4	18.5	10.5	6.0	4.6	4.4	3.7	3.3	3.0	5.6	13.8	9.0
M86	MANANANTANANA	TSITONDROINA	261.0	224.0	172.0	64.3	31.2	27.0	20.4	19.4	14.9	13.5	42.4	208.0	91.0
M87	NAMORONA	VOHIPARARA	19.6	27.6	23.6	14.3	10.0	9.6	8.9	8.9	6.3	4.8	6.8	12.3	12.6

For each of the gauging stations, the flow duration curve is determined and modelled by three different statistical models often used in hydrology: (i) Weibull, (ii) Gumbel and (iii) Log-Normal. Each model can be characterised by 2 parameters. The parameters of these three models are optimised to best adjust the measured flow duration curve. It should be remembered that these are monthly flows.

As an example, Figure 15 shows the flow curve for the Antsindra station on the Mananjary River and the three adjusted statistical models. We note that the Gumbel and Log normal laws best fit the observations, with the Log normal law making it possible to better represent the low flows, with an exceeding probability of more than 90%.

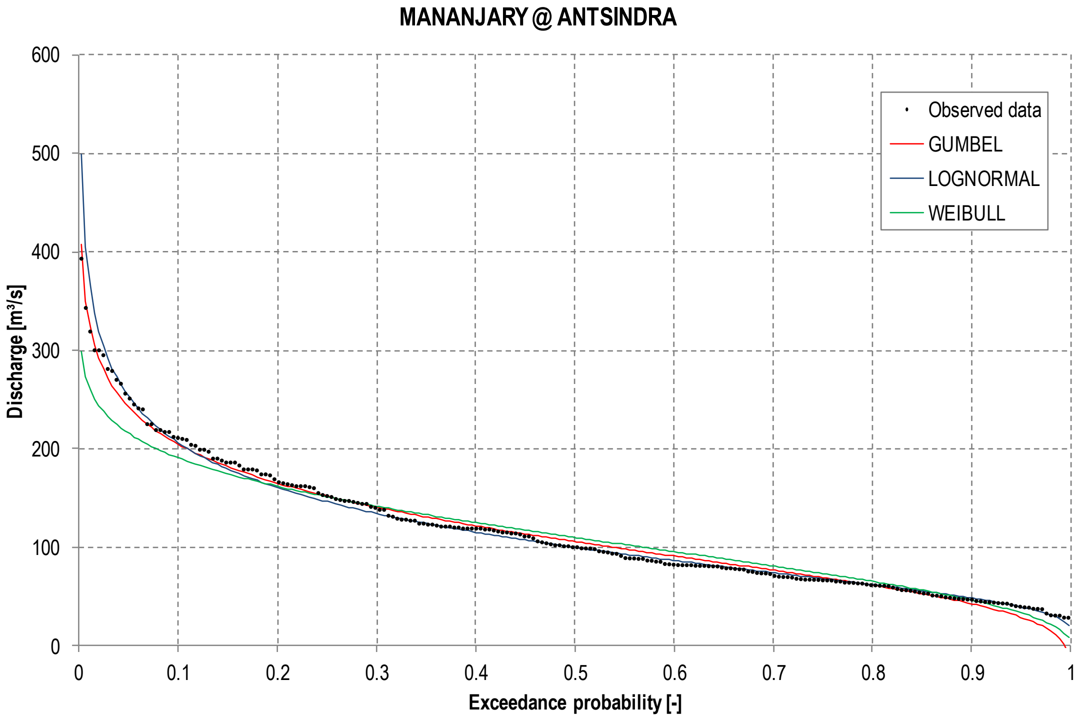


Figure 15. Flow duration curve and adjusted statistical models for the Station Antsindra on the Mananjary

5.3.3 Determination of the parameters characterising the gauged and ungauged watersheds

5.3.3.1 Watershed delineation

First, the watersheds of the gauged sites (43 flow measuring stations) and ungauged sites (34 potential hydropower sites) are delineated using the ArcHydro tool of the ESRI GIS software through the following intermediate steps:

1) Correction of the digital terrain model (DTM) in order to interpolate for all zones without values and to eliminate certain imperfections in the DTM.

2) Calculation of the flow direction for each cell of the DEM corresponding to the direction of the highest gradient between adjacent cells;

3) Calculation of the flow accumulation layer corresponding to the surface flow paths for each DEM cell, the calculation of the number of cells located upstream of each of the cells;

4) Visual validation of the location of the points for which the delimitation of the watersheds is requested (hydrometric stations and potential hydropower sites). This is to ensure that they are well positioned on the right accumulation stretch of the surface flows determined in the previous step, otherwise the delimitation of the watershed would be wrong.

5) Calculation of the watershed boundaries, based on the previous layers

6) Visual validation of watershed boundaries on topographic map background.

The results of these spatial analysis processes are different GIS layers (in vector and raster formats) and are a prerequisite for the further determination of the characteristics of the watersheds.

Code	Location		Altitude	River	Station name	Watershed area	Average annual rainfall	Average monthly flow [m³/s]												
	Lat (DD)	Lon (DD)	[masl]			[km²]	[mm/y]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Inter-annual
M01	13.6833	48.4500	13	SAMBIRANO	AMBANJA	2830	1585.7	275.0	368.0	336.0	214.0	105.0	56.1	35.8	26.2	20.8	19.4	36.5	120.0	133.1
M05	25.0500	46.4667	17	MANDRARE	AMBOASARY	12435	1445.1	242.0	187.0	121.0	37.0	19.6	14.1	10.8	10.6	7.5	9.0	28.1	152.0	69.5
M07	13.7500	48.5000	10	RAMENA	AMBODIMANGA	1080	1478.6	144.0	187.0	158.0	107.0	55.2	28.6	19.3	14.9	10.7	10.7	17.0	62.6	67.2
M08	16.9489	46.9608	146	ISINKO	AMBODIROKA	600	1449.3	51.6	65.6	58.3	21.5	9.4	7.1	5.5	4.2	3.2	2.8	12.3	26.4	22.1
M09	16.9333	46.9500	108	BETSIBOKA	AMBODIROKA	11800	2033.9	625.0	737.0	695.0	295.0	167.0	136.0	112.0	95.5	74.5	70.4	159.0	414.0	296.2
M10	14.6000	48.5333	1284	MAEVARANO	AMBODIVOHYTRA	2585	910.0	86.8	130.0	121.0	84.8	34.9	21.4	15.7	11.7	7.7	5.4	8.6	34.2	46.3
M11	18.9453	47.5989	1267	IKOPA	AMBOHIMANAMBOLA	1407	1389.5	42.0	41.2	40.0	25.9	22.8	23.0	23.9	25.0	23.4	23.1	27.2	37.4	29.5
M15	24.2167	46.3167	236	MANDRARE	ANDABOLAVA	4035	1548.0	115.0	90.1	57.3	25.2	15.3	11.2	9.0	9.0	6.5	6.9	22.5	72.9	36.5
M19	18.8000	48.9500	14	VOHITRA	ANDEKALEKA AVAL	2615	1421.2	234.0	256.0	274.0	151.0	105.0	97.5	105.0	110.0	81.2	66.8	77.3	127.0	139.9
M20	19.1861	47.5889	1353	SISAONY	ANDRAMASINA	318	1378.6	12.2	12.7	10.8	5.5	3.7	3.3	3.2	3.0	2.4	2.2	3.9	9.6	6.0
M21	17.4000	48.6333	741	MANIGORY	ANDROMBA	6855	1381.7	62.6	115.0	160.0	155.0	107.0	77.7	59.5	45.9	34.0	24.3	19.2	27.2	73.6
M23	21.9500	49.6500	825	ZOMANDAO	ANKARAMENA	610	1622.0	32.4	29.5	19.6	6.9	3.2	2.4	2.0	1.8	1.3	1.3	5.0	21.6	10.5
M31	19.6167	47.0833	1878	AMBOROMPOTSY	ANTSAMPANDRANO	95	1859.6	5.5	5.8	6.5	3.5	1.9	1.5	1.2	1.0	0.9	0.9	1.8	3.8	2.9
M32	17.4333	46.8833	450	IKOPA	ANTSATRANA	18645	1798.3	933.0	1050.0	1040.0	523.0	286.0	219.0	179.0	149.0	121.0	122.0	264.0	640.0	457.6
M33	20.9833	47.7333	423	MANANJARY	ANTSINDRA	2260	1441.1	178.0	216.0	208.0	152.0	102.0	82.1	80.5	82.5	63.7	48.6	66.0	128.0	116.8
M35	18.1833	49.2500	15	IVONGORO	RINGA-RINGAA	2560	1111.1	143.0	158.0	180.0	123.0	93.5	90.8	95.3	98.0	79.7	65.3	65.5	93.6	106.9
M36	21.7667	47.9167	11	FARAONY	VOHILAVA	2005	854.6	183.0	261.0	224.0	140.0	99.6	77.2	79.7	83.7	58.7	48.3	62.0	124.0	119.3
M39	18.1625	46.9483	974	IKOPA	BAC DE FIADANANA	9450	1150.7	362.0	391.0	361.0	203.0	111.0	82.2	71.3	60.9	47.2	43.3	106.0	268.0	174.5
M40	21.8000	44.2069	210	MANGOKY	BANIAN	50000	1417.0	1520.0	1370.0	999.0	419.0	221.0	181.0	154.0	129.0	101.0	97.8	234.0	858.0	519.9
M42	19.7167	44.9667	12	TSIRIBIHINA	BETOMBA	45000	1876.8	2390.0	3430.0	2020.0	937.0	399.0	297.0	248.0	223.0	202.0	223.0	424.0	1200.0	985.3
M44	24.8500	46.4500	47	MANANARA	BEVIA	1085	793.9	17.8	12.8	12.2	3.6	2.5	2.8	1.9	2.1	1.7	1.3	2.6	8.9	5.8
M46	18.8083	47.3200	1236	IKOPA	BEVOMANGA	4184	984.3	152.0	153.0	156.0	101.0	52.3	40.9	37.5	32.8	26.6	24.5	44.2	108.0	77.0
M48	18.8167	49.0667	12	RIANILA	BRICKAVILLE	6000	994.4	465.0	508.0	720.0	382.0	291.0	284.0	294.0	279.0	221.0	179.0	222.0	299.0	344.7
M49	20.4000	44.7833	91	MORONDAVA	DABARA	4640	1524.3	144.0	151.0	95.4	21.9	16.1	19.4	12.4	10.9	9.6	9.1	18.0	106.0	50.7
M51	24.9000	46.9000	21	EFAHO	FANJIHIRA	195	1441.6	21.3	30.9	22.7	12.8	8.7	5.8	10.2	9.9	3.7	3.3	7.2	9.3	12.0
M53	20.2833	46.8000	1269	MANIA	FASIMENA	6795	1188.1	285.0	330.0	276.0	175.0	119.0	100.0	94.4	87.2	74.1	71.0	100.0	193.0	157.8

Code	Location		Altitude	River	Station name	Watershed area	Average annual rainfall	Average monthly flow [m³/s]												
	Lat (DD)	Lon (DD)	[masl]			[km²]	[mm/y]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Inter-annual
M54	21.0500	47.7500	293	IVOHANANA	FATIHITA	835	525.6	73.2	104.0	96.1	67.1	52.3	33.4	31.7	31.8	25.5	20.1	26.0	47.6	50.4
M55	18.6667	48.9333	22	RIANILA	FETRAOMBY	1863	1280.2	245.0	233.0	216.0	146.0	107.0	100.0	104.0	140.0	94.4	80.8	85.2	115.0	138.4
M59	22.3833	46.1167	704	IHOSY	IHOSY	1500	710.5	50.0	42.1	28.3	13.3	7.4	5.8	4.8	4.4	3.3	3.4	5.6	24.9	16.0
M64	21.0167	45.8000	527	MATSIATRA	MALAKIALINA	11715	1099.5	652.0	531.0	431.0	166.0	92.6	77.4	64.0	58.8	47.3	39.1	90.2	680.0	243.4
M65	18.8833	48.1083	874	MANGORO	MANGORO GARE	3600	1398.4	155.0	185.0	179.0	105.0	66.6	53.8	49.1	43.1	33.4	30.0	53.1	119.0	88.9
M66	22.9333	46.9667	545	MANANARA SUD	MARANGATY	14160	783.7	496.0	545.0	435.0	249.0	145.0	110.0	108.0	115.0	76.8	61.9	108.0	303.0	227.8
M72	20.1167	47.0833	1376	SAHANIVOTRY	PK 197	430	1451.2	18.1	21.4	18.2	12.6	8.1	6.1	5.5	4.7	3.7	4.0	8.1	13.8	10.3
M73	18.8631	47.4581	1260	IKOPA	PONT DE MAHITSY	1684	1640.1	52.8	53.2	54.5	33.3	24.0	22.5	22.0	20.7	16.9	16.4	24.1	40.7	31.7
M75	18.8000	48.6000	374	VOHITRA	ROGEZ (ANDEKALEKA)	1910	2153.8	105.0	116.0	132.0	77.4	54.9	53.2	56.8	58.6	45.8	36.2	41.3	62.1	69.7
M78	20.1333	47.0833	1426	MANANDONA	SAHANIVOTRY	1450	2024.3	53.6	66.1	54.3	36.8	21.0	14.5	12.7	10.5	8.1	8.2	17.7	38.2	28.3
M81	23.5333	44.3167	79	ONILAHY	TONGOBORY	27700	1413.1	373.0	327.0	229.0	87.2	56.5	51.6	45.8	43.8	40.3	48.7	121.0	327.0	145.2
M82	24.7000	45.0667	201	MENARANDRA	TRANOROA	5330	1665.0	108.0	80.3	42.2	11.2	5.5	3.1	2.1	2.0	2.2	4.5	19.6	84.6	30.3
M83	25.3000	45.5000	88	MANOMBOVO	TSIHOMBE	2712	1387.3	15.3	14.5	6.5	1.4	0.4	0.2	0.2	0.0	0.2	0.6	3.6	12.4	4.6
M84	19.6333	47.6833	1603	ONIVE	TSINJOARIVO	3200	1419.6	137.0	166.0	149.0	89.2	47.3	34.3	30.8	27.1	20.2	16.6	42.4	110.0	72.0
M85	19.1333	47.5167	1360	AMDROMBA	TSINJONY	350	2022.7	17.0	18.4	18.5	10.5	6.0	4.6	4.4	3.7	3.3	3.0	5.6	13.8	9.0
M86	21.3167	45.9861	600	MANANANTANANA	TSITONDROINA	6510	1796.6	261.0	224.0	172.0	64.3	31.2	27.0	20.4	19.4	14.9	13.5	42.4	208.0	91.0
M87	21.2333	47.3833	1188	NAMORONA	VOHIPARARA	445	1068.5	19.6	27.6	23.6	14.3	10.0	9.6	8.9	8.9	6.3	4.8	6.8	12.3	12.6

Table 13. Main statistical characteristics of the selected flow gauging stations

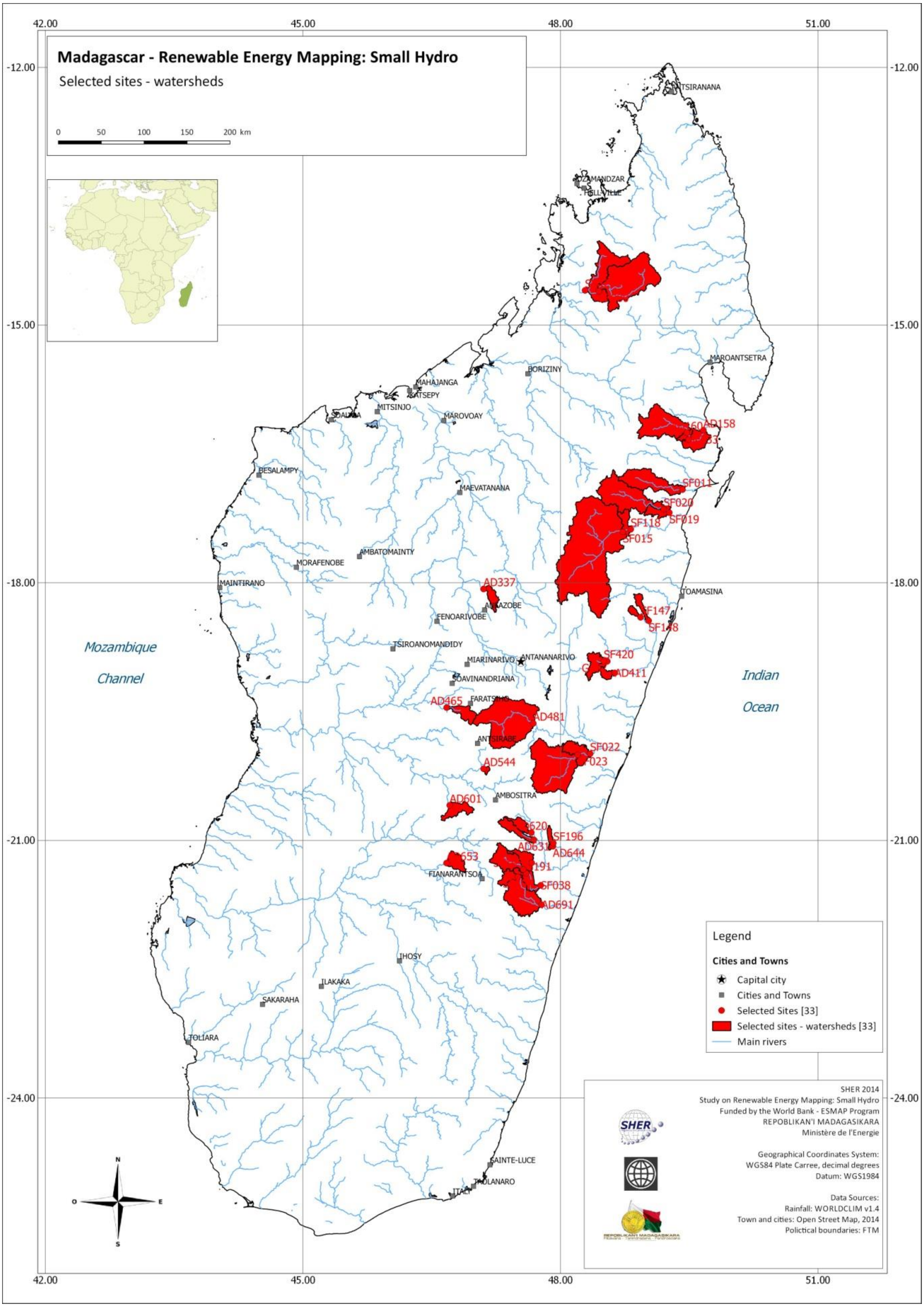


Figure 16. Watersheds of the 33 promising small hydropower sites

5.3.3.2 Determining the characteristic parameters of the watershed

These parameters include the meteorology (rainfall, temperature), the topography and the morphology (area, perimeter, altitude, coefficient of Gravelius, height differences, etc.)) of the watersheds. The parameters calculated for each of gauged and ungauged watersheds are shown in the Table below.

STATION		ALTITUDE (m)				ANNUAL RAINFALL (mm/y)				GEOMETRY	
ID	Hydrological Unit	Min	Max	Average	Standard deviation	Min	Max	Average	Standard deviation	Area (km2)	Perimeter (km)
M10	Tsaratanana side	994.0	2473.0	1288.0	236.0	1367.0	1552.0	1441.1	40.7	2646.8	400.5
M01	Tsaratanana side	4.0	2874.0	742.0	526.0	1418.0	2081.0	1665.0	196.0	2772.5	265.5
M07	Tsaratanana side	5.0	2835.0	841.6	512.2	1434.0	2043.0	1640.1	167.1	1022.3	249.4
M66	East side	436.0	2639.0	863.1	240.7	765.0	1786.0	1150.7	245.0	14483.6	1055.2
M55	East side	4.0	1543.0	674.7	345.0	1381.0	2714.0	2024.3	391.7	1874.4	364.1
M36	East side	1.0	1444.0	496.1	365.7	1368.0	2421.0	2033.9	313.9	2068.2	431.9
M35	East side	4.0	1462.0	730.8	359.0	1213.0	3031.0	1798.3	512.5	2109.1	417.9
M33	East side	345.0	1836.0	993.3	336.7	1408.0	2392.0	1876.8	304.8	2394.7	384.0
M54	East side	201.0	1696.0	927.1	330.3	1399.0	2406.0	1859.6	361.2	834.1	251.6
M31	East side	1777.0	2292.0	2049.1	68.3	1544.0	1612.0	1585.7	14.6	106.3	65.2
M65	East side	809.0	1619.0	1015.2	167.3	1253.0	1814.0	1524.3	137.1	3735.9	566.0
M84	East side	1479.0	2626.0	1703.8	158.3	1369.0	1607.0	1451.2	51.3	3282.4	315.2
M21	East side	640.0	1567.0	904.0	134.9	1071.0	1482.0	1188.1	74.5	8053.7	830.7
M87	East side	1117.0	1582.0	1254.1	76.7	1285.0	1520.0	1398.4	54.9	390.6	147.6
M19	East side	4.0	1538.0	775.5	342.1	1386.0	2745.0	2022.7	423.7	2613.5	399.1
M48	East side	2.0	1543.0	624.2	387.5	1381.0	2903.0	2153.8	452.2	6059.7	679.6
M75	East side	347.0	1538.0	956.8	153.7	1378.0	2618.0	1796.6	268.7	1895.8	378.1
M08	West side	119.0	1364.0	725.2	367.4	1428.0	1710.0	1622.0	92.1	607.8	239.7
M09	West side	60.0	1777.0	987.6	325.1	1221.0	1783.0	1478.6	138.2	11904.5	1092.5
M11	West side	1226.0	1800.0	1456.4	95.3	1313.0	1469.0	1389.5	29.2	1545.5	347.0
M20	West side	1293.0	1782.0	1513.4	84.0	1345.0	1425.0	1387.3	17.8	326.4	158.2
M32	West side	383.0	2598.0	1189.1	272.5	1302.0	1837.0	1548.0	151.8	18515.1	1002.4
M39	West side	921.0	2598.0	1361.0	165.6	1302.0	1642.0	1421.2	75.2	9532.8	660.7
M46	West side	1176.0	2598.0	1433.7	151.1	1302.0	1560.0	1378.6	44.6	4221.0	402.4
M73	West side	1224.0	1800.0	1444.4	103.8	1313.0	1471.0	1381.7	28.8	2422.6	293.3
M85	West side	1321.0	2598.0	1584.8	205.2	1347.0	1560.0	1445.1	51.5	356.0	158.6
M23	West side	752.0	2599.0	1257.3	406.5	923.0	1396.0	1068.5	114.5	613.3	176.9
M40	West side	44.0	2599.0	772.1	368.9	732.0	1525.0	994.4	202.1	50354.3	1854.0
M59	West side	684.0	1810.0	1094.0	230.8	764.0	1087.0	910.0	90.0	1542.4	417.1

STATION		ALTITUDE (m)				ANNUAL RAINFALL (mm/y)				GEOMETRY	
ID	Hydrological Unit	Min	Max	Average	Standard deviation	Min	Max	Average	Standard deviation	Area (km2)	Perimeter (km)
M64	West side	389.0	2001.0	1099.4	311.6	1116.0	1525.0	1280.2	61.1	11876.9	1175.7
M86	West side	519.0	2094.0	1003.4	245.3	957.0	1385.0	1111.1	73.4	6617.4	803.7
M49	West side	50.0	957.0	334.0	144.7	897.0	1294.0	1099.5	84.5	4705.6	541.4
M81	West side	55.0	1815.0	705.2	293.8	551.0	1094.0	783.7	88.2	28579.3	1341.6
M42	West side	3.0	2620.0	922.8	525.9	1092.0	1953.0	1419.6	117.2	45429.0	1528.4
M53	West side	987.0	2376.0	1528.8	209.1	1334.0	1612.0	1441.6	53.9	7026.2	538.5
M72	West side	1348.0	2060.0	1812.5	78.3	1392.0	1444.0	1413.1	10.2	432.8	144.6
M78	West side	1333.0	2376.0	1701.0	167.9	1347.0	1569.0	1417.0	43.3	1437.3	211.2
M05	South side	4.0	1966.0	378.4	273.5	526.0	1296.0	793.9	169.0	13349.5	597.7
M51	South side	4.0	1299.0	283.8	287.8	1099.0	1786.0	1449.3	206.5	258.5	97.6
M15	South side	177.0	1966.0	601.6	315.9	817.0	1295.0	984.3	94.3	3870.1	475.4
M44	South side	27.0	1875.0	389.6	283.8	669.0	1138.0	854.6	104.9	1124.3	234.2
M83	South side	35.0	692.0	213.6	87.9	441.0	688.0	525.6	54.4	4076.2	423.0
M82	South side	155.0	1423.0	448.9	150.6	553.0	855.0	710.5	72.6	5368.0	532.6

Table 14. Main characteristics of the gauged watersheds

5.3.3.3 Regional comparisons

As a reminder, Madagascar is characterised by five major natural hydrological units resulting from the superposition of climate and geomorphological features. These five major units are (i) the North side, (ii) Tsaratanana side, (iii) East side, (iv) West side, and (v) South side.

The flow gauging stations were grouped into these categories and for each of these, we have determined a relationship between the parameters of the most relevant statistical models (Weibull, GEV, Log-Normal or Log-Peason type 3) and the watershed characteristics determined in the previous step.

Watersheds on the East side - For the gauged watersheds of the Eastern region (discharging into the Indian Ocean), it appeared that the GEV statistical model was the most suitable to describe the flow duration curve. The variance-covariance analysis has shown that the parameters of the GEV model were the most correlated with the average altitude of the watersheds and the average annual rainfall of these. The linear regressions between the explanatory variables and the GEV model parameters are shown in Figure 17 below.

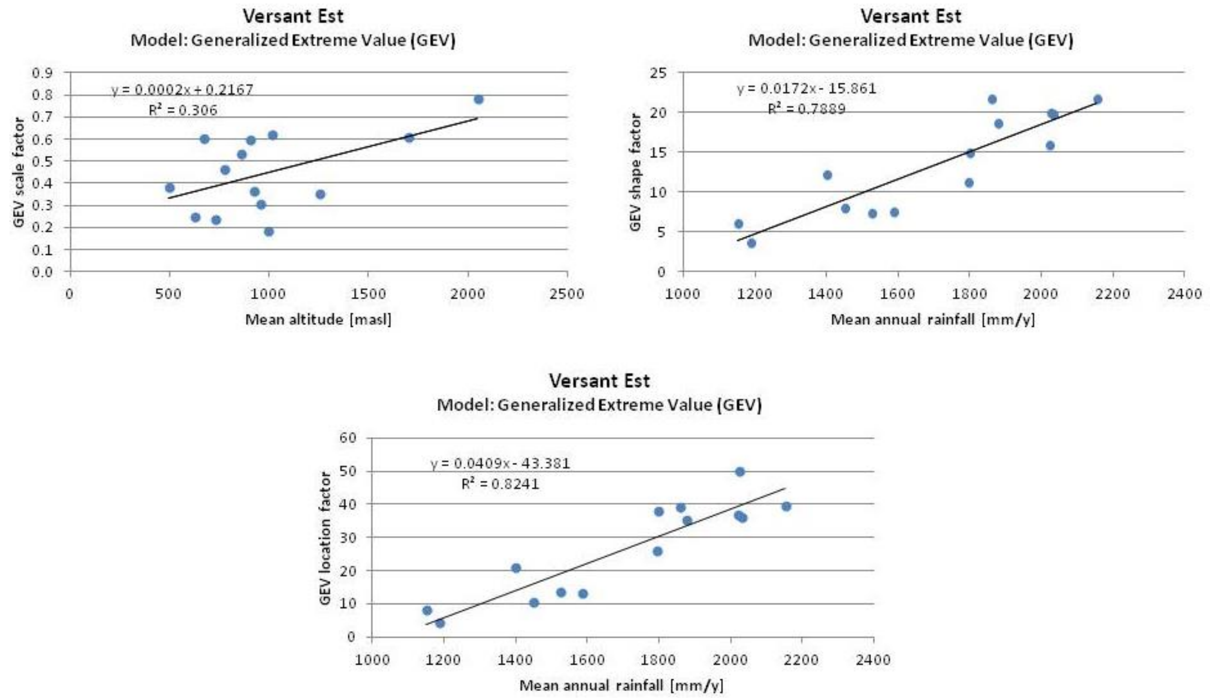


Figure 17. Explanatory variables of model parameters for the East side

Watersheds on the West side – For the gauged watersheds of the Western region (discharging into the Mozambic Canal), we see that the Weibull model is the most suitable to describe the flow duration curve of these sites. The analyses of the variance-covariance have shown that the parameters of the Weilbull model were better correlated with the average altitude of the watersheds and the average annual rainfall on the latter. The regressions between these variables and the Weibull model parameters are shown in Figure 18 below.

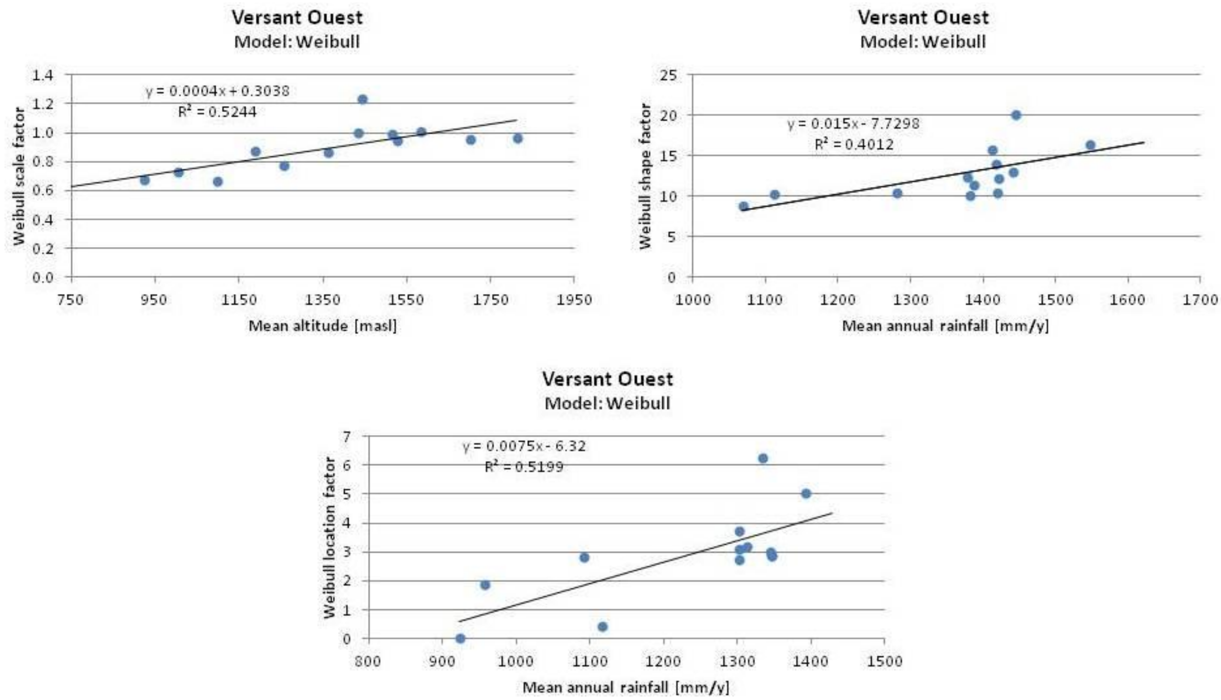


Figure 18. Explanatory variables of model parameters for the West side

Watersheds on Tsaratanana side – For the gauged Tsaratanana watersheds, only three flow measurement stations were available in our hydrological database and only one is located in the same watershed as the promising hydropower sites. Therefore, the estimation of the statistical characteristics of the flow duration curves for these sites will be done by the ratio of watershed area.

Watersheds on the South side – No model has been determined for these watersheds since no promising hydropower sites has been identified in the context of this study.

Watersheds at the North side – No model has been determined for these watersheds since no promising hydropower sites has been identified in the context of this study.

5.3.3.4 Model extrapolation to sites of interest and flow estimates.

Statistical characteristics - The statistical characteristics of the flow duration curves of the 34 promising hydropower sites were estimated based on the relationships (statistical regressions) determined in the previous steps;

Confidence index - A confidence index on the extrapolated statistics for the 34 ungauged sites is finally attributed to each of them based on the following:

- Presence or absence of a gauging station close to the site, in the subwatershed or more widely in the watershed;
- Presence of a gauging station in a neighbouring watershed;
- Comparison with flows measured near the sites during the field visit mission done between September and November 2014 (low water period). The measured flows are only ad hoc measures but taken during the low flow season, they allow to some extent to assess the consistency of the extrapolations explained in the previous sections;

The percentiles of the extrapolated flows of the 33 promising hydropower sites, as well as the confidence indices are presented on Table 15 below.

Site		River	Main	Specific Flow [L/s/km2]						Hydrological model	Confidence incdex	Comments
Code	Name		Watershed	Qs95	Qs90	Qs70	Qs50	Qs30	Qs05			
AD544	Analamanaha	Analamanaha	Tsiribihina	4.98	5.73	9.14	13.59	20.23	43.01	Weibull – West side	Medium	Ungauged sub basin (but river basin gauged elsewhere) - Gauged at 0.26 m3/s in October 2014
AD158	Vohipary	Mananara	Mananara	15.96	18.74	26.77	35.19	47.71	106.00	GEV – East side	Low	Ungauged river basin (and no other adjacent gauged river basin)
AD160	Ilengy	Mananara	Mananara	11.38	13.47	19.62	26.21	36.23	85.42	GEV - East side	Low	Ungauged river basin (and no other adjacent gauged river basin)
AD337	Tsaravao	Manankazo	Betsiboka	5.00	5.64	8.93	13.72	21.45	50.69	Weibull - West side	Low	Ungauged sub basin (but river basin gauged elsewhere) - Gauged at 1.5 m3/s in October 2014
AD411	Ambodimanga	Laroka	Rianila	29.08	33.39	46.02	59.47	79.81	178.28	GEV - East side	Medium	Ungauged sub basin (but river basin gauged elsewhere) - Gauged at 10.86 m3/s in October 2014
AD465	Marianina	Sahasarotra	Tsiribihina	6.80	7.76	12.01	17.53	25.71	53.61	Weibull - West side	Low	Ungauged sub basin (river basin gauged downstream at M42 but watershed ratio less than 10%) - Ungauged during site visit
AD481	Tsinjoarivo	Onive	Mangoro	3.79	5.34	8.32	12.75	24.71	67.55	Gauging station at site	High	M84 gauging station at site location
AD620	Behingitika	Manandriana	Mananjary	22.27	25.71	35.81	46.61	63.00	143.06	GEV - East side	Medium	Ungauged sub basin (but river basin gauged downstream after ungauged confluence) - Gauged at 4.8 m3/s in October 2014
AD631	Antanjona	Sahanofa	Mananjary	17.83	20.56	28.76	37.76	51.80	124.78	GEV - East side	Medium	Ungauged sub basin (but river basin gauged downstream after ungauged confluence) - Estimated at 7 m3/s in October 2014
AD644	Antaninaren	Manabano	Mananjary	30.85	35.97	50.33	64.78	85.38	172.71	GEV - East side	Medium	Ungauged river basin (but adjacent gauged river basin) - Gauged at 3.5 m3/s in October 2014
AD652	Tambohorano	Faravory	Mananjary	25.19	29.12	40.51	52.51	70.43	154.86	GEV - East side	Medium	Ungauged river basin (but adjacent gauged river basin) - Gauged at 10.0 m3/s in October 2014
AD691	Ambatosada	Faraony	Faraony	20.77	24.22	34.15	44.48	59.70	129.38	GEV - East side	Medium	Gauged river basin downstream (watershed area ratio 83%) - Gauged at 14 m3/s in October 2014
G191	Andriamanjavona	Namorona	Namorona	11.12	13.03	18.82	25.23	35.33	89.00	GEV - Versant Est	High	Gauged river basin upstream (watershed area ratio 48%) - Gauged at 10.8 m3/s in October 2014
G407	Fanovana	Sanatanora	Rianila	17.98	20.77	29.10	38.18	52.25	124.25	GEV - East side	Medium	Ungauged sub basin (but river basin gauged downstream after ungauged confluence) - Gauged at 8.32 m3/s in October 2014
SF011	SF011	Marimbona	Marimbona	12.43	14.66	21.23	28.22	38.82	90.34	GEV - East side	Low	Ungauged river basin (and no other adjacent gauged river basin) - Gauged at 64.23 m3/s in October 2014
SF019	SF019	Sandratsiona	Maningory	5.96	7.38	11.56	16.05	22.89	56.58	GEV - East side	Low	Ungauged river basin (and no other adjacent gauged river basin) - Gauged at 55.71 m3/s in October 2014
SF020	SF020	Sandratsio	Maningory	3.49	4.59	7.85	11.38	16.80	44.00	GEV - East side	Low	Ungauged river basin (and no other adjacent gauged river basin) - Gauged at 55.71 m3/s in October 2014

Site		River	Main	Specific Flow [L/s/km2]						Hydrological model	Confidence incdex	Comments
Code	Name		Watershed	Qs95	Qs90	Qs70	Qs50	Qs30	Qs05			
SF022	SF022	Nosivolo	Mangoro	21.82	25.19	35.10	45.71	61.87	141.30	GEV - East side	Low	Ungauged river basin - Gauged at 34 m3/s in October 2014
SF023	SF023	Nosivolo	Mangoro	20.85	24.05	33.51	43.73	59.39	137.60	GEV - East side	Low	Ungauged river basin - Gauged at 34 m3/s in October 2014
SF038	SF038	Namorona	Namorona	16.58	19.27	27.21	35.79	48.93	114.57	GEV - East side	Medium	Gauged river basin upstream (watershed area ratio 32%) - Gauged at 14.2 m3/s in October 2014
SF147	SF147	Iovay	Rianila	21.66	25.11	35.17	45.78	61.67	137.04	GEV - East side	Medium	Ungauged river basin (but adjacent gauged river basin) - Gauged at 4.98 m3/s in October 2014
SF148	SF148	Morongolo	Rianila	24.08	27.94	39.07	50.68	67.85	146.95	GEV East side	Medium	Ungauged river basin (but adjacent gauged river basin) - Gauged at 8.84 m3/s in October 2014
SF195	SF195	Namorona	Namorona	10.53	12.37	17.94	24.12	33.88	86.07	GEV - East side	High	Gauged river basin upstream (watershed area ratio 50%) - Gauged at 10.27m3/s in October 2014
SF196	SF196	Besana	Mananjary	31.24	36.35	50.73	65.29	86.20	176.23	GEV - East side	Medium	Ungauged river basin (but adjacent gauged river basin) - Gauged at 2.4 m3/s in October 2014
SF204	SF204	Faraony	Faraony	12.24	14.35	20.64	27.51	38.18	93.04	GEV - East side	Medium	Ungauged river basin (but adjacent gauged river basin) - Gauged at 5.1 m3/s in October 2014
SF420	SF420	Sahatandra	Rianila	16.80	19.45	27.34	35.97	49.35	118.10	GEV East side	Medium	Ungauged sub basin (but river basin gauged downstream after ungauged confluence) - Gauged at 8.32 m3/s in October 2014
SF533	SF533	Mananara	Mananara	12.14	14.37	20.89	27.79	38.18	87.81	GEV - East side	Low	Ungauged river basin (and no other adjacent gauged river basin)
SF118	SF118	Maningory	Maningory	0.85	1.06	3.26	5.79	10.20	27.44	Watershed ratio with M21 gauging station	High	M21 gauging station (at Lake Alaotra outlet) watershed area represents 95.6% of SF118 watershed
SF080	SF080	Maevarano	Maevarano	1.79	2.23	4.57	9.39	22.65	59.56	Watershed ratio with M10 gauging station	High	M10 gauging station watershed area represents 90% of SF080 watershed - Gauged at 12.3 m3/s in October 2014
SF079	SF079	Maevarano	Maevarano	1.79	2.23	4.57	9.39	22.65	59.56	Watershed ratio with M10 gauging station	Medium	Major affluent between M10 gauging station and SF079 site (watershed area ratio of 59%)
SF015	SF015	Maningory	Maningory	0.85	1.06	3.26	5.79	10.20	27.44	Watershed ratio with M21 gauging station	High	M21 gauging station (at Lake Alaotra outlet) watershed area represents 99.3% of SF015 watershed
AD653	Vohinaomby	Antsakoama	Mongoky	2.64	3.02	5.18	8.59	14.40	38.09	Weibull – West side	Low	Ungauged sub basin (but river basin gauged downstream - watershed area ratio less than 10%) - Gauged at 0.3 m3/s in October 2014
AD601	Antaralava	Imorona	Tsiribihina	4.09	4.63	7.49	11.76	18.73	45.69	Weibull – West side	Medium	Ungauged sub basin (but river basin gauged elsewhere) - Gauged at 1.2 m3/s in October 2014

Table 15. Specific flow extrapolated to the 33 promising hydropower sites

5.4 PRELIMINARY ECONOMIC EVALUATION OF THE MOST PROMISING SITES

To evaluate the 33 visited promising sites, the consultant adapted his "EconEval" software to the Malagasy context to be able to calculate expected production and project costs, based on the characteristics of the planned projects, the local context and the hydrology. From the production and the cost, he deducts the LCOE (Levelised cost of energy) for each site, allowing a harmonious comparison between the sites.

The aim of the EconEval program is the production of a complete database, including:

- Basic information, collected on site (topographical coordinates of main works for example) or resulting from a preliminary calculation (mainly for hydrology),
- Textual information about the nature of the site, the planned project, the topographic coordinates of the main infrastructure
- Information resulting from an economic calculation, such as the annual producible, the LCOE relative to different scenarios, etc.

This database enables the publication of standardised documents describing the sites.

A complete description of EconEval is given in Annex 2 (chapter 13.2).

5.4.1 Project cost

The main elements that are taken into consideration in the cost are summarised below:

- Hydropower type (run-of-the-river / storage reservoir)
- Design flood and flow duration curve
- Works design (Dam – Spillway – Sand trap – Supply works (channel or headrace tunnel) – Forebay or Surge chamber - Penstock - Powerhouse)
- Hydromechanical equipment (+ types of turbines)
- Access roads
- Electrical lines

The unit prices used for the estimation of costs have been determined using the costs of raw materials found in the subregion.

5.4.2 Electricity production cost of potential sites

The electricity production calculation depends on the type of hydropower planned (run-of-the-river or storage reservoir) and on the choice of the design flow, itself depending on the connection type (off-grid or grid connected). The energy is estimated based on the flow duration curve available in the hydrological study explained in part 5.2. We define the corresponding capacity to each flow interval associated with the planned hydropower type. For each specified capacity, we can deduct the energy created for each time interval. Depending on the design flow, different cases are possible.

We consider that the design flow is always above Q_{95} which is the minimum design flow for a run-of-the-river scheme operating off-grid.

5.4.3 LCOE - Levelised cost of energy

The levelised cost of energy (LCOE) is defined based on the investment costs (Capex – Capital Expenditure), the operating costs (Opex – Operational Expenditure) and the expected energy production.

The investment costs concern:

- Study and work supervision costs (considered as 10% of the total investment cost),
- Civil engineering and equipment investment costs (CE and EM),
- Ressettlement and environmental impact costs (considered as 10% of the total investment cost),
- Costs related to access and connection to the grid.

Annual operating costs are:

- Cost for worn parts replacement: 0.25% of the civil and equipment investments
- operation costs (O&M): 10€ / kW installed
- insurance costs: 0.1% of the CE and EM investments

The LCOE is then calculated based on expected production and costs from the following formula:

$$LCOE = \frac{NPV(Capex + Opex)}{NPV(Energy\,production)}$$

Where NPV is the Net Present Value which is obtained by: $NPV(valeur) = \sum_i \frac{valeur_i}{(1+n)^i}$ where n is the discount rate given by default as 10%.

The updated energy cost can be calculated for any time interval. Here, it was obtained for the lifespan of the project: 50 years. We consider the decommissioning costs will be 10% of the Civil and equipment investments.

5.5 MAIN FEATURES OF THE VISITED POTENTIAL SITES

The 33 promising small hydropower sites selected have a total firm capacity of around 176MW with an annual energy production of 1390GWh. This capacity and energy could increase up to 448MW and 3260GWh per year if all the sites are equipped with a flow corresponding to the method ($Q_{50\%}$). Note that for the three sites AD160, SF038, SF80, sized with two alternatives (A or B), it is the alternative with the lowest LCOE that was kept.

These 33 sites are mainly located along the Eastern part of Madagascar with 13 and 15 sites respectively in Fianarantsoa province and Toamasina province. Three sites were found in the province of Antananarivo and two others to the North of the Mahajanga province representing respectively 6.6% and 3.5% of the firm capacity while there is 58.7% in the Toamasina province and 31.2 % in the Fianarantsoa province.

The 33 promising sites (including 3 alternatives) has a large diversity when talking about project types. In fact, following the distribution of gross heads given in Figure 19, we can see that the available gross head varies between 15 m and 350 m for the AD544 site on the Analamanaha River. Twenty (20) sites have a gross head above or equal to 50 m and 6 sites have a gross head lower than 25 m.

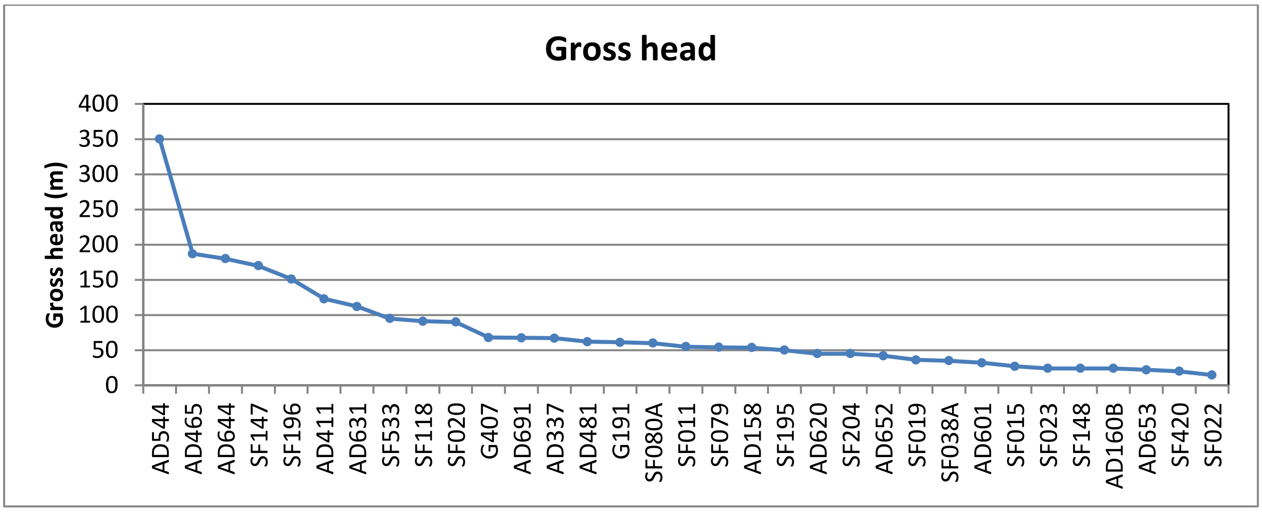


Figure 19. Distribution of available gross head at the 33 promising sites

The firm capacity of these sites varies between 180kW at the AD653 site to nearly 20MW at the AD691 site on the Faraony River. Four (4) promising sites have a firm capacity above 10MW and 9 sites have a firm capacity between 5MW and 10MW.

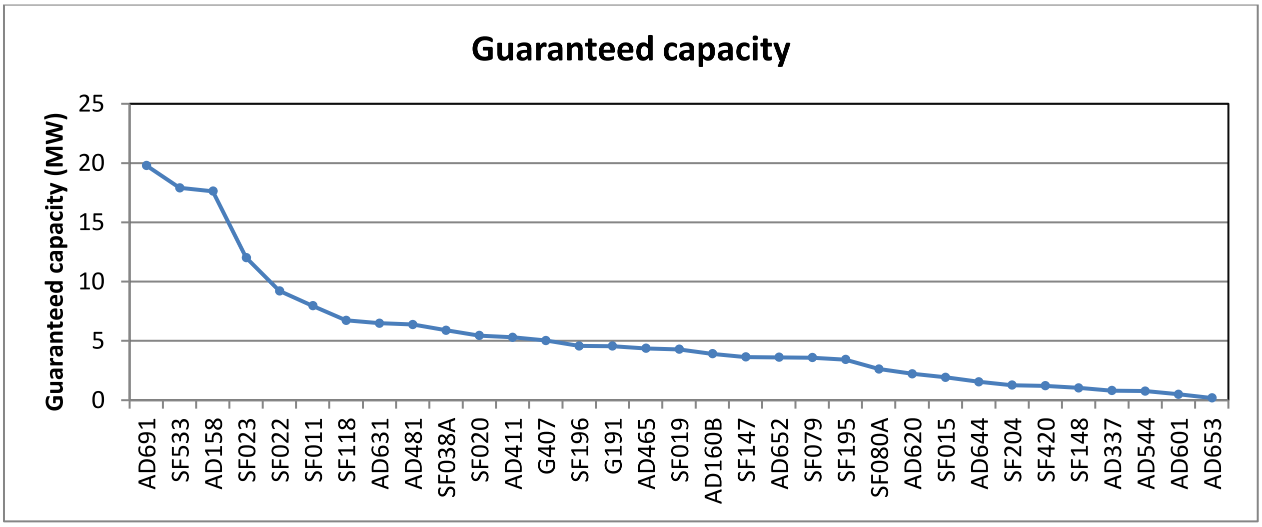


Figure 20. Distribution of available firm capacity at the 33 promising sites

Based on the case where these sites would be equipped with a design flow corresponding to the method ($Q_{50\%}$), the installed capacity of these sites varies between 42MW for the AD691 site and 600kW for the AD653 site. Note that the sites with the higher firm capacity don't necessarily have the strongest capacity if they are equipped with a flow corresponding to $Q_{50\%}$ because of different hydrological characteristics for each site.

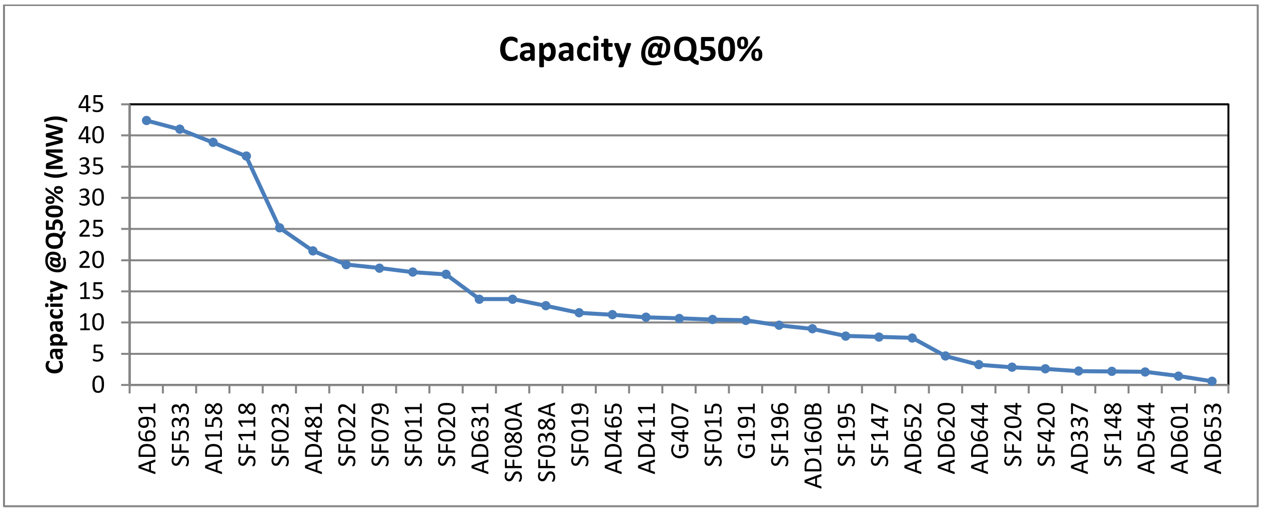


Figure 21. Distribution of the available capacity with a Q50% design flow at the 33 promising sites

SITE		COORDINATES		ADMINISTRATIVE INFORMATIONS				WATERSHED CHARACTERISTICS					GROSS HEAD	FIRM		@ $Q_{50\%}$	
		LAT	LON					AVERAGE RAINFALL	ALTITUDE MIN	ALTITUDE MAX	AREA	RIVER					
CODE	NAME	(DD)	(DD)	PROVINCE	REGION	DISTRICT	COMMUNE	(mm/y)	(m)	(m)	(km2)		(m)	CAPACITY (MW)	ENERGY (GWh/y)	CAPACITY (MW)	ENERGY (GWh/y)
AD544	Analamanaha	-20.167	47.105	Fianarantsoa	Amoron'i mania	Ambositra	Sahatsiho Ambohimanjaka	1406.4	1624.0	2122.0	54.1	Analamanaha	350.0	0.8	6.1	2.1	15.0
AD158	Vohipary	-16.225	49.665	Toamasina	Analanjirofo	Mananara	Antanambaobe	1780.2	80.0	1122.0	2494.8	Mananara	53.5	17.6	139.0	38.9	290.5
AD160	Ilengy - A	-16.254	49.473	Toamasina	Analanjirofo	Mananara	Tanibe	1590.8	836.0	836.0	1727.7	Mananara	24.0	3.9	30.8	9.0	66.8
AD337	Tsaravao	-18.073	47.104	Antananarivo	Analamanga	Ankazobe	Kiangara	1438.3	1190.0	1676.0	295.8	Manankazo	67.0	0.8	6.4	2.2	15.8
AD411	Ambodimanga	-19.050	48.633	Toamasina	Alaotra-Mangoro	Moramanga	Beforona	2289.0	377.0	1247.0	179.6	Laroka	123.0	5.3	41.8	10.8	81.9
AD465	Marianina	-19.454	46.674	Antananarivo	Vakinankaratra	Faratsiho	Miandrarivo	1622.8	1092.0	2315.0	415.7	Sahasarotra	187.0	4.4	34.5	11.3	81.1
AD481	Tsinjoarivo	-19.638	47.683	Antananarivo	Vakinankaratra	Ambatolampy	Tsinjoarivo	1451.5	1531.0	2606.0	3282.0	Onive	62.0	6.4	50.4	21.5	151.7
AD620	Behingitika	-20.910	47.661	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Ambohimanga Atsimo	2018.9	530.0	1680.0	267.7	Manandriana	45.0	2.2	17.5	4.7	35.0
AD631	Antanjona	-20.994	47.690	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Tsaratanana	1832.2	505.0	1851.0	393.6	Sahanofa	112.0	6.5	51.2	13.8	103.2
AD644	Antaninaren	-21.069	47.912	Fianarantsoa	Vatovavy Fitovinany	Mananjary	Ambodinonoka	2404.0	248.0	468.0	34.1	Manabano	180.0	1.6	12.2	3.3	24.6
AD652	Tambohorano	-21.261	47.664	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Ifanadiana	2143.4	404.0	1289.0	413.6	Faravory	42.0	3.6	28.5	7.5	56.8
AD691	Ambatosada	-21.749	47.780	Fianarantsoa	Vatovavy Fitovinany	Manakara-Sud	Fenomby	1975.4	154.0	1438.0	1708.7	Faraony	67.5	19.8	156.1	42.4	318.3
G191	Andriamanjavona	-21.382	47.600	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Ifanadiana	1569.3	460.0	1568.0	813.2	Namorona	61.0	4.6	36.0	10.4	76.8
G407	Fanovana	-18.916	48.545	Toamasina	Alaotra-Mangoro	Moramanga	Ambatovola	1841.3	611.0	1334.0	496.4	Sanatanora	68.0	5.0	39.6	10.7	80.0
SF011	SF011	-16.916	49.422	Toamasina	Analanjirofo	Soanierana-Ivongo	Andapafito	1633.2	135.0	1203.0	1408.6	Marimbona	55.0	8.0	62.8	18.1	134.5
SF019	SF019	-17.184	49.268	Toamasina	Analanjirofo	Fenoarivo Atsinanana	Vohipeno	1377.7	91.0	1361.0	2419.6	Sandratsiona	36.0	4.3	33.9	11.6	84.0
SF020	SF020	-17.145	49.202	Toamasina	Analanjirofo	Fenoarivo Atsinanana	Vohipeno	1279.6	246.0	1361.0	2093.4	Sandratsio	90.0	5.4	43.0	17.7	126.2
SF022	SF022	-19.991	48.346	Toamasina	Atsinanana	Mahanoro	Ambinanindrano	1999.9	191.0	1901.0	3489.7	Nosivolo	14.6	9.2	72.7	19.3	145.1
SF023	SF023	-20.003	48.201	Toamasina	Atsinanana	Marolambo	Marolambo	1958.0	368.0	1901.0	2897.0	Nosivolo	24.0	12.0	94.8	25.2	189.5
SF038	SF038A	-21.524	47.770	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Androrangavola	1791.5	153.0	1568.0	1224.6	Namorona	35.0	5.9	46.5	12.7	95.2
SF147	SF147	-18.403	48.933	Toamasina	Atsinanana	Ampasimanolotra	Anjahamana	2002.0	362.0	1290.0	120.1	Iovay	170.0	3.6	28.7	7.7	57.8
SF148	SF148	-18.442	49.027	Toamasina	Atsinanana	Ampasimanolotra	Anjahamana	2105.5	169.0	1463.0	216.7	Morongolo	24.0	1.0	8.2	2.2	16.4
SF195	SF195	-21.339	47.567	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Kelilalina	1546.0	551.0	1568.0	784.2	Namorona	50.0	3.4	27.0	7.8	58.1
SF196	SF196	-21.032	47.917	Fianarantsoa	Vatovavy Fitovinany	Mananjary	Ambodinonoka	2414.3	229.0	675.0	117.4	Besana	151.0	4.6	36.1	9.6	72.2
SF204	SF204	-21.426	47.505	Fianarantsoa	Vatovavy Fitovinany	Ikongo	Ambohimisafy	1617.5	515.0	1438.0	277.5	Faraony	45.0	1.3	9.9	2.8	21.1
SF420	SF420	-18.912	48.505	Toamasina	Alaotra-Mangoro	Moramanga	Ambatovola	1794.8	763.0	1334.0	433.4	Sahatandra	20.0	1.2	9.5	2.6	19.4
SF533	SF533	-16.333	49.492	Toamasina	Analanjirofo	Mananara	Sandrakatsy	1624.4	288.0	1122.0	1878.9	Mananara	95.0	17.9	141.2	41.0	304.6
SF118	SF118	-17.378	48.818	Toamasina	Analanjirofo	Vavatenina	Andasibe	1190.0	648.0	1577.0	8422.6	Maningory	91.0	6.7	53.1	36.7	243.6
SF080	SF080A	-14.598	48.441	Mahajanga	Sofia	Bealanana	Beandrarezona	1438.1	552.0	2478.0	2952.9	Maevarano	60.0	2.6	20.7	13.7	89.3
SF079	SF079	-14.596	48.287	Mahajanga	Sofia	Analalava	Ambaliha	1453.3	142.0	2478.0	4484.7	Maevarano	54.0	3.6	28.2	18.7	121.7
SF015	SF015	-17.402	48.726	Toamasina	Alaotra-Mangoro	Amparafaravola	Andrebakely I	1188.4	747.0	1577.0	8109.6	Maningory	27.0	1.9	15.2	10.5	69.7
AD653	Vohinaomby	-21.264	46.673	Fianarantsoa	Haute matsiatra	Ikalamavony	Mangidy	1158.0	838.0	1819.0	381.1	Antsakoama	22.0	0.2	1.4	0.6	4.1
AD601	Antaralava	-20.593	46.711	Fianarantsoa	Amoron'i mania	Ambatofinandrahana	Itremo	1330.7	1163.0	2016.0	463.2	Imorona	32.0	0.5	4.0	1.4	10.2
AD160	Ilengy - B	-16.254	49.473	Toamasina	Analanjirofo	Mananara	Tanibe	1590.8	836.0	836.0	1727.7	Mananara	24.0	3.9	30.8	9.0	66.8
SF038	SF038B	-21.524	47.770	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Androrangavola	1791.5	153.0	1568.0	1224.6	Namorona	35.0	10.1	79.4	21.7	162.7
SF080	SF080B	-14.598	48.441	Mahajanga	Sofia	Bealanana	Beandrarezona	1438.1	552.0	2478.0	2952.9	Maevarano	60.0	3.0	23.8	15.8	102.7

Table 16. Main characteristics of the visited promising small hydropower sites

5.6 SELECTION OF THE PRIORITY SMALL HYDRO SITES FOR SHORT TERM DEVELOPMENT

The selection process of the priority small hydro sites among the 33 promising sites is a process of reflection and further analysis and is detailed in the sections below.

5.6.1 Line costs

Sites prioritisation is particularly done in relation to the production cost of the works. Therefore it is important to take into account the distance and cost of the lines which can be significant in small hydropower projects.

Three voltages adapted to the Malagasy electrical system (35, 63 and 90 kV), have been proposed with the following unit costs:

Tension (en kV)	Section du cable (en mm²)	Prix de la ligne au km (en millier de $)
35	77.5	81.25
63	148	150
63	288	175
90	366	212.5

The consultant did not accept the wooden poles for transmission lines but the concrete ones. The choice of the used voltage depends on both the power to be evacuated and the distance to the load centres:

The table below shows the maximum distance at which the energy may be transported according to the power to be evacuated and the used technology. This limitation comes from a physical criterion (we want to limit losses in lines), and an economic criterion (it is imposed not to exceed a certain cost on the lines to avoid that the project is not profitable anymore).

Puissance (MW)	Voltage (kV)	Distance max (km)	Voltage (kV)	Distance max (km)
0 à 3 MW	35	35	63	60
3 à 5 MW	35	20	63	100
5 à 10 MW	63	75	90	160
10 à 15 MW	63	50	90	120
15 à 20 MW	63	35	90	72
20 à 30 MW	90	50		

5.6.2 Demand identification

The attraction of a project depends on the energy demand which it will be able to satisfy. It is not within the mandate of the study to analyse in detail the application or other possible sources of electricity supply (Thermal HFO, thermal GO, wind, solar, geothermal, biomass, etc.). However, for each identified site, the producible energy has been calculated (corresponding to the average energy that one can hope to produce).

The following step is to determine the actual production: one that will meet the demand, which will be valued.

For each site, the load centres nearby have been identified. This can be:

- An interconnected grid that can be connected;
- Thermal isolated groups that belong to the Jirama or private.

The value of the current production of these load centres indicates the energy demand that our projects are able to satisfy. It is important that the installed capacity of our projects will not be disproportionate to the nearby load centres as this could threaten the financial viability of the project.

The consultant has then identified:

- all remote projects which have little or no nearby demand;
- all projects for which capacity for Q_{50} flow is much higher than the demand in the area.

5.6.3 Selection of the 20 prioritized small hydro sites for short term development

For the selection of the 20 prioritized sites, we then process per workgroup located in the same geographical area that can be connected either to an existing network or to a single centre with a thermal generator. In fact, all the sites that are close to each other will be in direct competition to supply the same load centres. It is therefore necessary to prioritise them in this logic.

The criteria used to select the 20 prioritized sites are presented in the table below:

1. Group of sites for the same load centre or grid;
2. Estimated capacity between 1 and 20 MW;
3. $Q_{50\%}$ and hydropower work suited for small hydropower [$Q_{50\%} < 50$ m³/s];
4. LCOE (excluding access and off-line)< 70 US$/MWh or LCOE (with access and lines) < 120 US$/MWh (Interconnected Network) or < 200 US$/MWh (Remote Centre);
5. No evidence of environmental stress including sediment transport.

We review the five criteria used below:

Group of sites for the same load centre or grid

The projects are grouped by ability to connect to the nearest load centre, either to one of the 3 interconnected networks or to a remote network with a generator.

Predicted capacity between 1 and 20 MW

This criterion is clearly stated in the terms of reference. Note however that this criterion had been slightly adapted in previous phases given the uncertainty of the collected data. We do not want to risk the elimination of good projects. Note however that some sites are located in areas where the uncertainty of hydrological data is very important, which can have a positive or negative influence on the installed capacity or production.

Q50% and hydropower work suited for small hydropower [Q50% < 50 m³/s]

In order to stay in the flow ranges and equipment relevant to small hydropower, it is recommended not to exceed 50 m³/s. Above these rates, projects are starting to be more complex: major floods require appropriate flood evacuation works dimensions, water transmission facilities have become substantial and fiscal risks more important.

LCOE (excluding access and off-line) < 70 US$/MWh or LCOE (with access and lines) < 120 US$/MWh (Interconnected Network) or < 200 US$/MWh (Remote Centre);

In accordance with the economic constraints, the consultant has set a maximum threshold of US$ 70 / MWh taking account only of the project without the access and connection costs (which makes a good project or not). Conservatively, we retain the intermediate position in the costs range per kWh of Jirama 2011 (40 to 100 US$ / MWh) which is 70 US$ / MWh.

A second economic indicator is to look at the LCOE of the project including the cost of access and connection to the network or to a remote site. We hold as a maximum 120 US$ / MWh for sites that can be connected to one of three interconnected networks and 200 US$ / MWh for remote sites connected to a thermal group.

No evidence of environmental constraint including sediment transport

Site visits have allowed us to identify readily identifiable criteria limiting the development of promising potential sites. These include the common ownership with a protected area, the presence of Lavaka or an important sediment transport even in the dry season.

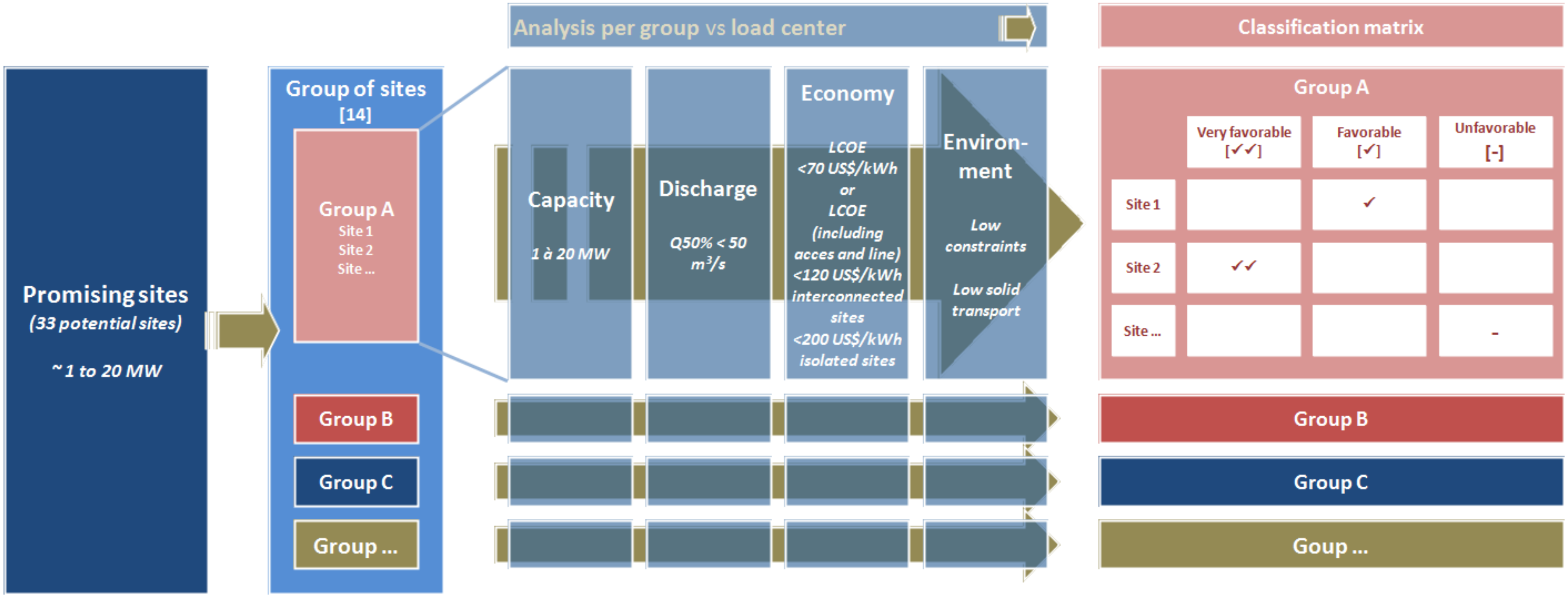


Figure 22. Selection process of the 20 prioritized sites

The projects with lower production cost including lines and access will be the most attractive and competitive compared with the thermal.

Otherwise, a site that seems less interesting may be prioritized if it is located in an area where no other project has been identified. It is attractive if its production cost is lower than that of the thermal or replacement with diesel. To compare, the cost per MWh for different sources of production from a JIRAMA presentation (2011) are summarized in the table below:

	Unit	Hydro	Thermal HFO	Thermal GO	Wind	Solar
Investment	$/kW	1500 to 3000	800 to 1000	800 to 1200		
Exploitation	%	1,50%	14%	7,20%		
Cost per MWh (2011)	US$/MWh	40 to 100	180 to 250	300 to 340	250 to 290	460

Table 17. Costs per MWh for different sources of production

The prices of the Antetezambato work survey in 2012 are shown in the table below:

JIRAMA price (*) in 2012	GO	HFO
Density	0,84	0,94
Average price in €/kg	**1,03**	**0,71**
Average consumption in litres/kWh	300	240
Average consumption in grams/kWh	252	225
Average cost of combustibles in €/MWh	**260**	**160**

Table 18. Price levels of GO and FO combustibles

(*) VAT excl: 20%

The current prices are much lower, but it is a cyclical situation, due to the competition of shale gas with oil.

It is important to note that this prioritization was made based on economic (cost of production and local energy demand) and on technical criteria. However preliminary additional data to be collected and not included at this stage of the survey will allow a final ranking at the end of phase 4 (in particular: hydrological measurements, surface geology, timeframes, socioeconomic).

The tables below show the different groups of sites grouped according to the served load centres with their prioritization and the comments of the Consultant.

Code	Name	Group	Grid / Remote	Municipality	River
SF079	SF079	A	Remote network	Ambaliha	Maevarano
SF080	SF080A		Remote network	Beandrarezona	Maevarano
AD158	Vohipary	B	Remote network	Antanambaobe	Mananara
AD160	Ilengy - B		Remote network	Tanibe	Mananara
SF533	SF533		Remote network	Sandrakatsy	Mananara
SF011	SF011	C	Remote network	Andapafito	Marimbona
SF019	SF019		Remote network	Vohipeno	Sandratsiona
SF020	SF020		Remote network	Vohipeno	Sandratsio
SF015	SF015	D	Remote network	Andrebakely I	Maningory
SF118	SF118		Remote network	Andasibe	Maningory
AD337	Tsaravao	E	Remote network	Kiangara	Manankazo
SF147	SF147	F	RIT	Anjahamana	Iovay
SF148	SF148		RIT	Anjahamana	Morongolo
AD411	Ambodimanga	G	RIA	Beforona	Laroka
AD465	Marianina		RIA	Miandrarivo	Sahasarotra
AD481	Tsinjoarivo		RIA	Tsinjoarivo	Onive
AD544	Analamanaha		RIA	Sahatsiho Ambohimanjaka	Analamanaha
G407	Fanovana		RIA	Ambatovola	Sanatanora
SF420	SF420		RIA	Ambatovola	Sahatandra
SF022	SF022	H	RIA	Ambinanindrano	Nosivolo
SF023	SF023		RIA	Marolambo	Nosivolo
AD601	Antaralava	I	Remote network	Itremo	Imorona
AD653	Vohinaomby	J	Remote network	Mangidy	Antsakoama
AD620	Behingitika	K	Remote network	Ambohimanga Atsimo	Manandriana
AD644	Antaninaren	L	Remote network	Ambodinonoka	Manabano
SF196	SF196		Remote network	Ambodinonoka	Besana
AD631	Antanjona	M	RIF	Tsaratanana	Sahanofa
AD652	Tambohorano		RIF	Ifanadiana	Faravory
G191	Andriamanjavona		RIF	Ifanadiana	Namorona
SF038	SF038A		RIF	Androrangavola	Namorona
SF195	SF195		RIF	Kelilalina	Namorona
SF204	SF204		RIF	Ambohimisafy	Faraony
AD691	Ambatosada	N	Remote network (important capacity problem)	Fenomby	Faraony

Table 19. Site groups according to their connection option

The 14 groups (noted from A to N) including the 33 promising sites are presented on the map of the following chart.

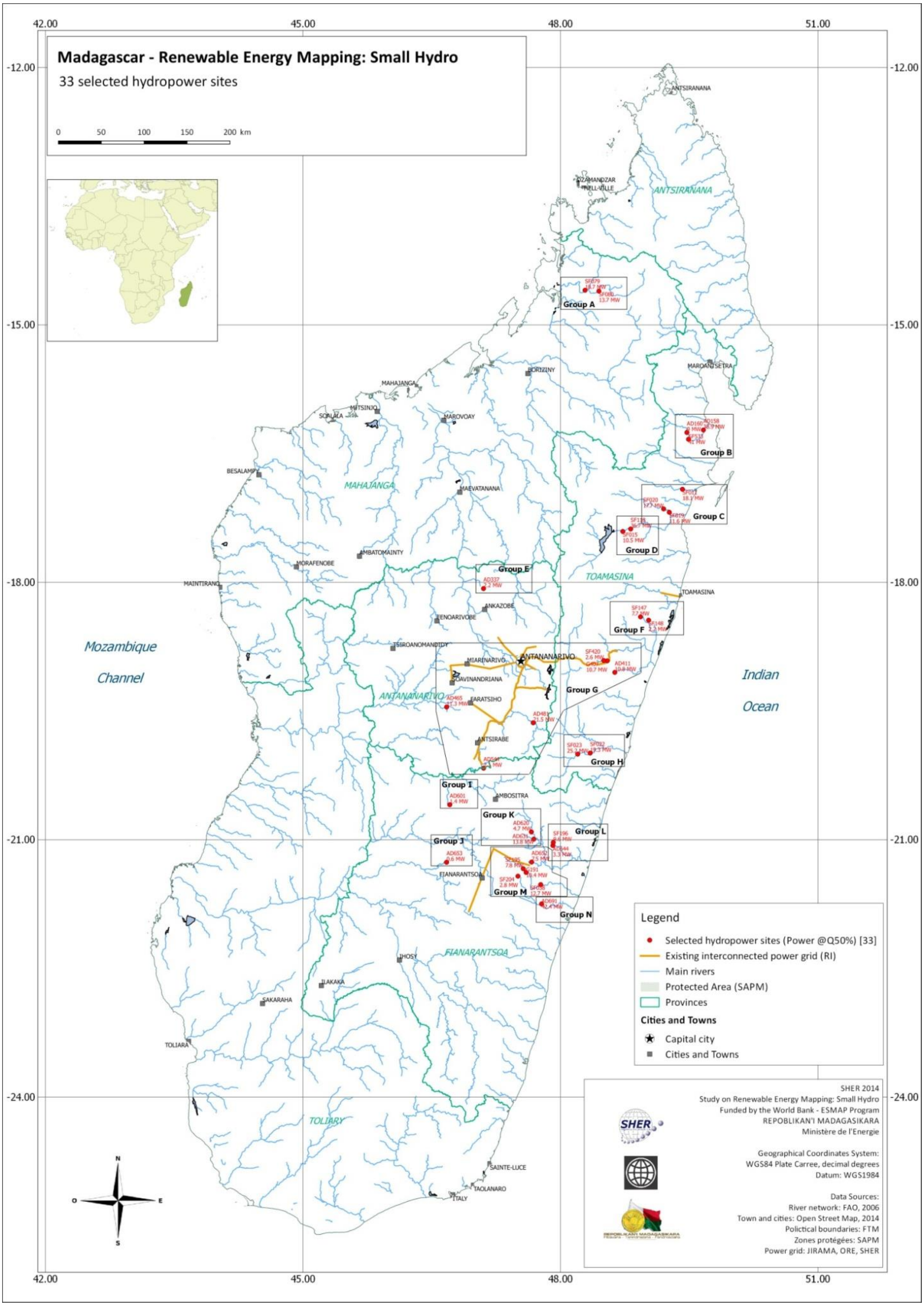


Figure 23. Map locating groups of promising sites

5.6.4 Group analysis (connection to the distribution/load centre)

Group A: connection to an isolated grid (Bealanana/Antsohihy, Antsohihy/Ambanja, Nosybe)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
SF079	SF079	4484,7	42,10	54,0	18,7	121,7	129,4	126,9	178,2	2	Sediment transport	-
SF080	SF080A	2952,9	27,72	60,0	13,7	89,3	41,9	56,9	142,4	1	Low	-

The previous table groups the 2 sites SF079 and SF080. These sites have an installed capacity of 14MW and 19MW and are found in the north next to Bealanana, Antsohihy and Ambanja. The required investments to create the network comprised between 200 and 300 km penalise much these projects. Note that the SF080 site should be equipped with an effective sand trap system for significant flow. The shortfall related to sand removal operations will be a test to analyze in detail if one day this site should be selected.

Group B : connection to an isolated grid (Ambodiatafana, Mananara Avaratra, Sainte-Marie)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD158	Vohipary	2494,8	87,80	53,5	38,9	290,5	130,0	54,1	63,0	2	Sediment transport	-
AD160	Ilengy - B	1727,7	45,28	24,0	9,0	66,8	29,3	53,1	120,0	2	Sediment transport	✓✓
SF533	SF533	1878,9	52,22	95,0	41,0	304,6	108,5	43,4	54,0	2	Sediment transport	-

The previous table groups the 3 sites AD158, AD160 and SF533. These sites have an installed capacity of 9 to 40MW and are found in the North of the Sainte-Marie Island and at more than 100km which makes them economically less competitive. From a point of view of the current application, only the smallest site is feasible and could support the development of coastal activities to Maroantsetra. A multiple phase planning of the AD160 site must be considered regarding the current low consumption in the area. AD160 could be primarily connected to the Mananara Avaratra plant which has a generator of 905kW, a distribution network and nearly 1200 subscribers. île Sainte-Marie has a generator of 1800kW, a distribution network and nearly 1500 subscribers. Ambohdiatafana has a generator of 30kW.

It is important to remember that the rivers in this area of Madagascar are currently not gauged and that their hydrology is very uncertain. Consequently, technical and economic parameters mentioned above are indicative and could significantly differ from the new estimations based on available future hydrological information.

Group C: connection to an isolated grid (Fenoarivo, Sainte-Marie)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
SF011	SF011	1408,6	39,76	55,0	18,1	134,5	71,5	64,0	81,0	1	Low	✓✓
SF019	SF019	2419,6	38,84	36,0	11,6	84,0	42,4	60,9	100,8	2	Sediment transport	✓✓
SF020	SF020	2093,4	23,82	90,0	17,7	126,2	43,5	42,1	77,4	1	Low	✓✓

The previous table groups the 3 sites SF011, SF019 and SF020. These sites with an installed capacity between 12 and 18MW are found in the south of the île Sainte-Marie and in the north of the Fenerife area and respectively at 60, 85 and 90 km. They can power the coastal area of the île Sainte-Marie. Sainte-Marie has a generator of 1800kW, a distribution network and 1500 subscribers; Fenoarivo has a generator of 2340kW, a distribution network and just over 2300 subscribers. These three projects have generally good characteristics and can be selected. Note that SF019 and SF020 are two cascade sites and their joint facility enables the realisation of economies of scale especially for paths and access roads and for the transport lines.

It is important to keep in mind that the rivers in this area of Madagascar are not currently gauged and that their hydrology is very uncertain. Consequently, the technical and economic parameters mentioned above are indicative and could significantly differ from new estimations based on hydrological information available in the future.

Group D: connection to an isolated grid (Alaotra Lake)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
SF015	SF015	8109,6	46,92	27,0	10,5	69,7	30,1	52,4	72,8	2	Sediment transport	✓✓
SF118	SF118	8422,6	48,73	91,0	36,7	243,6	75,8	38,2	48,9	2	Sediment transport	✓

The SF015 and SF118 sites above have certain specifications. Their hydrology is characterised by the particularly different low water, because of the Alaotra Lake found upstream and the important water withdrawals for irrigation in the dry season. A private network operated by the BETC company exists within the lake's area and should be taken into account for any new project in the area. BETC is developing the 1.6MW hydropower project of Androkabe. For existing thermal unities of production around the Alaotra Lake, Imerimandroso has a generator of 64kW, Ambatosoratra also has a generator of 64kW, Ambatondrazaka has a 3440kW generator, Ampitatsimo has a 64kW generator, Tanambe has a 930kW generator, Amparafaravola has a 376kW generator, Andilamena has a 476kW generator and Bejofo has a 60kW generator.

Thus, choosing a design flow of Q_{50} can present a certain hydrological risk because there is very little production during low water periods. It would be interesting to undersize the SF118 site to get a smaller capacity (more adequate for local demand), while having a higher firm capacity.

To conclude, the SF118 site, which could have been eliminated because its capacity is too high compared to local demand and had been kept and undersized to offer a better firm capacity. The comparative study of the two sites after collection of additional technical elements (hydrology, geology, etc.) enables a better planning of the development of the area.

Group E: connection to a remote network (Ankazobe)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m³/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD337	Tsaravao	295,8	4,06	67,0	2,2	15,8	30,5	228,8	287,0	2	Sediment transport	-

The AD337 site with an installed capacity of 2MW is north of Antananarivo. Considering its low capacity, the problems linked to sediment transport management and its kWh cost, it was removed by the Consultant because of the high cost.

Group F: connection to the RIT (Toamasina)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m³/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
SF147	SF147	120,1	5,50	170,0	7,7	57,8	26,2	54,7	115,3	1	Low	✓✓
SF148	SF148	216,7	10,98	24,0	2,2	16,4	8,8	64,3	205,4	2	Sediment transport	✓

The previous table groups the 2 sites SF147 and SF 148. These sites with an installed capacity between 2 and 8MW are found close to Toamasina and are located respectively at 65 and 55km. They are economically medium attractive. Nevertheless these two sites could be a good alternative to replace the thermal energy of the Toamasina network at a competitive cost. Toamasina has thermal generators of 30.6MW and 18MW, a distribution network and a little more than 28000 subscribers. The RIT is also powered by the plant of Volobe of 6.7MW.

The SF148 site could see its economic indicator (LCOE including the line and access) with a prior project to SF147. This is why it wasn't eliminated despite an unfavourable LCOE and a sediment transport management that would need to be taken into account.

Group G: connection to the RIA (Antananarivo)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD411	Ambodimanga	179,6	10,68	123,0	10,8	81,9	24,6	36,7	46,3	1	Low	✓✓
AD465	Marianina	415,7	7,29	187,0	11,3	81,1	38,1	56,8	72,5	2	Sediment transport / holes	-
AD481	Tsinjoarivo	3282,0	41,85	62,0	21,5	151,7	54,2	43,6	50,3	2	Sediment transport	-
AD544	Analamanaha	54,1	0,74	350,0	2,1	15,0	12,2	97,7	114,3	1	Competition irrigation	✓
G407	Fanovana	496,4	18,95	68,0	10,7	80,0	22,0	33,8	39,9	1	Low	✓✓
SF420	SF420	433,4	15,59	20,0	2,6	19,4	9,6	60,0	76,7	1	Protected area	-

The previous table groups 6 sites AD411, AD465, AD481, AD544, G407 and SF420 which can be connected to the RIA (Antananarivo). These sites have an installed capacity of between 3 and 22MW. The AD465 and AD544 sites are presented as eventual competitors to other facilities such as Lily (3.5MW).

The AD465-Marianina and AD481-Tsinjoarivo sites have sediment-filled water even during low flow. Desilting basin facilities are to be provided on these sites because of the important flows. The shortfall connected to Desilting basin operations will be an important criterion to analyse in detail if one day the site shall be chosen. In this study these sites were not considered priority because of technical elements.

The AD465-Marianina site has many landslides and gullies which could make it difficult or even impossible to work there.

One site, SF420, borders a protected area on its left shore and doesn't have favourable conditions. The consultant recommends not including this site in the 20 prioritized sites.

The AD544 site cannot be considered as an integrated irrigation / hydropower project because it is used in a traditional way for irrigation. Two dams to be restored were built later. One integrated project on this site would help to improve its LCOE by integrating its economic agricultural potential but also its social impact. It would also enable the stabilisation of its environment which is constantly deteriorating because of uncontrolled irrigation and drainage. The AD544 site has therefore not been chosen as a priority by the consultant but is in second place and can be discussed to be part of the 20 prioritized sites. Note that it will help to provide the RIA via the Sahanivotry post.

Group H: Isolated grid to supply coastal towns and villages or connection to the RIA (Antananarivo)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
SF022	SF022	3489,7	159,53	14,6	19,3	145,1	63,3	52,7	91,1	2	Sediment transport	-
SF023	SF023	2897,0	126,69	24,0	25,2	189,5	57,1	36,9	60,5	2	Sediment transport	-

The previous table groups the 2 sites SF022 and SF023. These sites, with an installed capacity of 20 to 25MW, are relatively far from load centres and are hard to connect to the RIA from Moramanga. Given the important specific flows observed during site visit and during the hydrological study, these sites were not chosen during the selection process. Note that this does not take anything away from their intrinsic characteristics and that in a far future these sites could be developed when the access and lines pass closer taking into account the sediment transport management.

It is important to keep in mind that the rivers in this area of Madagascar are not actually gauged and that their hydrology is very uncertain. As a result the technical and economic parameters mentioned above are indicative and could significantly differ from the new estimations based upon available future hydrological information.

Group I: Isolated grid to supply Ambatofinanhandrana and Manandriana

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD601	Antaralava	463,2	5,45	32,0	1,4	10,2	5,9	69,7	114,0	2	Sediment transport / Competition irrigation	✓

In the same way as for AD544 site-Analamanaha, the AD601 site-Antaralava cannot be considered as an integrated irrigation / hydropower project because it is currently used for irrigation via an existing sill. An integrated facility at the site would help improve its LCOE by integrating its economic agricultural potential and its social impact. The AD601 site, even less of a priority, could be part of the 20 prioritized sites selection because it can be connected to the site of Ambatofinandrahana which has a 248kW generator, a distribution network and a little less than 431 subscribers.

Group J: isolated grid to supply Ikalamavony

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	H_{cude} (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD653	Vohinaomby	381,1	3,27	22,0	0,6	4,1	4,1	117,7	175,8	2	Sediment transport	✓

The AD653 site of about 1MW doesn't have a very interesting cost per kWh. The AD653 site, even with a low priority, could be part of the 20 prioritized sites selection because it can be connected to the site of Ikalamavony which has a generator of 290kW and a little less than 400 subscribers.

Group K: isolated grid to supply South Ambohimanga or the RIF

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD620	Behingitika	267,7	12,48	45,0	4,7	35,0	12,5	43,5	59,6	1	Low	✓✓

The previous table includes the AD620 site. This site has an installed capacity of 5MW and could supply the south part of South Ambohimanga. A new network has to be created, as this town being only supplied by small private generators.

Note that in the future it may be possible to increase the capacity of the AD620 site through operating a few waterfalls downstream of the planned power plant.

Group L: isolated grid to supply Betampona and Mananjary

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD644	Antaninaren	34,1	2,21	180,0	3,3	24,6	17,5	85,3	125,8	2	Sediment transport	-
SF196	SF196	117,4	7,67	151,0	9,6	72,2	20,1	34,1	54,4	1	Low	✓✓

The previous table groups the 2 sites AD644 and SF196. These sites have an installed capacity between 3 and 10 MW and could supply Mananjary passing through Vohilava. Mananjary has a generator of 1304 kW, a distribution network and a little more than 2300 subscribers, and Vohilava has a generator of 30 kW.

The AD644 site was not chosen because the sediment inflow could impede its operation.

Group M: connection to the RIF (Fianarantsoa)

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD631	Antanjona	393,6	14,86	112,0	13,8	103,2	36,0	42,4	57,3	1	Low	✓✓
AD652	Tambohorano	413,6	21,72	42,0	7,5	56,8	24,0	51,2	58,9	1	Low	✓✓
G191	Andriamanjavona	813,2	20,52	61,0	10,4	76,8	27,6	43,6	48,1	1	Low	✓✓
SF038	SF038A	1224,6	43,83	35,0	12,7	95,2	35,4	45,3	59,5	1	Low	✓✓
SF195	SF195	784,2	18,92	50,0	7,8	58,1	16,2	34,3	54,4	1	Low	✓✓
SF204	SF204	277,5	7,63	45,0	2,8	21,1	12,4	70,9	101,2	1	Low	-

All the 6 proposed sites AD631, AD652, G191, SF038, AD195 and SF204 are located mainly in the East of Fianarantsoa. They initially enable to supply and strengthen the Interconnected Network of Fianarantsoa (RIF) in the mid and long term and to supply later the two remote centres of Mananjary and Manakara on the east coast of Madagascar.

The SF195, G191 and SF038 sites operate in a cascade over Namorona on which the plant Namorina 1 is implemented along the water at 5.6 MW. See chapter 2.12 of the "Hydro Planning report" for more information.

Group N: isolated grid to supply a future coastal grid from Mananjary to Farafangana

Code	Name	Water-shed (km2)	$Q_{50\%}$ (m^3/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Desilting basin 1 - necessary 2 - intense	Environ-mental restriction	Selection
AD691	Ambatosada	1708,7	76,00	67,5	42,4	318,3	144,0	54,7	63,6	2	Sediment transport	-

The previous table presents the AD691 site. This site could be connected to the coastal areas Mananjary, Manakara, Vohipeno, Ankaramalaza and Farafaranga. Mananjary has a 1304 kW generator, a distribution network and a little more than 2300 subscribers, Manakara has a 3420 kW thermal generator, a distribution network and a little more than 2600 subscribers. Vohipeno has a 242kW thermal generator, a distribution network and a little more than 450 subscribers. Ankaramalaza has a 32kW thermal generator. Farafaranga has a 1608 kW thermal generator and a distribution network of a little more than 1500 subscribers Neverless this site doesn't meet the requirements of the framework because its capacity does not correspond to the study range (1-20 MW) nor the capacity of coastal towns to use such a quantity of energy in a medium term.

The table below gives a short description of the prioritized sites selection as proposed by the consultant.

Code	Name	Group	River	Water-shed (km²)	$Q_{50\%}$ (m³/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX line and access included (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Environmental restriction	Selection
SF079	SF079	A	Maevarano	4484,7	42,10	54,0	18,7	121,7	181,7	126,9	178,2	Sediment transport	-
SF080	SF080A		Maevarano	2952,9	27,72	60,0	13,7	89,3	104,9	56,9	142,4	Low	-
AD158	Vohipary	B	Mananara	2494,8	87,80	53,5	38,9	290,5	155,4	54,1	64,7	Sediment transport	-
AD160	Ilengy - B		Mananara	1727,7	45,28	24,0	9,0	66,8	66,2	53,1	120,0	Moderate sediment transport	✓✓
SF533	SF533		Mananara	1878,9	52,22	95,0	41,0	304,6	140,5	43,4	56,2	Sediment transport	-
SF011	SF011	C	Marimbona	1408,6	39,76	55,0	18,1	134,5	90,7	64,0	81,3	Low	✓✓
SF019	SF019		Sandratsiona	2419,6	38,84	36,0	11,6	84,0	70,2	60,9	100,8	Moderate sediment transport	✓✓
SF020	SF020		Sandratsio	2093,4	23,82	90,0	17,7	126,2	80,1	42,1	77,4	Low	✓✓
SF015	SF015	D	Maningory	8109,6	46,92	27,0	10,5	69,7	41,8	52,4	72,8	Moderate sediment transport	✓✓
SF118	SF118		Maningory	8422,6	48,73	91,0	36,7	243,6	97,1	38,2	48,9	Moderate sediment transport	✓
AD337	Tsaravao	E	Manankazo	295,8	4,06	67,0	2,2	15,8	38,3	228,8	287,0	Sediment transport	-
SF147	SF147	F	Iovay	120,1	5,50	170,0	7,7	57,8	55,1	54,7	115,3	Low	✓✓
SF148	SF148		Morongolo	216,7	10,98	24,0	2,2	16,4	28,0	64,3	205,4	Moderate sediment transport	✓
AD411	Ambodimanga	G	Laroka	179,6	10,68	123,0	10,8	81,9	31,0	36,7	46,3	Low	✓✓
AD465	Marianina		Sahasarotra	415,7	7,29	187,0	11,3	81,1	48,6	56,8	72,5	Sediment transport / Gully	-
AD481	Tsinjoarivo		Onive	3282,0	41,85	62,0	21,5	151,7	62,6	43,6	50,3	Sediment transport	-
AD544	Analamanaha		Analamanaha	54,1	0,74	350,0	2,1	15,0	14,3	97,7	114,3	Competition irrigation	✓
G407	Fanovana		Sanatanora	496,4	18,95	68,0	10,7	80,0	26,0	33,8	39,9	Low	✓✓
SF420	SF420		Sahatandra	433,4	15,59	20,0	2,6	19,4	12,3	60,0	76,7	Zone protégée	-
SF022	SF022	H	Nosivolo	3489,7	159,53	14,6	19,3	145,1	109,3	52,7	91,1	Sediment transport	-
SF023	SF023		Nosivolo	2897,0	126,69	24,0	25,2	189,5	93,7	36,9	60,5	Sediment transport	-
AD601	Antaralava	I	Imorona	463,2	5,45	32,0	1,4	10,2	9,6	69,7	114,0	Moderate sediment transport / competition irrigation	✓
AD653	Vohinaomby	J	Antsakoama	381,1	3,27	22,0	0,6	4,1	6,1	117,7	175,8	Moderate sediment transport	✓
AD620	Behingitika	K	Manandriana	267,7	12,48	45,0	4,7	35,0	17,1	43,5	59,6	Low	✓✓
AD644	Antaninaren	L	Manabano	34,1	2,21	180,0	3,3	24,6	25,8	85,3	125,8	Sediment transport	-

Code	Name	Group	River	Water-shed (km²)	$Q_{50\%}$ (m³/s)	Head (m)	Capacity @ $Q_{50\%}$ (MW)	Energy @ $Q_{50\%}$ (GWh/y)	CAPEX line and access included (MUS$)	LCOE @$Q_{50\%}$ (US$/MWh)	LCOE @$Q_{50\%}$ + line +access (US$/MWh)	Environmental restriction	Selection
SF196	SF196		Besana	117,4	7,67	151,0	9,6	72,2	32,0	34,1	54,4	Low	✓✓
AD631	Antanjona	M	Sahanofa	393,6	14,86	112,0	13,8	103,2	48,6	42,4	57,3	Low	✓✓
AD652	Tambohorano	M	Faravory	413,6	21,72	42,0	7,5	56,8	27,7	51,2	58,9	Low	✓✓
G191	Andriamanjavona	M	Namorona	813,2	20,52	61,0	10,4	76,8	30,4	43,6	48,1	Low	✓✓
SF038	SF038A	M	Namorona	1224,6	43,83	35,0	12,7	95,2	46,6	45,3	59,5	Low	✓✓
SF195	SF195	M	Namorona	784,2	18,92	50,0	7,8	58,1	25,7	34,3	54,4	Low	✓✓
SF204	SF204	M	Faraony	277,5	7,63	45,0	2,8	21,1	17,7	70,9	101,2	Low	-
AD691	Ambatosada	N	Faraony	1708,7	76,00	67,5	42,4	318,3	167,4	54,7	63,6	Sediment transport	-

Table 20. Synoptic table of the 20 prioritized sites

The heads vary between 22m for the smallest and 350m for the biggest. The average watershed is 1500km²: the smallest has a surface area of 54km² and the largest 8420km². The estimated flows ($Q_{50\%}$) vary from 0.75 m³/s to 48 m³/s.

We can see in the table above that the 20 prioritized hydropower sites have an average LCOE (offline and access) of US$ 54/MWh between US$ 33.8/MWh and US$ 117.7/MWh and an average LCOE (including line and access) of US$ 85/MWh between US$ 39.9/MWh and US$ 205.5/MWh.

The average investment costs (CAPEX including access and lines) are MUS$ 42, the smallest project being at MUS$ 6.1 for a capacity of 600 kW and the largest at MUS$ 97.1 for a capacity of 36.7 MW.

The mass capacity of the 20 prioritized sites is 205 MW with a mass production of 1490 GWh/y. These projects could contribute to the increase of the current installed capacity (552 MW) of about 37% for investments of around MUS$ 844. These 20 projects could replace thermal energy (389 MW) of about 53% if we consider the nominal, or more than 100% is we consider the available (188 MW).

6 Selection of promising sites amongst potential sites studied at an advanced stage in previous studies or considered in master plans

6.1 BIBLIOGRAPHICAL ANALYSIS

The objective of the small hydro mapping study is to identify a certain number of sites which could be subject to preliminary visits and enabling the enrichment of the small hydropower offer with capacities between 1 MW and 20 MW. Logically, the sites with more advanced studies than those planned by this Mapping study should not be visited: the gain of a quick visit is very low compared to a medium or long term multidisciplinary study with improved human, time and equipment resources. This paragraph gives the potential sites studied at an advanced stage in previous studies or included in the plans of the Ministère de l'Energie and associated agencies.

The bibliographical collection and the analysis of documents provided to the consultant enabled the identification of 51 sites already studied and/or planned for development by the Ministère de l'Energie, the OER or Jirama. Note the consultant has not been given access to all the complete studies.

The consultant carried out research and matching of these sites that appeared several times in the different lists and inventories, under different alternatives. For example the Talaviana site on the Manandona River is referenced four times in the inventories:

ATLAS_ID	SITE	RIVER	ORIGIN	Gross head [m]	Flow m³/s	Installed capacity MW	Comments
FR136	Talaviana	Manandona	HQI 2005	118	15	15	Site with coherent data but whose location is wrong
FR137	Talaviana	Manandona	SOGREAH	0	7	15	Site with incomplete data, but whose location is correct. The flow doesn't correspond to what the HQI 2005 study mentioned.
G665	Talaviana	Manandona (Mania)	Inventory of the energy sector	0	0	7,31	Site with incomplete data on gross head and flow and a wrong location (the site is 5km north of the given location)
G666	Talaviana	-	Inventory of the energy sector	131	0	0,09	Site with incomplete flow data and a wrong location (the site is 6.5km east of the given location)
-	Talaviana	Manandona	OER website	121	15	15	No location but complete technical data.

Table 21. Talaviana: example of a multi referenced hydropower site

Given that the only site referenced FR137 has exact coordinates, it is the only one chosen in the list of the 51 studied or planned sites. Generally the multi referenced sites are kept in the database of the 1438 sites (First screening).

For the sites with several facility alternatives, all of them were kept in the database. It is like this that 51 sites represent a total of 76 alternatives. The distribution of these potential sites by province is illustrated in Table 22 below. This table also shows the sum of potential capacities of each chosen site, by province and by region, meaning that when several alternative schemes are possible, only the one with the highest installed capacity will be chosen for the estimation. This is how we find that the most studied hydropower potential in Madagascar is found in the province of Mahajanga, mainly with the sites of Ambodiroka on Betsiboka (300MW), Isandrano on Ikopa river (130MW), Antanandava on Ikopa river (410MW), Belavenona on Betsiboka river (370MW) and Antafofo on Ikopa river (580MW). Then there is the province of Antananarivo, mainly with the sites of Mahavola on Ikopa (520MW), Vohitsara on Ikopa (250MW), Ranomafana on Ikopa river (70MW) and Mandraka II on Mandraka river (56MW).

Provinces	Regions	Number of Sites already studied	Number of alternative schemes	Potential capacity (MW)
Antananarivo	Analamanga	5	10	828.8
	Bongolava	2	3	71.3
	Itasy	1	1	3.5
	Vakinankaratra	3	3	17.4
	Subtotal	**11**	**17**	**921.0 *(21.5%)***
Antsiranana	Diana	3	5	74.5
	Sava	3	4	8.5
	Subtotal	**6**	**9**	**83.0 *(1.9%)***
Fianarantsoa	Amoron'i mania	4	5	327.5
	Atsimo-Atsinana	2	2	360.4
	Ihorombe	2	2	2.5
	Vatovavy Fitovinany	2	2	38.0
	Hautre Matsiara	0	0	0
	Subtotal	**10**	**11**	**728.4 *(17.0%)***
Mahajanga	Betsiboka	5	12	1790.0
	Melaky	1	1	0.6
	Sofia	4	5	5.1
	Boeny	0	0	0
	Subtotal	**10**	**18**	**1795.7 *(41.9 %)***
Toamasina	Alaotra-Mangoro	4	6	33.9
	Analanjirofo	1	1	18.8
	Atsinanana	6	11	539.0
	Subtotal	**11**	**18**	**591.7 *(13.8 %)***
Toliary	Anosy	1	1	1.2
	Menabe	2	2	159.7
	Androy	0	0	0
	Atsimo-Andrefana	0	0	0
	Subtotal	**3**	**3**	**160.9 *(3.8%)***
	Total	**51**	**76**	**4280.7**

Table 22. Potential sites previously studied or planned for development: statistics

The complete list of sites is given in Table 22 and their location in Figure 24.

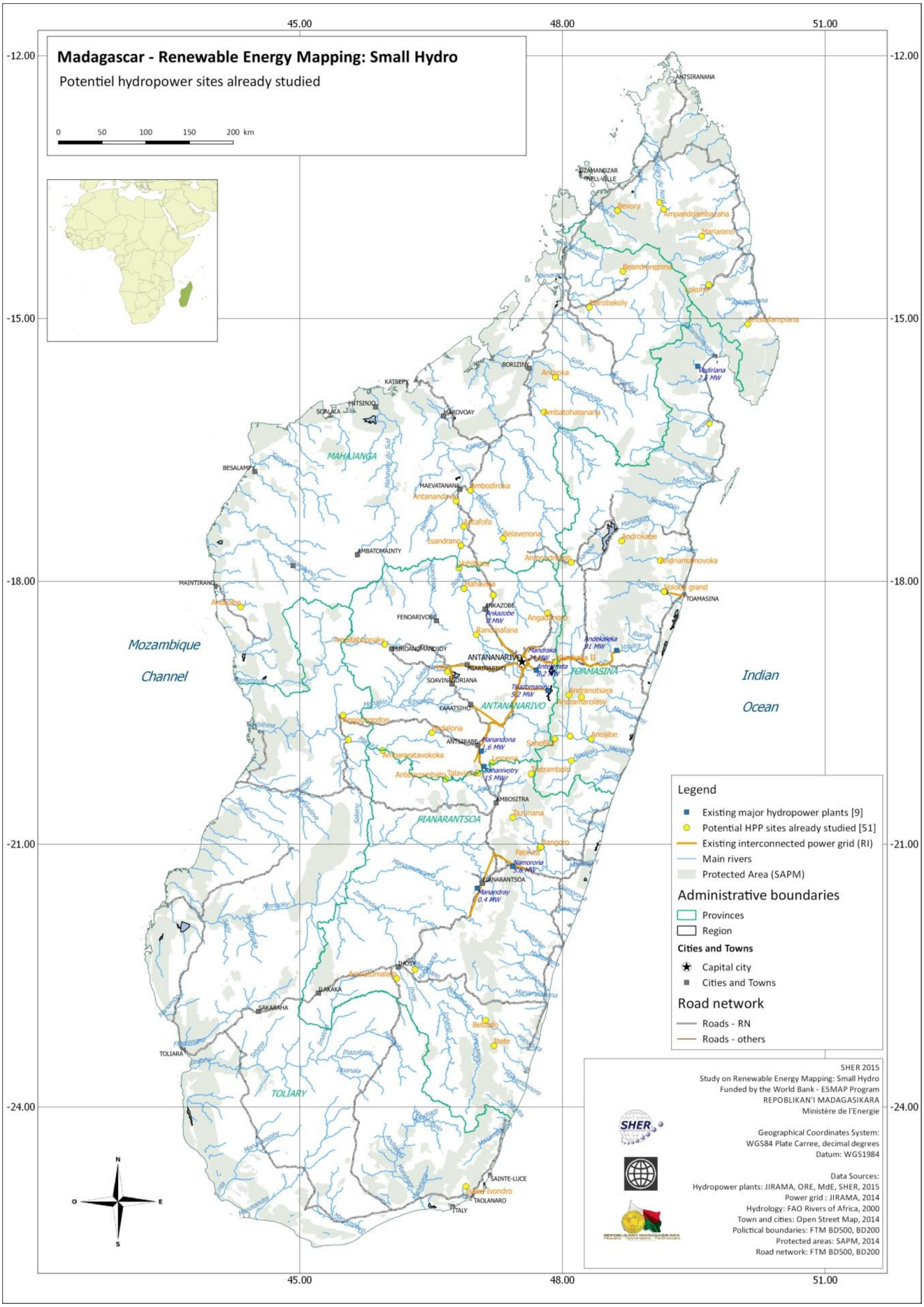


Figure 24. Potential sites previously studied or planned for development

PROVINCE	REGION	CODE	LAYOUT	NAME	RIVER	Gross head (m)	Design flow (m³/s)	Capacity (MW)	Status	SOURCE
Antananarivo	Analamanga	FR102	FR102A	Mahavola	Ikopa	243	210	520	Pre-feasability	ORE / JIRAMA
Antananarivo	Analamanga	FR102	FR102C	Mahavola	Ikopa	231	176	325		ORE / JIRAMA
Antananarivo	Analamanga	FR102	FR102B	Mahavola	Ikopa	231	162	300		ORE / JIRAMA
Antananarivo	Analamanga	AD315	AD315A	Vohitsara	Ikopa	110	240	250		ORE / JIRAMA
Antananarivo	Analamanga	AD315	AD315B	Vohitsara	Ikopa	110	284	250	Identification (map based)	ORE / JIRAMA
Antananarivo	Analamanga	G028	G028	Mandraka II	Mandraka	483	0	56		ORE
Antananarivo	Analamanga	G507	G507B	Angadanoro	Mananara	43.3	7	2.274	Pre-feasability	ORE / JIRAMA
Antananarivo	Analamanga	AD342	AD342A	Manankazo	Manankazo	44.7	1.4	0.5		ORE/JIRAMA
Antananarivo	Analamanga	AD342	AD342B	Manankazo	Manankazo	46.5	1	0.349	Design (APS)	ORE/JIRAMA
Antananarivo	Analamanga	G507	G507A	Angadanoro	Mananara	14	0.8	0.055	Pre-feasability	ORE / JIRAMA
Antananarivo	Bongolava	G606	G606	Ranomafana	Ikopa	70.5	120	70	Pre-feasability	ORE / JIRAMA
Antananarivo	Bongolava	AD386	AD386B	Ampitabepoaky	Manambolo	20.2	8.5	1.3	Design (APS)	ORE / JIRAMA
Antananarivo	Bongolava	AD386	AD386A	Ampitabepoaky	Manambolo	15.6	6.5	0.765	Design (APS)	ORE / JIRAMA
Antananarivo	Itasy	FR092	FR092	Lily	Lily	74.9	6	3.5	Design (APS)	ORE / JIRAMA
Antananarivo	Vakinankaratra	FR137	FR137	Talaviana	Manandona	121	15	15	Pre-feasability	JIRAMA
Antananarivo	Vakinankaratra	AD490	AD490	Andalona	Andratsay	50	0	1.2		ORE
Antananarivo	Vakinankaratra	FR091	FR091	Lemena	Sahanivotry	38.5	4	1.2	Design (APS)	ORE / JIRAMA
Antsiranana	Diana	FR027	FR027A	Ampandriambazaha	Mahavavy nord	150	50	53		ORE / JIRAMA
Antsiranana	Diana	FR027	FR027B	Ampandriambazaha	Mahavavy nord	150	10	13		ORE / JIRAMA
Antsiranana	Diana	AD041	AD041	Andranomamofana	Mahavavy nord	103	20	15	Reconnaissance	JIRAMA
Antsiranana	Diana	G323	G323B	Bevory	Ramena	89	10	6.5	Pre-feasability	ORE / JIRAMA
Antsiranana	Diana	G323	G323A	Bevory	Ramena	77	9.7	6.35		ORE / JIRAMA
Antsiranana	Sava	AD077	AD077	Lokoho	Lokoho	0	16.562	6		ORE / JIRAMA
Antsiranana	Sava	AD077	AD077B	Lokoho	Lokoho	53	15	6	Feasibility	ORE / JIRAMA
Antsiranana	Sava	G539	G539	Mariarano	Bemarivo	35	0	1.45		ORE / JIRAMA / BM - PERER/HYDROSCOUT
Antsiranana	Sava	G325	G325	Antsiafampiana	Sahafihatra	10	15	1.05	Reconnaissance	ORE / JIRAMA / BM - PERER/HYDROSCOUT
Fianarantsoa	Amoron'i mania	FR062	FR062A	Antetezambato	Mania	220	115	210	Pre-feasability	ORE / JIRAMA / BM -

PROVINCE	REGION	CODE	LAYOUT	NAME	RIVER	Gross head (m)	Design flow (m³/s)	Capacity (MW)	Status	SOURCE
										PERER/HYDROSCOUT
			FR062B			195	120	182.52	Pre-feasability	ORE / JIRAMA / BM - PERER/HYDROSCOUT
		AD521	AD521	Ambararatavokoka	Iandratsay	175	80	105		JIRAMA
		AD609	AD609	Tazonana	Maintinandry	100	10	8	Pre-feasability	ORE / JIRAMA
		G691	G691	Tratrambolo	Tratrambolo	92	6	4.5	Pre-feasability	ORE/ BM - SERMAD
		AD725	AD725	Betoafo	Mananara sud	400	110	360	Identification (map based)	ORE / JIRAMA
		AD734	AD734	Itete	Masianaka	300	0.2	0.42	Reconnaissance	ORE / JIRAMA
	Ihorombe	AD711	AD711	Befanaova	Sahambano	15	0	2.16		ORE / JIRAMA
		AD715	AD715	Ambatomalam	Ianabono	113	0	0.35		JIRAMA
	Vatovavy Fitovinany	AD642	AD642	Fatihita	Ivoanana	217	15	24		JIRAMA
		G392	G392	Dangoro	Maintinandry	350	5	14	Pre-feasability	JIRAMA
Mahajanga	Betsiboka	FR059	FR059B	Antafofo	Ikopa	195	395	580	Pre-feasability	ORE / JIRAMA
			FR059A			120	150	160	Pre-feasability	ORE / JIRAMA
			FR059C			130	100	105	Pre-feasability	ORE / JIRAMA
		AD257	AD257	Antanandava	Ikopa	133	396	410	Pre-feasability	ORE / JIRAMA
		G351	G351	Belavenona	Betsiboka	123	400	370		ORE / JIRAMA
		AD233	AD233A	Ambodiroka	Betsiboka	134	279	300	Reconnaissance	ORE / JIRAMA
			AD233B			70	72	40	Detailed design (APD)	ORE / JIRAMA
			AD233D			56	90	40	Feasibility	ORE / JIRAMA
			AD233C			56.4	45	19.5	Feasibility	ORE / JIRAMA
		G452	G452A	Isandrano	Ikopa	65	240	130	Pre-feasability	ORE / JIRAMA
			G452B			65	242	126	Pre-feasability	ORE / JIRAMA
			G452C			65	56	29	Pre-feasability	ORE / JIRAMA
	Melaky	AD354	AD354	Andriabe	Demoka	8.6	10	0.6	Reconnaissance	ORE / JIRAMA
	Sofia	G023	G023	Ambatoharanana	Bemarivo	25	0	1.91		ORE / JIRAMA / BM - PERER/HYDROSCOUT
		G219	G219B	Androka	Anjobony	16	15	1.9	Reconnaissance	ORE / JIRAMA / BM - PERER/HYDROSCOUT

PROVINCE	REGION	CODE	LAYOUT	NAME	RIVER	Gross head (m)	Design flow (m³/s)	Capacity (MW)	Status	SOURCE
			G219A			15.9	6.4	0.815	Reconnaissance	ORE / JIRAMA / BM - PERER/HYDROSCOUT
		G546	G546	Marobakoly	Anjingo	20.7	5	0.83	Reconnaissance	ORE / JIRAMA
		AD064	AD064	Beandrarezona	Beandrarezona	35.8	1.6	0.47	Design (APS)	ORE / JIRAMA
Toamasina	Alaotra-Mangoro	FR128	FR128B	Sahofika	Onive	650	20	105		ORE / JIRAMA
		G166	G166	Andranotsara	Mangoro	0	0	30.8		BM - Energie
		FR049	FR049A	Androkabe	Lovoka	162	1.3	1.7	Design (APS)	ORE / JIRAMA
			FR049B			75	3	1.688	Design (APS)	ORE / JIRAMA
		AD313	AD313	Ampondrokoh	Maheriara	125	0.779	0.955		JIRAMA
		G151	G151	Andramarolasy	Mahamavo	0	0	0.41		ORE / JIRAMA
	Analanjirofo	FR148	FR148	Vohibato	Mananara	42	0	18.8	Reconnaissance	ORE / JIRAMA
	Atsinanana	FR128	FR128A	Sahofika	Onive	700	53	300	Design (APS)	ORE / JIRAMA
			FR128C			700	28.6	160		ORE / JIRAMA
		G476	G476A	Lohavanana	Mangoro	96.5	150	120	Pre-feasability	ORE / JIRAMA
			G476C			109	150	120		ORE / JIRAMA
			G476B			106	110	93		ORE / JIRAMA
		FR150	FR150A	Volobe amont	Ivondro	100	115	90	Pre-feasability	ORE / JIRAMA
			FR150B			100	56	45		ORE / JIRAMA
			FR150C	Grand Volobe		83	47	31		ORE / JIRAMA
		G148	G148	Andriamamovoka	Onibe	152	20	22.8		JIRAMA
		FR078	FR078	Chute d'Andriamamovoka	Sndranamby	40	11	4.32		JIRAMA
		G268	G268	Anosibe	Sahananga	250	0	1.89		JIRAMA
Toliary	Anosy	AD777	AD777	Isaka-Ivondro	Efaho	157	1	1.2	Design (APS)	ORE
	Menabe	G680	G680	Tazoalava	Mania	100	110	88	Pre-feasability	JIRAMA
		AD471	AD471	Angodogodon	Mahajilo	26	0	71.68		ORE / JIRAMA

Table 23. Potential hydropower sites previously studied or planned for development

6.2 SELECTION PROCESS OF PROMISING SITES FOR SHORT-TERM INVESTMENTS

This paragraph presents the process allowing the selection of promising sites, amongst the ones studied at an advanced stage or planned for development, matching the study criteria.

The following figure introduces the selection process and criteria that were applied to select the promising sites for short-term investment.

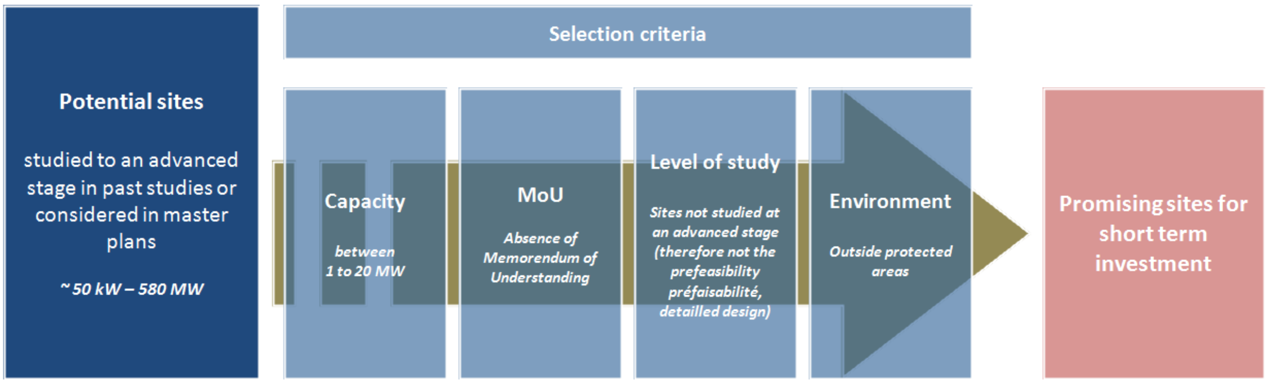


Figure 25. Selection criteria for promising sites for short-term investments

The criteria are:

- An expected installed capacity between 1 to 20 MW
- No Memorendum of Understanding (MoU) signed between a potential investor and the Government of Madagascar. Please note that the existing list at the Ministère de l'Energie could be updated.
- A low level of study. The sites with an advanced study (prefeasibility, feasibility, detailed design) are not included.
- The sites must be located outside protected areas.

The Table 24 below presents the results of the selection process for promising sites matching the selection criteria, amongst the sites studied at an advanced stage or planned for development.

CODE	LAYOUT	NAME	RIVER	Gross head (m)	Design flow (m³/s)	Capacity (MW)	Status	Capacity	MoU	Level of study	Environment	Selection
FR102	FR102A	Mahavola	Ikopa	243	210	520	Pre-feasability	-	yes	-	outside protected area	-
	FR102C			231	176	325						
	FR102B			231	162	300						
AD315	AD315A	Vohitsara	Ikopa	110	240	250		-	no	✓	outside protected area	-
	AD315B			110	284	250	Identification (map based)					
G028	G028	Mandraka II	Mandraka	483	0	56		-	yes	✓	protected area	-
G507	G507B	Angadanoro	Mananara	43.3	7	2.274	Pre-feasability	✓	yes	-	outside protected area	-
AD342	AD342A	Manankazo	Manankazo	44.7	1.4	0.5		-	no	-	protected area	-
	AD342B			46.5	1	0.349	Design (APS)					
G507	G507A	Angadanoro	Mananara	14	0.8	0.055	Pre-feasability	-	no	-	outside protected area	-
G606	G606	Ranomafana	Ikopa	70.5	120	70	Pre-feasability	-	yes	-	outside protected area	-
AD386	AD386B	Ampitabepoaky	Manambolo	20.2	8.5	1.3	Design (APS)	✓	yes	-	outside protected area	-
	AD386A			15.6	6.5	0.765	Design (APS)					
FR092	FR092	Lily	Lily	74.9	6	3.5	Design (APS)	✓	no	-	outside protected area	-
FR137	FR137	Talaviana	Manandona	121	15	15	Pre-feasability	✓	yes	-	protected area	-
AD490	AD490	Andalona	Andratsay	50	0	1.2		✓	no	✓	outside protected area	✓
FR091	FR091	Lemena	Sahanivotry	38.5	4	1.2	Design (APS)	✓	no	-	outside protected area	-
FR027	FR027A	Ampandriambazaha	Mahavavy nord	150	50	53		-	yes	✓	outside protected area	-
	FR027B			150	10	13						
AD041	AD041	Andranomamofana	Mahavavy nord	103	20	15	Reconnaissance	✓	no	✓	outside protected area	✓
G323	G323B	Bevory	Ramena	89	10	6.5	Pre-feasability	✓	yes	-	protected area	-
	G323A			77	9.7	6.35						
AD077	AD077	Lokoho	Lokoho	0	16.562	6		✓	no	-	outside protected area	-
	AD077B			53	15	6	Feasibility					
G539	G539	Mariarano	Bemarivo	35	0	1.45		✓	no	✓	outside	✓

CODE	LAYOUT	NAME	RIVER	Gross head (m)	Design flow (m³/s)	Capacity (MW)	Status	Capacity	MoU	Level of study	Environment	Selection
											protected area	
G325	G325	Antsiafampiana	Sahafihatra	10	15	1.05	Reconnaissance	✓	yes	✓	outside protected area	-
FR062	FR062A	Antetezambato	Mania	220	115	210	Pre-feasability	-	no	-	outside protected area	-
	FR062B			195	120	182.52	Pre-feasability					
AD521	AD521	Ambararatavokoka	Iandratsay	175	80	105		-	no	✓	outside protected area	-
AD609	AD609	Tazonana	Maintinandry	100	10	8	Pre-feasability	✓	yes	-	protected area	-
G691	G691	Tratrambolo	Tratrambolo	92	6	4.5	Pre-feasability	✓	yes	-	outside protected area	-
AD725	AD725	Betoafo	Mananara sud	400	110	360	Identification (map based)	-	yes	✓	outside protected area	-
AD734	AD734	Itete	Masianaka	300	0.2	0.42	Reconnaissance	-	no	-	protected area	-
AD711	AD711	Befanaova	Sahambano	15	0	2.16		✓	no	✓	outside protected area	✓
AD715	AD715	Ambatomalam	Ianabono	113	0	0.35		-	no	✓	outside protected area	-
AD642	AD642	Fatihita	Ivoanana	217	15	24		-	no	✓	protected area	-
G392	G392	Dangoro	Maintinandry	350	5	14	Pre-feasability	✓	yes	-	outside protected area	-
FR059	FR059B	Antafofo	Ikopa	195	395	580	Pre-feasability	-	yes	-	outside protected area	-
	FR059A			120	150	160	Pre-feasability					
	FR059C			130	100	105	Pre-feasability					
AD257	AD257	Antanandava	Ikopa	133	396	410	Pre-feasability	-	no	-	outside protected area	-
G351	G351	Belavenoa	Betsiboka	123	400	370		-	no	✓	outside protected area	-
AD233	AD233A	Ambodiroka	Betsiboka	134	279	300	Reconnaissance	-	yes	-	outside protected area	-
	AD233B			70	72	40	Detailed design (APD)					
	AD233D			56	90	40	Feasibility					
	AD233C			56.4	45	19.5	Feasibility					
G452	G452A	Isandrano	Ikopa	65	240	130	Pre-feasability	-	no	-	outside protected area	-
	G452B			65	242	126	Pre-feasability					

CODE	LAYOUT	NAME	RIVER	Gross head (m)	Design flow (m^3/s)	Capacity (MW)	Status	Capacity	MoU	Level of study	Environment	Selection
	G452C			65	56	29	Pre-feasability					
AD354	AD354	Andriabe	Demoka	8.6	10	0.6	Reconnaissance	-	yes	✓	outside protected area	-
G023	G023	Ambatoharanana	Bemarivo	25	0	1.91		✓	no	✓	outside protected area	✓
G219	G219B	Androka	Anjobony	16	15	1.9	Reconnaissance	✓	no	✓	outside protected area	✓
	G219A			15.9	6.4	0.815	Reconnaissance					
G546	G546	Marobakoly	Anjingo	20.7	5	0.83	Reconnaissance	-	no	✓	outside protected area	-
AD064	AD064	Beandrarezona	Beandrarezona	35.8	1.6	0.47	Design (APS)	-	no	-	protected area	-
G166	G166	Andranotsara	Mangoro	0	0	30.8		-	no	✓	outside protected area	-
FR049	FR049A	Androkabe	Lovoka	162	1.3	1.7	Design (APS)	✓	yes	-	outside protected area	-
	FR049B			75	3	1.688	Design (APS)					
AD313	AD313	Ampondrokoh	Maheriara	125	0.779	0.955		✓	no	✓	outside protected area	✓
G151	G151	Andramarolasy	Mahamavo	0	0	0.41		-	no	✓	protected area	-
FR148	FR148	Vohibato	Mananara	42	0	18.8	Reconnaissance	✓	yes	✓	outside protected area	-
FR128	FR128A	Sahofika	Onive	700	53	300	Design (APS)	-	no	-	protected area	-
	FR128C			700	28.6	160						
G476	G476A	Lohavanana	Mangoro	96.5	150	120	Pre-feasability	-	yes	-	outside protected area	-
	G476C			109	150	120						
	G476B			106	110	93						
FR150	FR150A	Volobe amont	Ivondro	100	115	90	Pre-feasability	-	yes	-	outside protected area	-
	FR150B			100	56	45						
	FR150C	Grand Volobe		83	47	31						
G148	G148	Andriamamovoka	Onibe	152	20	22.8		-	no	✓	outside protected area	-
FR078	FR078	Chute d'Andriamamovoka	Sndranamby	40	11	4.32		✓	no	✓	outside protected area	✓
G268	G268	Anosibe	Sahananga	250	0	1.89		✓	no	✓	outside protected area	✓

CODE	LAYOUT	NAME	RIVER	Gross head (m)	Design flow (m³/s)	Capacity (MW)	Status	Capacity	MoU	Level of study	Environment	Selection
AD777	AD777	Isaka-Ivondro	Efaho	157	1	1.2	Design (APS)	✓	no	-	protected area	-
G680	G680	Tazoalava	Mania	100	110	88	Pre-feasability	-	no	-	protected area	-
AD471	AD471	Angodogodon	Mahajilo	26	0	71.68		-	no	✓	protected area	-
								selection criteria : Capacity between 1 and 20 MW : ✓ Existing Memorandum of Understanding (MoU) : yes Low study level (no prefeasibility or feasibility or detailed) : ✓ Site located outside the protected areas				9 sites corresponding to the criteria

Table 24. Results of the selection process matching the criteria for short-term investment

7 Campaign of hydrological measurements

7.1 INTRODUCTION AND OBJECTIVES

The objective of this Phase 2 activity (Ground-based data collection) is to carry out a hydrological monitoring campaign of six rivers considered as priorities for the small hydropower development in Madagascar. These measures will substantially improve the hydrological knowledge of areas in Madagascar that have not been measured in the past.

The selection process for these six rivers took place during the previous phases of this study and the selection has been validated during the workshop held on 11 March 2015 in Antananarivo at the Ministère de l'Energie et des Hydrocarbures.

The hydrological monitoring campaign includes not only the acquisition and installation of water level measurement equipment, but also the determination of preliminary rating curves (relationship between measured water level and river flow) at each site, through gauging operations.

The hydrological monitoring campaign covered a hydrological year (12 months, from October 2015 to October 2016) and provided (i) time series of water height at daily time step and (ii) preliminary rating curves, for each of the sites, making it possible to transform the water heights into flow rates.

Finally, a capacity building of Malagasy institutions benefiting from the project has been carried out through specific training and participation in gauging and maintenance missions.

The location of the six stations is shown in Table 25 and in Figure 26 below.

Table 25.Location of gauging stations

RIVER (MAJOR WATERSHED)	SITE NAME	LONGITUDE [DD]	LATITUDE [DD]	WATERSHED AREA [KM²]	INSTALLATION DATE
Besana (watershed of Mananjary)	SF196 (Mahatsara)	47.915	-21.03	124.9	22/10/2015
Sahatandra (watershed of Rianila)	G407 (Fanovana)	48.533	-18.919	511.7	18/10/2015
Namorona (watershed of Namorona)	G191 (Namorona 2)	47.597	-21.378	862.3	20/10/2015
Manandriana (watershed of Mananjary)	AD620 (Amohimanga du Sud)	47.592	-20.876	250.2	25/10/2015
Marimbona (watershed of Marimbona)	SF011 (Fotsialanana)	49.458	-16.92	1495.4	21/10/2015
Sandratsiona (watershed of Maningory)	SF020 (Ambatoharanana)	42.212	-17.151	2389.3	23/10/2015

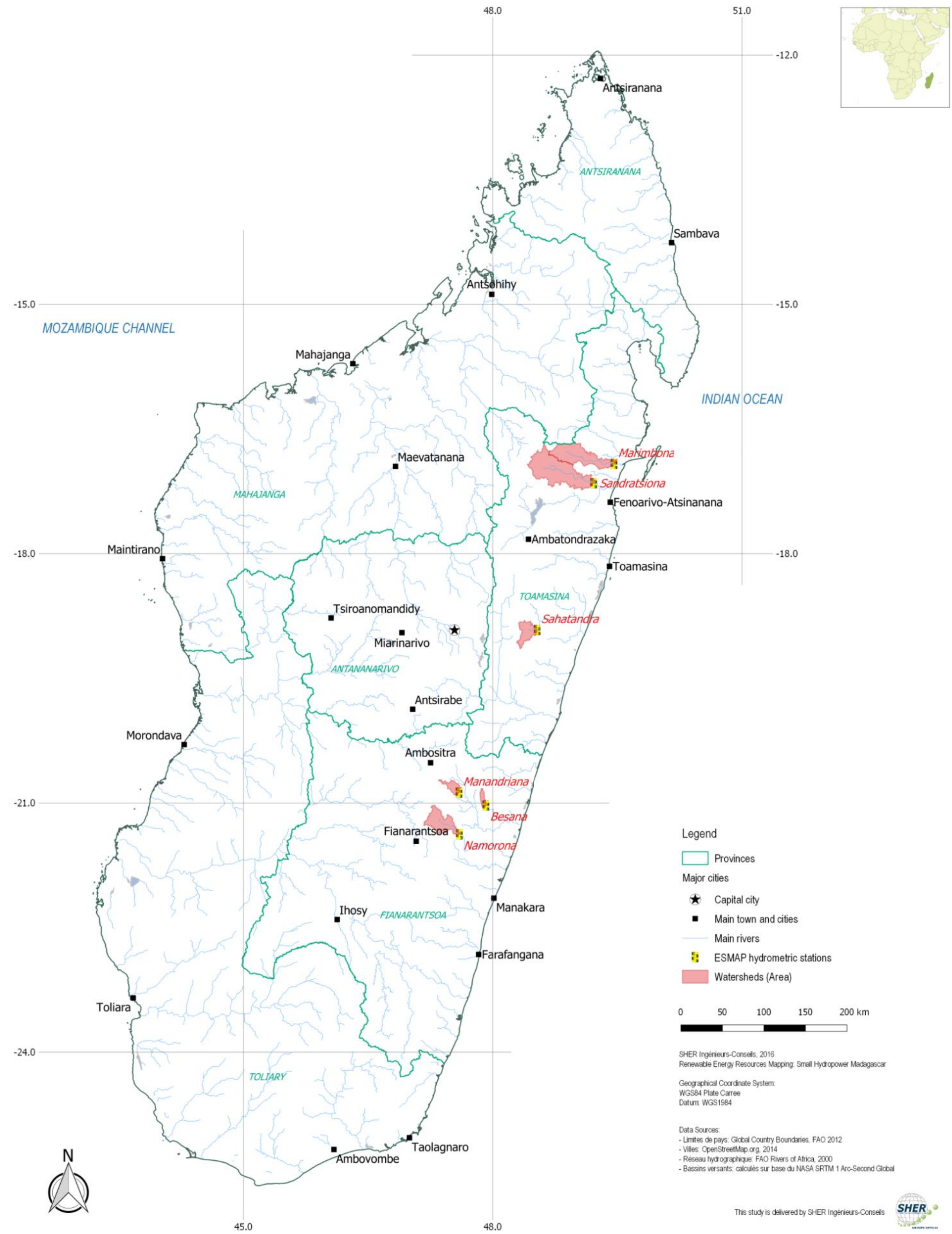


Figure 26. Location of hydrological monitoring stations installed in the frame of the study ESMAP Small Hydro Madagascar

The "*Hydrological Resource Report*" has been produced in the context of Phase 2 (Ground based data collection) and aims to give an overview of the hydrological monitoring network set up in the context of this study as well as to comment on the hydrological data. All the activities carried out as well as the results are described in Appendix F of this Hydro Mapping Report.

7.2 CONCLUSIONS AND RECOMMENDATIONS

Six hydrometric stations were successfully installed on the six selected rivers in Madagascar. These installations allowed the monitoring of water heights and the establishment of preliminary rating curves.

The records cover a complete hydrological year (except for the Marimbona River) from October 2015 to October 2016, which appears to be particularly deficient this year. It is therefore important to continue the hydrological monitoring of these rivers in order to better characterize the hydrological dynamics of these rivers during the normal and wetter years. Indeed, only long historical hydrological measurements (beyond 20 years of measurement) are relevant for the design of infrastructure projects such as hydropower projects.

As highlighted in this report, the rating curves established in the frame of this study are only preliminary results, with a quality level varying from one site to another. A rating curve is by definition dynamic and can change over time due to changes in the geometry of the river (for example, riverbed deepening). The generation of these curves takes place over several years in order to obtain a good understanding of the measurement sites from a hydrological and hydraulic point of view. It is therefore strongly recommended that river gauging continue beyond the duration of this study to confirm the preliminary results presented in this report and to reduce the uncertainties inherent to a single measurement year.

It is strongly recommended that the Government of Madagascar rapidly establishes a hydrological monitoring network for the rivers with high hydraulic potential in order to better understand the available water resources and thus promote the development of hydropower projects throughout the country. It is only in a context of reduced uncertainties through reliable, recent and acquired data over long periods (more than 20 years) that technical parameters and economic and financial analyses of hydropower projects can be defined precisely, enabling optimization of their design and control of design flood of the infrastructure (temporary and permanent).

8 Further investigations

Further investigations have been carried out in the frame of PHASE 2 (Ground-based data collection) of the study. The results of these investigations are presented in the "*Site Investigation Report*" in Appendix E of this report. It provides an overview of the 17 most promising potential hydropower sites in Madagascar.

The selection of the 17 sites is the result of a process carried out during PHASE 1, for which the results were validated during the workshop held in Antananarivo in June 2015 at the Ministère de l'Energie et des Hydrocarbures.

This selection is the result of a complex spatial planning exercise which was based especially on economic, environmental and energy demand and supply matching criteria and consists of a list of priority sites for short term development of small hydropower in Madagascar. Among these 17 sites, three (3) were recommended for the development of isolated rural areas and three (3) other sites come from (after a visit to the 8 potential sites meeting the criteria established in Phase 1) the potential sites studied previously at a more or less advanced stage (up to the APS level) and/or foreseen in the energy sector development plans by the Ministère de l'Energie.

The selection process showing the origin of the 17 selected sites is illustrated in Figure 27 below and their location is illustrated in Figure 28 below.

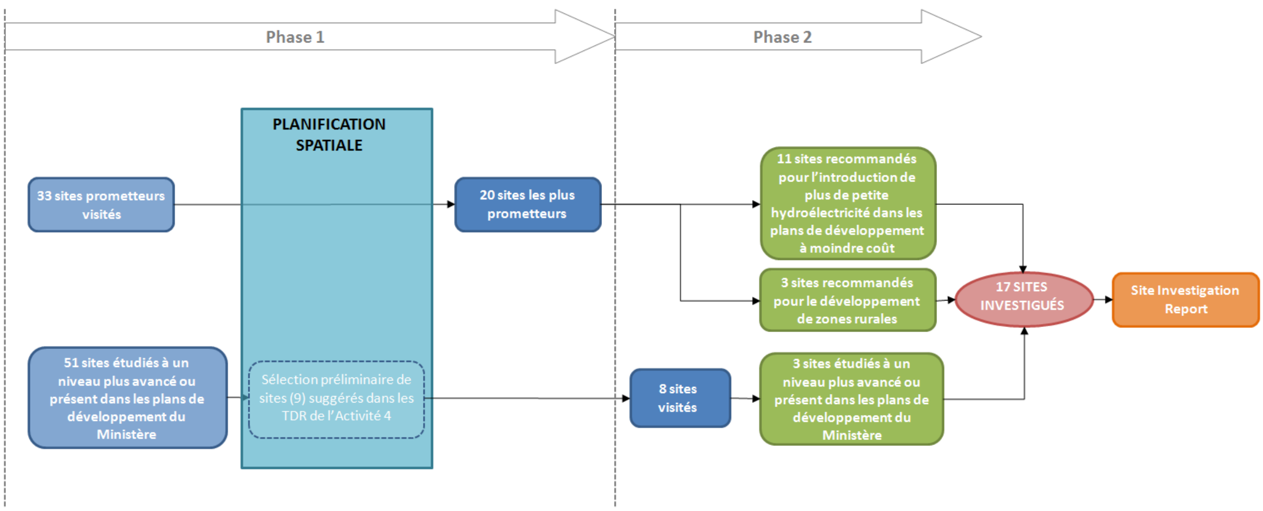


Figure 27. Illustration of the site selection process

The results presented in the "*Site Investigation Report*" are based on preliminary technical site investigations including site visits, topographic surveys (based on the processing of ortho-photogrammetric images acquired by a light aircraft), characterization of the surface geology, the socio-economic environment as well as a regional hydrological study. All parameters, information, data and recommendations presented in this report are provided for information purposes only. They are not intended to be used for design purposes and should be confirmed at the prefeasibility, feasibility and detailed design stage.

Figure 28. Map with the location of the 17 potential hydropower sites

9 Prefeasibility studies for two hydropower projects

9.1 INTRODUCTION AND OBJECTIVES

In the frame of PHASE 2 (Ground-based data collection) of the study and in accordance with our terms of reference (Revised Terms of References for Phase 2 (Activity 4) of the Project, 16 April 2015), two potential sites have been the subject of a prefeasibility study. The two selected sites for the prefeasibility studies are from the list of 17 potential sites recommended for small hydropower development in Madagascar, presented in the "Site Investigation Report" (see previous section).

9.2 DESCRIPTION OF SITE SELECTION CRITERIA FOR PREFEASIBILITY STUDIES

This section presents the most relevant site selection criteria for the prefeasibility studies. These criteria are based on additional information and data acquired during the field investigations (Phase 2), in particular related to topography, surface geology as well as the environmental and social aspects.

These criteria have been presented to the World Bank as well as to the Ministère de l'Energie et des Hydrocarbures and the associated entitites during a video conference held on June 17, 2016.

Important remark: It is important to note that the uncertainties on the baseline data allowing to assess the real potential of a site are variable. The main source of uncertainty is about the hydrology of the concerned rivers. Indeed, for many of the potential hydropower sites in this study, there is little or no accurate information on their hydrological regime. We have therefore developed a methodology to obtain an estimate of the statistical characteristics of the flow time series at the sites of interest based on data available at other flow measurement stations distributed over the territory of Madagascar. These hydrological characteristics have a major role in the estimation of the technical and economic parameters of the hydropower site plans as well as their development planning and type of connection for the evacuation of the produced energy.

That's the reason why criterion 4, as explained in the section about multi-criteria analysis below, is crucial for the selection of the limited number of candidate sites for the prefeasibility studies to be carried out in the frame of this ESMAP study.

Nevertheless, all the sites mentioned in this study are still good sites with an interesting potential, but some of them require more confidence in their baseline data before being candidates for further studies . These are sites for which hydrological data do not exist (either a station installed by SHER or the existence of historical data for a neighboring watershed).

9.2.1 Criterion 1: Estimated capacity between 1 and 20 MW

This criterion corresponds to the capacity range of the sites in this study, as clearly stated in the terms of reference. It should be noted, however, that this criterion had been slightly adapted in the previous phases given the high uncertainty of the collected data. We did not want to eliminate good projects.

9.2.2 Criterion 2: $Q_{50\%}$ and hydraulic structures suited to small hydro [$Q_{50\%}$< 50 m³/s]

In order to remain within the range of flows and equipment which are considered as small hydro, it is recommended not to exceed 50 m³/s. Above these flows, projects start to be more complex: large floods require appropriate dimensions of the flood drainage structures, the water transport structures become big and the budgetary risks are more important.

9.2.3 Criterion 3: Levelized cost of energy (LCOE) : LCOE (without access and lines) < 70 US$/MWh or LCOE (with access and lines) < 120 US$/MWh

Criterion 3.1: In compliance with the budget constraints, the consultant has set a maximum threshold of 70 US $ / MWh, taking into account only the project without the access and connection costs (making it a good project or not) . In a conservative matter, we retain the intermediate position in the range of costs per kilowatt hour of JIRAMA 2011 (40 to 100 US $ / MWh) or 70 US $ / MWh.

Criterion 3.2: A second economic indicator is to look at the LCOE of the project including the access and connection costs to the network or to an isolated center. At this stage of the study, we retain a ceiling of 90US$/MWh for sites that can be connected to one of the three interconnected networks and 200 US$/MWh for isolated sites connected to a thermal group.

9.2.4 Criterion 4: Availability of hydrological information

As illustrated during Phase 1 of the study, the hydrological monitoring of the rivers in Madagascar is very limited, particularly since the early 1980s. Only some watersheds have historical measures dating from the period that ORSTOM was present in Madagascar. For this reason, a campaign of hydrological measurements has been put in place since October 2015 on six rivers considered as priorities for the development of hydropower projects and for which a follow-up will substantially improve the hydrological knowledge of regions of Madagascar which have not been or less gauged.

In the selection process, the sites for which hydrological data exist (either by the presence of a station installed by SHER or by the existence of historical data in the neighbouring watershed) will be favoured in order to allow a better estimation of parameters and hydrological series required for the technical design of the selected hydropower development projects, as well as their energy and economic performances.

The six stations installed in the frame of this study are located in the following watersheds:

River and main watershed	Longitude [DD]	Latitude [DD]
Besana (Mananjary basin)	47.915	-21.030
Sahatandra (Rianila basin)	48.533	-18.919
Namorona (Namorona basin)	47.597	-21.378
Manandriana (Mananjary basin)	47.592	-20.876
Marimbona (Marimbona basin)	49.458	-16.920
Sandratsiona (Maningory basin)	42.212	-17.151

9.2.5 Criterion 5: No obvious environmental and social constraints including solid transport

The first site visits (Site Visit Report, 2015) allowed us to identify immediately the criteria limiting the development of promising potential sites. We can mention the presence of protected area, Lavakas or an important solid transport even in the dry season.

As a second step, the additional investigations carried out by the team of experts for the environmental and social impact analysis made it possible to determine the operational policies (OPs) of the World Bank which should be applied to each of the 17 sites for their development.

The environmental and social constraints have been classified into three categories:

- "low": few environmental and/or social constraints identified at this stage of the study;

- "average": mitigation measures exist for the identified environmental and/or social constraints;

- "high": the identified environmental and/or social constraints could prevent the development of the project.

The category "high" is considered as an exclusion criterion in our multicriteria analysis.

9.2.6 Criterion 6: No major geological constraint identified

The additional investigations carried out by the team of geologists made it possible to describe the surface geology at the different sites and thus to identify the major constraints for the development of these sites. These constraints have been classified into two categories:

- "low": geological constraints that are non-existent or easily manageable, identified at this stage of the study;
- "important": the identified geological constraints could prevent the development of the project or significantly increase its cost.

The category "significant" is considered as an exclusion criterion in our multicriteria analysis.

9.3 MULTICRITERIA ANALYSIS

The application of the criteria, as explained in the previous sections, to the 17 potential sites recommended for small hydro development in Madagascar is presented in the table below.

Table 26. Results of the multicriteria analysis

Code Atlas	CRITERION 1 (Installed capacity)		CRITERION 2 (Flows)	CRITERION 3.1 (Energy production cost)	CRITERION 3.2		CRITERION 4 (Hydrological data)		CRITERION 5 (Environmental and/or social constraints)		CRITERION 6 (Geology)	SELECTED SITES FOR THE FEASIBILITY STUDIES		
	<1MW	>20 MW	> 50m³/s	> 70 $/MWh	>90$/MWh if RI > 200$/MWh if isolated or Mini Grid		2 x no		Low = few or no constraints Average= existance of mitigation measures High =constraints which could prevent the development of the site		Low = few or no constraints Significant = constraints which could prevent the development of the site			
	Firm capacity @Q95% [MW]	Capacity @Q50% [MW]	Median flow (Q50%) [m³/s]	LCOE (without lines and access) [$/MWh]	LCOE [$/MWh]	RI / Mini Grid / isolated	Hydrometric station ESMAP [yes/no]	Historical information (ORSTOM) [yes/no]	Solid transport [Low / Average / Elevé]	Environmental / social constraint [Low / Average / High]	Geological constraint [Low / Important]	√ = selected site - = site which has not been selected	Groups of competing sites for energy supply	Remarks
AD313	0.125	0.445	3.2	110	190	Mini Grid	No	yes	Low	Low	Low	-	-	
AD342	0.315	0.54	2.2	131	237	Isolated	No	no	Low	Low	Low	-	-	
AD411	2	5.76	7.1	54	94	RI	No	no	Low	Low	Important	-	-	
AD601	0.78	1.7	6.7	62	87	Isolated	No	no	Average	Average	Low	-	-	
AD620	0.65	1.94	9.7	74	229	Isolated	Yes	no	Low	Low	Low	-	-	
AD631	3.75	10.44	13.0	64	103	RI	No	yes	Low	Low	Low	-	-	
AD652	1.79	4.98	17.0	62	77	RI	No	yes	Low	Low	Low	√	A (connection of RIF)	
AD653	0.305	0.66	4.7	79	229	Isolated	No	no	Average	Average	Important	-	-	
FR148	5.76	16.08	93.7	54	64	Mini Grid	No	no	Average	Average	Low	-	-	
G191	4.318	12.78	24.4	51	57	RI	Yes	yes	Low	Low	Low	√	A (connection of RIF)	This site could correspond to Namorona II.
G407	3.01	9.42	16.7	42	48	RI	Yes	no	Low	Average	Low	√	B (connection of RIA)	Possible technical constraint related to railway proximity of the site
SF011	12.48	33.9	45.1	75	87	Mini Grid	Yes	no	Low	Low	Low	-	-	
SF015	1.3	7.11	46.9	51	98	Mini Grid	Yes	yes	Average	Average	Low	√	D (Connection to Mini Grid of Lake Alaotra)	
SF020	11.38	35.6	53.8	55	92	Mini Grid / RI	Yes	no	Low	Low	Low	-	-	
SF038	2.67	7.11	44.2	49	90	RI	Yes	no	Average	Average	Low	-	-	
SF195	1.64	4.9	23.0	55	86	RI	Yes	yes	Low	Low	Important	-		
SF196	1.575	5.64	4.7	51	126	MiniGrid	yes	no	Low	Low	Low	√	C (connection of Mini Grid Mananjary + isolated municpalities)	

Legend: Non satisfying criterion

Satisfying criterion

9.4 CONCLUSIONS AND SELECTED SITES

The results show that five (5) sites have been selected: AD652 (Tambohorano), G191 (Andriamanjavona), G407 (Fanovana), SF015 and SF196. Their location is described in the table below.

CODE ATLAS	RIVER	PROVINCE	REGION	DISTRICT	MUNICIPALITY	CAPACITY AT MEDIAN FLOW [MW]	ENERGY PRODUCTION AT MEDIAN FLOW [MWH/YEAR]	GROUPS OF COMPETING SITES FOR ENERGY SUPPLY
AD652 (Tambohorano)	Faravory	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Ifanadiana	5	35710	A (connection of RIF)
G191 (Andriamanjavona)	Namorona	Fianarantsoa	Vatovavy Fitovinany	Ifanadiana	Ifanadiana	12.8	92270	
G407 (Fanovana)	Sahatandra	Toamasina	Alaotra-Mangoro	Moramanga	Ambatovola	9.4	66 520	B (connection of RIA)
SF015	Maningory	Toamasina	Alaotra-Mangoro	Amparafaravola	Andrebakely	7.1	47 800	D (Connection to Mini Grid of Lake Alaotra)
SF196	Besana	Fianarantsoa	Vatovavy Fitovinany	Mananjary	Ambodinonoka	5.6	40 340	C (connection of Mini Grid Mananjary + isolated municipalitie s)

According to the statistics on the parks of Concessionnaires and Permissionnaires published on the ORE[12] website in June 2014, Madagascar has an installed electricity capacity of 552 MW, with 162 MW and 389 MW produced respectively by hydropower and thermal plants. The rest is produced by other renewable energy sources such as wind and solar energy and biomass. From this installed capacity of 552 MW, only 303 MW are currently available (June 2014), or 54.9%. The 17 recommended sites for short term development of small hydropower have an installed capacity of 159 MW. Their short term development could double the current installed hydropower capacity. The five selected sites represent a total of about 40 MW, or 25% of the hydropower capacity currently installed.

12 www.ore.mg

From the five selected sites, two (AD652 and G191) are intended to be connected to the Fianarantsoa Interconnected Network (RIF). They can therefore be considered as competing sites in terms of connection point for the supply of capacity and energy to the RIF, in the context of short term planning and given the budget constraints of this project, limiting the prefeasibility studies at 2 sites maximum. The RIF has currently[13] an installed capacity of 9.95 MW distributed between 6.1MW of hydropower and 3.85MW of thermal power. The projections of ORE indiacte a peak capacity demand of 10.9 MW in 2020 and 18.3 MW in 2030. The two selected sites, G191 (~ 12.8 MW) and AD652 (~ 5 MW), could therefore contribute significantly to the current and future deficit between supply and demand in terms of capacity and energy. It should be noted that the G191 site is located downstream of the existing Namorona 1 run-of-the-river power plant with a capacity of 5.6 MW.

The G407 site (~ 9.4 MW) is intended to be connected to the Antananarivo Interconnected Network (RIA) in order to reinforce the latter. All the capaciy and energy produced by this site would be immediately absorbed by the RIA, given the peak demand projections of 258MW in 2020 and 381MW in 2030 (compared to a demand of 196 MW in 2013).

The other two sites, SF196 and SF015, are to be connected to respectively the Mini Grid of Mananjary and Lake Alaotra.

Mananjary currently has a thermal group of 1304 kW and a distribution network and a little more than 2,300 subscribers. The municipality of Vohilava, which would also be supplied by the SF196 site because located on the proposed power evacuation line, currently has a group of 30 kW. The SF196 site, with an installed capacity of ~ 5.6 MW, would therefore cover the projections of capacity and energy demand of this Mini Grid at the medium term.

The SF015 site presents a hydrological regime characterized by a particularly pronounced low water level due to the upstream Alaotra lake and the significant abstractions for irrigation during the low water season. A private network operated by BETC is present in the lake area and should be taken into account for any new project in the area. BETC is developing the 1.6 MW Androkabe Hydropower Project. There is currently a group of thermal units with a total available capacity of about 5 MW. The SF015 site would allow a substitution of the thermal production and/or the coverage of the increase in local demand.

At the JIRAMA level, the total energy production increased between 2013 and 2014 by 64,106 MWh (+ 4.5%)[14]. This increase in production has to be compared with the estimated annual production for the five selected sites: the commissioning of the G191 or G407 sites would represent a production increase which is higher than that of the whole of JIRAMA for the period 2013-2014, while the others sites would nevertheless contribute significantly.

13 Statistics of the 'Office de Régulation de l'Electricité (ORE) of June 2013 avaibale on their website : www.ore.mg

14 Electricity production 2013-2014 *(Source : Jirama, Direction de de la Production Electricité (DPE)) - http://www.jirama.mg/index.php?w=scripts&f=Jirama-page.php&act=offreselec)*

In a context of short term development of small hydropower for the private sector (as mentioned out in the Activity 4 Terms of Reference), our recommendation would therefore be that the two priority sites are not within a same competing group, as explained above.

Taking into account this analysis and the discussion held by videoconference between SHER Consulting Engineers, the World Bank, the Ministère de l'Energie et des Hydrocarbures and the entities held on June 17, 2016, the **discussions conclude that the following sites will be selected for prefeasibility studies: G407 (Fanovana) and SF196 (Mahatsara).**

The prefeasibility studies cover the following aspects:

- Review of the existing data and information, including GIS data;
- Additional visits of the two selected sites as well as the main load centres/connection points to the national network, by experts in the field;
- Additional topographic and geological studies, update of the hydrological study and assessment of the environmental and social impact in order to achieve the prefeasibility study level.
- Preparation of a first draft of the design and plans at prefeasibility study level; schematic layout of the hydropower plant, weir (if applicable), waterways and transmission lines to the main load center or point of connection with the national grid;
- Preparation of a cost estimation including the costs related to the environmental and social impacts as well as the energy production cost for a range of different installed capacities.
- Preliminary economic analysis.

9.5 SUMMARY OF THE FEASIBILITY STUDY FOR THE FANOVANA SITE (G407)

Table 27 below summarizes the main features of the alternative schemes considered for the Fanovana site on the Sahatandra River.

Table 27. Main features of the hydropower project for the Fanovana site

FEATURE	PARAMETER	VALUE	UNITS
Location	Region	Alaotra-Mangoro	-
	River	Sahatandra	-
Hydrology	Watershed area	520.4	km²
	Median streamflow ($Q_{50\%}$)	14.1	m³/s
	Firm streamflow ($Q_{95\%}$)	6.7	m³/s
Weir and intake	Watershed closure	Overflowing weir + flushing gates (3 bays)	-
	Type	Concrete gravity	-
	Average height	3.20	m
	Crest elevation	582.20	m
	Crest length	123	m
Spillway	Type	Overflowing Ogee-type weir	-
	Crest elevation	582.20	m
	Design flood (100 years)	1351	m³/s
	Water head at design flood	3.0	m
Waterways	Intake structure		
	Invert elevation	580.0	m
	Design flow	16	m³/s
	Number of bays	5	-
	Canal		
	Length	410	m
	Average slope	0.05	%
	Forebay	Equipped with an emergency spillway	-
	Forebay operating water level	581.90	m
	Penstock		
	Number	1	-
	Diameter	2.0	m
	Length	95	m
Hydropower Plant	Type	Surface type structure	-
	Location	Right river bank	-
	Number of bays	3	-
	Tailwater level	509.40	m
	Floor elevation	510.40	m
	Available gross head	72.50	m
	Number of turbines and type	2 vertical shaft Francis turbines	-
	Rated output of each turbine	4.615	MW
	Rated discharge	8	m³/s
	Installed capacity	9.230	MW
	Average annual energy generation	61.78	GWh
Economics	Capital expenditure costs (CAPEX) – *Without transmission lines and existing access roads to be rehabilitated*	13.634	M€
	Levelized Cost of Energy (LCOE) - *Without transmission lines and existing access roads to be rehabilitated*	0.0264	€/kWh
	Capital expenditure costs (CAPEX) – *Incl. transmission lines and existing access roads to be rehabilitated*	22.08	M€
	Levelized Cost of Energy (LCOE) – *Incl. transmission lines and existing access roads to be rehabilitated*	0.0418	€/kWh

The hydrological study revealed that the Sahatandra River was characterized by a sustained low water level which should be confirmed by further hydrological monitoring carried out during the hydrological year 2015-2016 in the framework of the ESMAP study on the mapping of the small hydro potential in Madagascar.

The preliminary geological surface investigations conclude that from a geological point of view the site is not opposed to the execution of the project as long as the appropriate measures and precautions are put in place. The site has no major problems of stability and permeability. However, further investigations will be necessary during future studies.

The preliminary socio-environmental studies show that the development of the Fanovana site has no major impacts that couldn't be mitigated by relevant measures.

The economic analysis shows the significant impact of the costs for rehabilitating existing accesses and the construction of power evacuation lines (63 kV) to Moramanga. The Fanovana hydropower project is an economically attractive site with a total LCOE (including lines and rehabilitation of existing access) of 0.0418 USD/kWh. This LCOE drops to 0.0264 USD/kWh excluding line costs and existing access to be rehabilitated. The Fanovana site has production costs which are significantly lower than the thermal production costs (0.18 to 0.25 US$/kWh for HFO thermal and between 0.30 to 0.34 US $ / kWh for the thermal GO).

It is therefore recommended that the rehabilitation of the road between the RN2 and the village of Fanovana as well as the construction of the 63kV power evacuation line to Moramanga should be carried out and financed in the frame of the structuring projects of the Government of Madagascar.

The Fanovana hydropower project could be developed via a Public Private Partnership (PPP), according in particular to the law of 9 December 2015 organizing PPPs. The procedures for selection and invitation to tender must be clearly defined and a firm specialized in PPPs must be recruited to accompany the tendering process.

It is important to note that the conclusions of this economic analysis are conditioned by the validation of the estimated flow duration curve in the hydrological study. This validation can only be carried out by continuing the hydrological monitoring of the Sahatandra River at the hydrometric station installed in October 2015 at a few kilometers upstream from the site of the hydropower project. This hydrological monitoring should include not only the continuation of the water level recording, but also the river gaugings for the establishment of a validated rating curve.

9.6 SUMMARY OF THE FEASIBILITY STUDY FOR THE MAHATSARA SITE (SF196)

Table 28 below summarizes the main features of the hydropower project of the Mahatsara site (code Atlas SF196) on the Besana River.

Table 28. Main features of the hydropower project for the Mahatsara site (SF196)

FEATURE	PARAMETER	VALUE	UNITS
Location	Region	Vatovavy Fitovinany	-
	River	Besana	-
Hydrology	Watershed area	125	km²
	Median streamflow ($Q_{50\%}$)	6.6	m³/s
	Firm streamflow ($Q_{95\%}$)	2.9	m³/s
Weir and intake	Watershed closure	Seuil déversant à profil Creager + vannes de chasse (3)	-
	Type	Poids béton	-
	Average height	3.5	m
	Crest elevation	237.5	m
	Crest length	46.50	m
Spillway	Type	Seuil déversant à profil Creager	-
	Crest elevation	237.5	m
	Design flood (100 years)	514	m³/s
	Water head at design flood	3.0	m
Waterways	Intake structure		
	Invert elevation	235.0	-
	Design flow	6.2	m³/s
	Number of bays	2	-
	Canal		
	Length	21m (en plus du dessableur)	m
	Average slope	0.05	%
	Tunnel		
	Length	480	m
	Average slope	2.20	m
	Surge chamber / forebay	Équipée d'un déversoir de sécurité	-
	Surge chamber / forebay operating water level	237.20	m
	Penstock		
	Number	1	-
	Diameter	1.40	m
	Length	280	m
Hydropower Plant	Type	Surface type structure	-
	Location	Right river bank	-
	Number of bays	5	-
	Tailwater level	85.0	m
	Floor elevation	90.0	m
	Available gross head	146.70	m
	Number of turbines and type	4 Pelton turbines	-
	Rated output of each turbine	1.85	MW
	Rated discharge	7.30	MW
	Installed capacity	47.8	GWh
Economics	Average annual energy generation	15.92	M€
	Capital expenditure costs (CAPEX) – *Without transmission lines and existing access roads to be rehabilitated*	0.0497	€/kWh
	Levelized Cost of Energy (LCOE) - *Without transmission lines and existing access roads to be rehabilitated*	33.45	M€
	Capital expenditure costs (CAPEX) – *Incl. transmission lines and existing access roads to be rehabilitated*	0.0983	€/kWh

The hydrological study revealed the existence of uncertainties about Besana River hydrology. Given the latter, it seems appropriate to be careful in the choice of the design flow and reasonable to make the technical choices allowing to equip the site in an evolutionary way with respect to the electromechanical equipment:

- the civil engineering works (intake, channel, sand trap, gallery and penstock, powerhouse) will be sized for a design flow of 6.2 m^3/s corresponding to the Q40% of the flow duration curve which has been extrapolated based on data from the Fatihita station;

- the site will be initially only equipped with electromechanical equipment corresponding to a firm design flow of 3.1 m^3 / s.

These choices will make it possible to add the required electromechanical equipment when the hydrological regime of Besana will be better understood through hydrological measurements over longer and more recent periods. The final choice of the design flow should be made at the stage of detailed studies on the basis of an economic analysis of the variants. The flow duration curve should also be validated by the additional hydrological data that will be available in the future at the hydrometric station located at the site (Mahatsara village).

The hydrological study also showed that the Mahatsara site could potentially present a significant solid transport, particularly during flood events, which would cause operation and maintenance problems of the hydropower station.

The geological field investigations conclude that from a geological point of view the site is favourable to the execution of the project. The site has no major problems of stability and permeability. However, further investigations will be necessary during future studies.

The preliminary socio-environmental studies show that the development of the Mahatsara site has no major impacts that couldn't be mitigated by relevant measures.

The economic analysis shows the significant impact of the costs for rehabilitating existing accesses and the construction of power evacuation lines to Mananjary. The Mahatsara hydropower project is an economically attractive site with a LCOE of 0.0497 USD/kWh (excluding line costs and existing access to be rehabilitated). The Mahatsara site has production costs which are significantly lower than the thermal production costs (0.18 to 0.25 US$/kWh for HFO thermal and between 0.30 to 0.35 US$/kWh for the thermal GO in case of isolated networks).

Therefore, it is recommended that:

- the rehabilitation of the road between between Vohilava and the village of Ambohinanambo (21.9 km) and to the village of Mahatsara (4.7 additional km) as well as (partially or entirely) the RN24 from its intersection with the RN 25 (or an additional distance of about 37 km)
- the construction of the 63kV power evacuation line produced by Mahatsara

are carried out and financed in the frame of the structuring projects of the Government of Madagascar, with the objective of opening up the Vohilava region and consequently developing the local economy.

The Mahatsara hydropower project could be developed via a Public Private Partnership (PPP), according in particular to the law of 9 December 2015 organizing PPPs. The procedures for selection and invitation to tender must be clearly defined and a firm specialized in PPPs must be recruited to accompany the tendering process.

It is important to note that the conclusions of this economic analysis are conditioned by the validation of the estimated flow duration curve in the hydrological study. This validation can only be carried out by continuing the hydrological monitoring of the Besana River at the hydrometric station installed in October 2015 at a few kilometers upstream from the site of the hydropower project.

This hydrological monitoring should include not only the continuation of the water level recording, but also the continuation of the river gaugings for the establishment of a validated rating curve.

10 Capacity building and training

10.1 GEOGRAPHIC INFORMATION SYSTEM

10.1.1 Part 1: Introduction to GIS

A first training on Geographic Information Systems took place in March 2015. Each session started with a short theoretical introduction and a demonstration. Then practical exercises have been proposed.

The first session is designed for technical and non-technical staff:

- General presentation of the GoogleEarth database for managers and technicians (easily accessible by non-technical staff) - Presentation of the basic capabilities of the GIS format.

The next sessions are designed for technical staff:

- Installation of software, introduction to GIS, introduction to the use of layers;
- Consulting and updating (editing) the database;
- Updating the database using geographic coordinates, GoogleEarth or GPS data.

10.1.2 Part 2: Use and update of the database linked to HydroAtlas

As the basic knowledge has been acquired during the first training sessions, this additional module will be dedicated to the following aspects:

- Reminder of the basic concepts;

- Familiarization with the content of the geographic database linked to HydroAtlas;

- Updating the database.

Participation in previous sessions is not a prerequisite, but desirable.

10.2 RIVER HYDROLOGICAL MONITORING

10.2.1 Part 1: Network of hydrological measurements

A theoretical and practical training on all aspects related to hydrological measurement networks was successfully conducted in Antananarivo on the 26th and 27th January 2016. Eighteen (18) engineers and technicians from the Ministère de l'Energie et des Hydrocarbures, ADER, ORE, JIRAMA and the Direction Générale de la Météorologie participated in this training (list of participants in the annex), with the following detailed content:

1. Theoretical training :
   - Criteria for identification of a measurement site.
   - Selection of the appropriate measurement technology to the local conditions.
   - Overview of different river level measurement technologies.
   - Basic approach of data recording technologies.
   - Data acquisition process.
   - Establishment of a rating curve.
   - Height-flow conversion.
   - Telecommunication systems for transmission of data from "slow" phenomena.
   - Maintenance operations for a hydrological measurement station.
   - Hydrological databases.
   - SCADA systems.
   - Data processing and validation.
2. Practical training :
   - Familiarization with the electronic measuring equipment (voltmeter, ammeter).
   - Measurement of electronic signals generated by a sensor.
   - Connection of the sensors to an acquisition unit.
   - Configuration of an acquisition unit.
   - Connection of an acquisition unit to a GPRS telecommunication system.
   - Periodic preventive maintenance.
   - Curative maintenance of the 1st level.
   - Collection and transfer of data recorded by an acquisition unit.
   - Implementation of gaugings.
   - Use of software for building rating curves.
   - Database management.
   - Data processing.

- Data validation.
- Data consultation.

Figure 29. Theoretical training in Antananarivo (26/01/2016)

Figure 30. Practical training on the site of Fanovana le 27/01/2016

Figure 31. Visite of site G191 (Chute d' Andriamanjavona) on the Namorona River and gauging at ADCP with with JIRAMA representatives (03/02/2016)

In addition to this training, one person from the Direction Générale de la Météorologie participated in almost all the maintenance missions of the stations as well as in the river gauging missions. This continuous training has enabled a sustainable capacity strengthening as well as the acquisition of the theoretical and practical knowledge making it possible to contribute to the sustainability of the measurement network put in place.

10.2.2 Part 2: Concepts of hydrological measurements applied to hydropower

As the basic knowledge is acquired, this additional module will be dedicated to the following aspects:

- Hydrological monitoring of rivers: technological choices adapted to the context;
- River gauging: Theory and available techniques;
- Establishment and updating of the rating curves;
- Application to hydropower (flow duration curves).

10.3 BASIC HYDROPOWER CONCEPTS

The exploitation and optimal updating of the database of potential hydropower sites in Madagascar requires an adequate knowledge of the design of hydropower projects. That is the reason why a training module dedicated to these aspects will be given on the 21st February 2017 in Antananarivo. This training will cover the following topics:

- Theoretical aspects of capacity and energy calculations;
- Types of projects and main components;
- Risks associated with bad design;
- Preliminary assessment of the hydropower potential of a site

11 Hydro Atlas of Madagascar

The Hydro Atlas of Madagascar is a document that contains all the information directly or indirectly related to hydropower and collected during Phase 1 of this study. The information has been compiled and processed in a Geographic Information System (GIS) and presented as thematic maps, tables, graphs and various illustrations. The Hydro Atlas also includes the results of the prioritization of promising sites, as discussed during the pre-diagnosis phase and presented in the inception report of August 2014.

The information of this Atlas presents the hydropower potential of Madagascar including the new potential sites identified by the consulting engineering firm SHER/ARTELIA within the framework of this study, using the SiteFinder tool as well as the existing hydropower sites. The creation of the Atlas started with Activity 1 of the study. The Atlas has been finally updated at the end of Activity 4, by including new information collected in the field (site visits, hydrological measurements campaign) and updating the contextual information.

The Geographic Information System has been designed to meet the compatibility and standardization requirements defined in the terms of reference so that geographic data can be easily published on the World Bank GIS platform. In addition, the consultant used the GIS software QuantumGIS, free of charge, for processing and publishing the geographic data, which makes it possible to disseminate and transfer the data free of charge during the training sessions carried out under Activity 3.

The present Hydro Atlas of Madagascar focuses exclusively on potential sites in the range of capacities between 1 and 20 MW. The Hydro Atlas is presented in **Appendix D** of this report.

12 Conclusions

All the information with a geographical component related to the hydropower sector in Madagascar has been compiled into a Geographic Information System (GIS). More specifically, the raw database of potential hydropower sites is the result of the integration of information from different sources and contains 2,045 potential hydropower sites: 1470 coming from the literature and 575 newly identified by SiteFinder, a spatial analysis tool to identify river stretches with high hydropower potential based on rainfall and topography (tool developed by SHER Ingénieur-Conseils). A first detailed screening of this database has eliminated duplicated and inconsistent sites, reducing the number of potential hydropower sites to 1301. A second phase of validation has allowed to confirm a total of 403 potential hydropower sites.

In collaboration with the Ministère de l'Energie and the associated entities, a portfolio of hydropower projects meeting the criteria of the study has been identified. This process of multi-criteria analysis considered the following parameters: the Energy Policy and the growth areas of Madagascar, the hydrological constraints, the power capacity range corresponding to the terms of reference of the study (between 1 and 20 MW), the costs for development of hydropower projects (calculated based on the approximate length of the access road(s), the cost for the transmission lines to the grid or to a remote centre and the costs for the infrastructure) and finally the potential environmental and social impacts. At the end of this process, a portfolio of 33 promising sites has been identified and visited by the Project Team.

Parallel to the site selection process, the hydrological study showed that the available hydrological data in Madagascar are generally limited and/or no-existent for some watersheds. For the majority of the sites in this study, there is no or little accurate information on their hydrological regime. Therefore, a methodology to obtain a high-level estimate of the statistical characteristics of stramflows at the sites of interest, based on data available on other gauging stations in other parts of Madagascar, has been developed and implemented. A confidence index of hydrological estimates has been attributed to the different sites.

The 33 promising sites have been visited by the Project Team between late September 2014 and late November 2014. The site visits allowed to validate the information and the assumptions made during the desk-based phase and to propose relevant and realistic hydropower projects taking into account the local constraints of the potential sites.

The report also includes a presentation of the results of Activity 4 related to the data collection and final validation. These results have validated the key figures of the 20 prioritized sites based on additional investigations with respect to the topography, the geology, the natural and social environment and the hydrological measurements. Regarding the hydrological measurement campaign, six hydrometric stations have been successfully installed on the six selected rivers in Madagascar. These stations allowed to monitor the water levels and to set up the preliminary rating curves. The records cover a complete hydrological year (except for the Marimbona River), from October 2015 to October 2016, which appears to be a particularly deficient year.

Through the mapping of the hydropower potential of Madagascar, it is clear that this potential is very important and still largely under-exploited. The country benefits from a good relief and a favourable rainfall, especially in the eastern part of the country. Opportunities exist in all capacity ranges. The development of this potential is however hampered by the size of the country, the obsolescent state of the road network and tracks and the dispersion of the urban areas. Soil degradation - erosion, gold and artisanal mining, Lavaka - in some areas (especially in the South, Midwest and West) is worrying and may question the viability and even the feasibility of some hydraulic projects. This context of watershed degradation and sediment management should be taken into account in all future hydropower projects, whether large or small. In general, any new development must be part of an Integrated Watershed Resources Management (IWRM) in order to preserve the natural water resources of Madagascar in a sustainable way.

The development of the Hydro Atlas, including the databases supporting the formats described in this report (GIS), is therefore an appropriate tool to facilitate the planning process of the responsible Malagasy agencies. Indeed, the Hydro Atlas is a unique tool that integrates all the information from the different institutions involved in the hydropower sector. It provides an overview of the sector, in terms of existing assets and potential allowing a better visualisation of the matching of supply and demand for the prioritisation of future project development. The Hydro Atlas should be a dynamic and evolving tool that must be updated according to future development of the hydropower sector in Madagascar and the increasing availability of information (hydrological measurements, update of site surveys, etc).

13 Annexes

13.1 SITEFINDER: A TOOL TO DETECT SMALL HYDROPOWER POTENTIAL SITES

The purpose of the SiteFinder software is to detect natural waterfalls or river stretches with a steep slope, associated with a flow, to highlight the potential river stretches for hydropower development. The program is mainly based on a Digital Terrain Model (DTM) and a number of climatic and/or hydrological data.

The basic principle of the software is to detect waterfalls associated with a watershed size determined according to the needs of the study. The mean river flow is estimated using the watershed size and/or from the distribution of the annual rainfall data. The software computes the specific capacity for each river stretch. These results, displayed on the screen, make it possible to identify the potential sites.

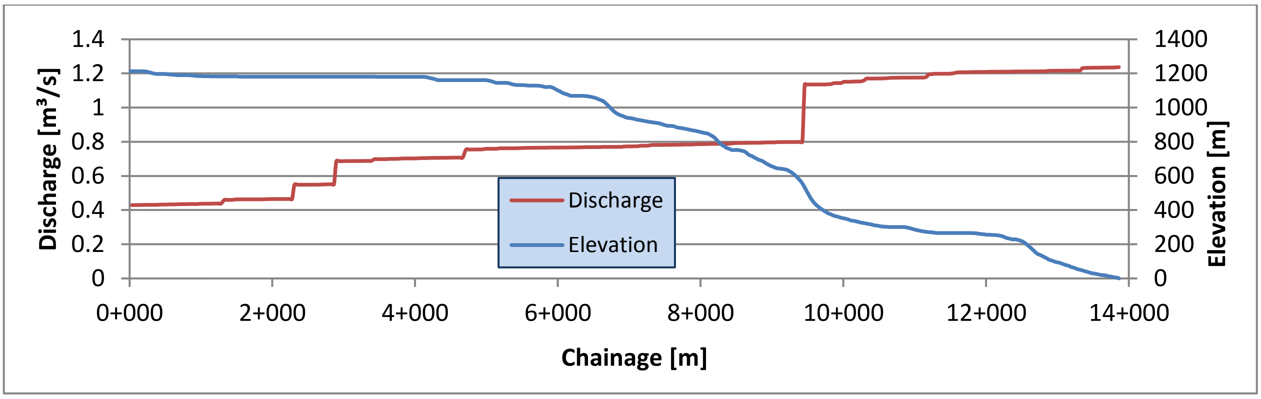


Figure 32. Example of the profile of a river compared to the flow

There are two methods available in the model to calculate the specific capacity per river stretch. The first method is based on the digital elevation model (DTM) and the map of the annual rainfall. The software simulates the runoff of the water volume from the annual rainfall and computes flow values. This method is well suited for small areas where the distribution of the annual rainfall is well known. Small areas make it possible to work on small watersheds where the approximation of the proportional relationship between precipitated volume and run-off volume is acceptable.

The second method consists in assigning a flow value based on gaugings in neighbouring watersheds (where the hydrological regime is known). When the information is available, the distribution of the specific flows can also be used to determine the flow for each site. This method works well for regions where the extent induces an important variation in the hydrology from one watershed to another and where the size of the watershed leads to a complex annual relationship between rainfall and flow. This has been applied here.

Note that these are of course the natural waterfalls that are detected. That is the reason why hydropower sites where the head is generated only by artificial elevation of the upstream water level are not detected, because the software is based on a height of natural fall given by the DTM.

13.1.1.1.1 Determination of the minimum size of the watershed

The minimum size of the watershed to consider for SiteFinder is fixed at 16km². This value corresponds to a low flow value of about 0.5m³/s. This value is the maximum value that the low flow can reach in the most favourable hydrological region of the country (at the east side of the country) obtained from the hydrological station where the maximum median specific low flow is 30 l/s/km² (Fleuves et Rivières de Madagascar, 1998). This watershed value is therefore a conservative value because in most cases, the low flow of such a watershed is below 0.5m³/s.

13.1.1.1.2 Determination of the flow

In our case, the flows for the sites found by SiteFinder have been computed based on the distribution of specific flows as reported in "Fleuves et Rivières de Madagascar" , Chaperon et al, 1993. The watershed is first determined for each site. On this basis, the average flow rate is determined for the corresponding watershed and the low flow is deduced.

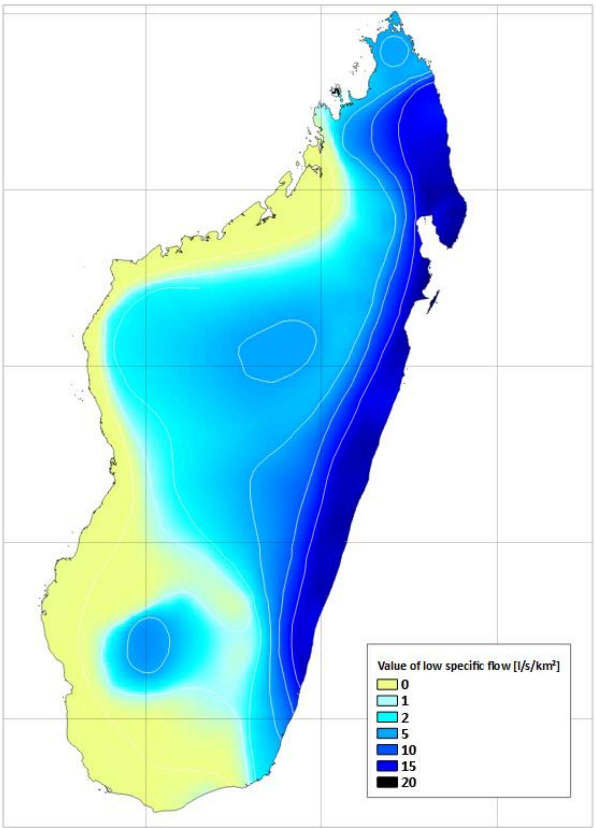


Figure 33. Distribution of the minimum specific flow

13.1.1.1.3 Individual analysis of potential SiteFinder sites

When processing the data, the topographic maps at 1: 100,000 have been used to compare the results obtained by the software with the information on the maps. If possible, and based on the remarks on the quality of DEM data above, the height difference of the sites has been derived from the maps. However, it was not possible in most cases to find the height differences on the topo maps. In this case, the ASTER digital elevation model has been used. The 1: 100,000 scale gives indeed little detail. However, this scale makes it possible to check if the river stretches have an interesting profile. When analyzing the results, the sites have been systematically checked using these maps.

13.1.1.1.4 Capacity estimation

The capacity has been calculated using the formula below:

$P = \eta \times H_{gross} \times Q_{low\ flow} \times 9.81$

Based on the above remarks, it should be clear that the calculated capacities are used to determine an order of magnitude, which must be still confirmed by further analysis. These values may in no case be used for detailed studies without prior verification.

13.1.1.1.5 Hydrological data used by Sitefinder

The hydrological data sources are mainly the following:

- Monography "Fleuves et Rivières", 1993, Chaperon et al.
- Monthly data from the GRDC (Global Runoff Data Center)
- Monthly data from the "Département météorologie et climatologie"

13.1.1.1.6 Determination of the design flowof the sites

The design flow of the sites is determined by considering all the run-of-the-river systems in operation where we try to approach the flow which is firm most of the time. This flow is extrapolated based on the geographic distribution of specific low water flows (Chaperon et al, 1993). Therefore, the average of the specific flow in the concerned watershed is calculated in the model. This value is then associated with the size of the watershed to give the value used for the calculation of the capacity.

Note that this method has also been extended to the sites mentioned in the literature where the gross head is specified but without flow information.

13.1.1.1.7 Topographical data

The sources for the topographical data are SRTM and ASTER.

- SRTM[15]

The Shuttle Radar Topography Mission (SRTM) is an international project led by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The mission obtained topographic data on an area covering almost all the Earth's emerging parts and has allowed to generate the most complete high-resolution topographical database on the

[15] http://www2.jpl.nasa.gov/srtm/

Earth at the time of its creation. SRTM consists of one specially modified radar system onboard the Space Shuttle Endeavour during a mission of 11 days in February 2000.

The data resolution is 3 arcseconds (~90 m – and up to 30m in the United States).

In 2013, NASA made version 2 of the SRTM (know as the "finished version") available to the public. This version is the result of a substantial editing effort by the NGA and shows well-defined characteristics with respect to the coastlines, as well as the absence of *spikes* and *wells* (unique pixel errors). Nevertheless, certain areas have missing data (*voids*).

- ASTER[16]

The Japanese Ministry of Economy, Trade, and Industry (METI) and NASA (National Aeronautics and Space Administration) jointly announced, on the 17 October 2011, the release of the *Advanced Spaceborne Thermal Emission and Reflection Radiometer* (ASTER) *Global Digital Elevation Model Version 2* (GDEM V2), the second version of the global digital terrain model ASTER.

The first version of ASTER GDEM, released in June 2009, was generated by pairs of stereoscopic images collected by ASTER instruments, loaded onto the TERRA satellite. The ASTER model covered the Earth's surface between the latitudes 83° north and 83° south, which is 99 percent of the whole planet's surface.

The ASTER GDEM V2 mode contains 260,000 additional pairs of stereographic images, improving the coverage and reducing the artefacts. The refined algorithm gives a better spatial resolution with an increased horizontal and vertical precision, as well as a better coverage and detection of waterbodies. The version 2 keeps the same GeoTIFF format and meshing and cutting as the version 1, with a pixel size of 30m by 30m and a cutting of 1° by 1°.

The version 2 presents significant improvements compared to the previous version. However, the users are informed that the data still have anomalies and artefacts that can hamper the performance of the model for certain applications. The data are raw and neither NASA, nor METI/Japan Space Systems (J-spacesystems) can be held responsible for damage resulting from the use of these data.

The resolution of the data is 30 m.

- Compared resolution

ASTER's resolution is 9 times better than the resolution of SRTM: for each SRTM value (1 pixel is 90mx90m), ASTER has 9 values (1 pixel fait 30mx30m). Nevertheless, this is not the only criterion because, as the ASTER producers announced, numerous artefacts (local errors) still exist in the version 2. Below we bring out certain highlights of the differences between the 2 DEM. The results reproduced are issued from the algebraic difference between the 2 rasters and are given in metres ([ASTER] - [SRTM]). The corresponding legend is the following:

---

[16] http://www.jspacesystems.or.jp/en_/

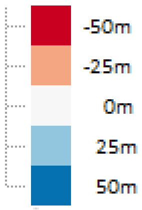
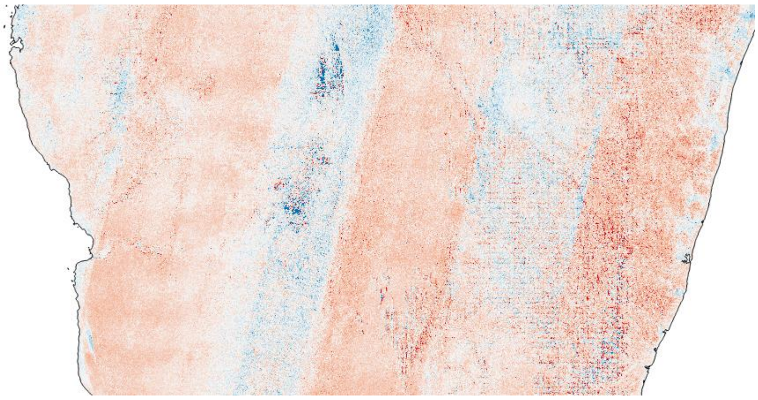


Figure 34. Scale used for the comparison of results between SRTM and ASTER

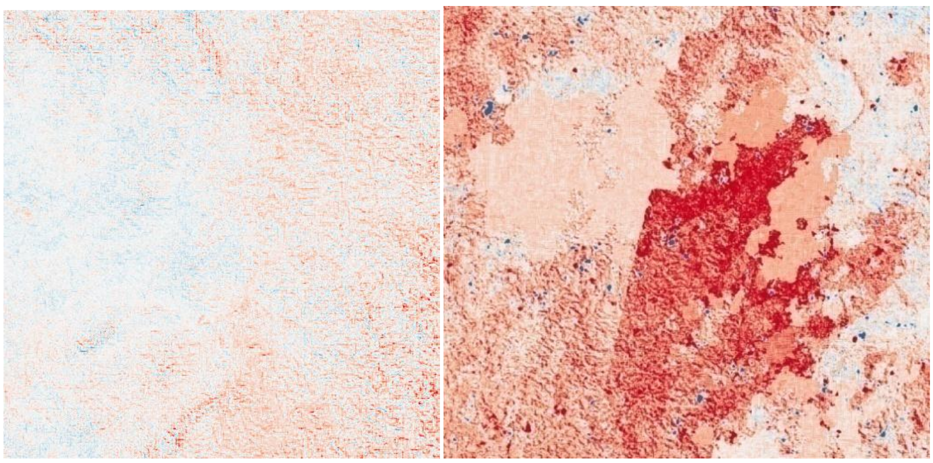
- Global differences

A global view of the results shows that the typical path of the satellites is visible. This highlights the inconsistencies between the 2 measuring systems.

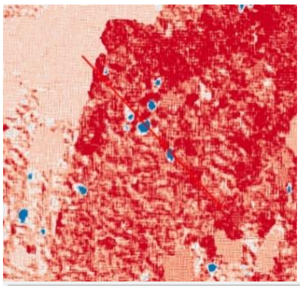


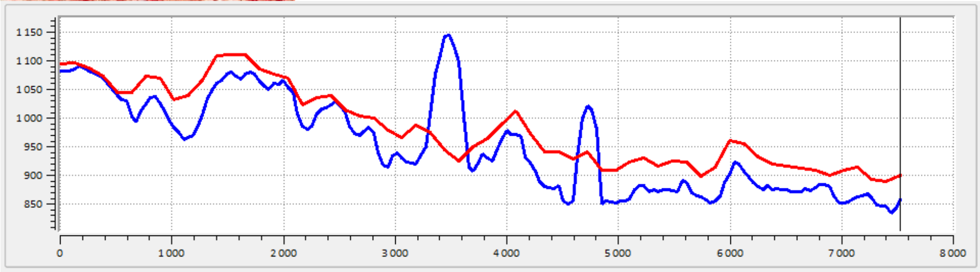
- Local differences

Locally, the differences are irregular. Certain regions don't show relatively important differences (Chart A), while others show significant differences in the results (Chart B).

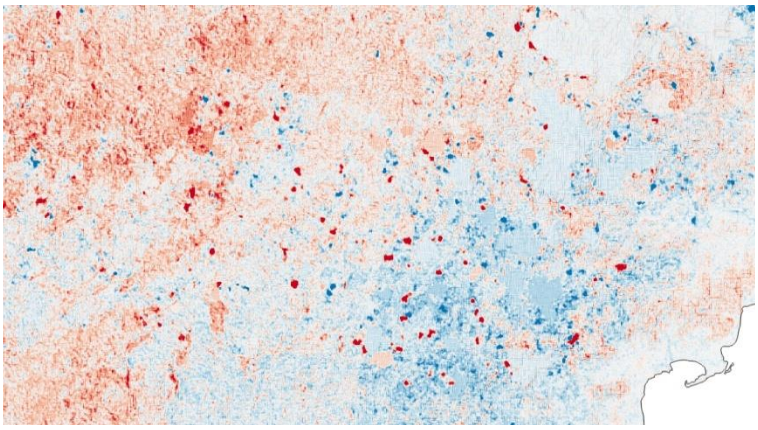


A section on chart B above gives the following profile for each of the DEMs. This profile highlights 2 artefacts (local errors) of ASTER where 2 peaks are visible (blue dots on the image to the left). These peaks do not exist in reality. Otherwise, this section also shows the significant differences between the 2 systems for this area. We must remember here that the exposed area is one of the areas where the differences are particularly marked.

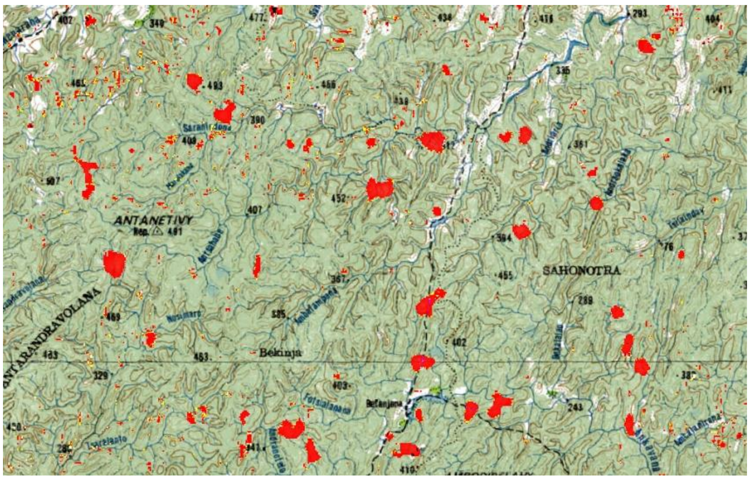




Finally, the following images show the presence of artefacts in the ASTER data that can be harmful for the SiteFinder application. The figure below shows a series of red and blue "marks" which represent differences of several dozens of meters between the two data sources.



If we refer to these errors on the topographical map on a scale of 100,000, we can see that the distribution of these artefacts is random in a given area: theserrors are located near to the river or on a hill, etc.



13.1.1.1.8 National coverage of topographic maps

Usually, the SiteFinder results are verified on a topographic map at a scale of 1:50,000 or any higher[17] scale. These maps show indeed a level of detail that provides a first comprehension of the physical context of a site. It also allows to verify the value of the waterfall height more precisely.

In the case of Madagascar, there is only a partial coverage at a scale of 1:50,000. Therefore, the maps at scale 1:100,000 have been used. These maps do not have yet a sufficient level of detail and it is difficult to determine the waterfall height for a small river stretch, except for the cases where elevation points exist at the falls.

13.1.1.1.9 Limitations due to availability of the data

The results presented below show that some caution is still required in using these data. The ASTER DEM still contains many artefacts in certain regions of the country. The SRTM, although generally validated, still contains some areas without data and has a lower resolution than ASTER.

Given the importance of the area of the country and the irregular topography, a multitude of sites are suitable for hydropower use higher than 1 MW . The program has been calibrated for this value, but it should be noted that the data accuracy (especially DTMs and maps at scale 1:100,000) does not ensure the identification of all sites of more than 1 MW.

The head and flow values used for the estimation of the available capacity were obtained based on rough estimations. These values will generally be corrected based on the studies and site investigations. The flow was chosen based on the specific regional low flow, as determined in Fleuves et Rivières (Chaperon and al, 1993). These values have been extrapolated to ungauged watersheds. Thus, sites indicating height differences can be without height differences. In other cases, long stretches with a steep slope could not be favourable or economically feasible. It is also obvious that all the sites could not be found and that a precise analysis based on a more detailed DEM is advised for the future.

[17] Small scale means a large number in the denominator (example: 1: 1,000,000th = 0.000001) and large scale a small number in the denominator (example: 1: 1,000th = 0.001)

13.2 ECONEVAL – A PRELIMINARY ECONOMIC CALCULATION TOOL OF HYDROPOWER SITES

13.2.1 Objective

The main objective of the economical evaluation is to define the Levelized Cost Of Energy (LCOE). The LCOE is a stream of equal payments, normalized over expected energy production periods that would allow a project owner to recover all costs, an assumed return on investment, over a predetermined life span.

LCOE has the following basic cost components:

- Fixed costs, such as initial investment (construction, environmental and social mitigation, interim replacement costs, decommissioning, etc.).
- Variable costs, such as operations and maintenance (O&M) and fuel.

The LCOE is defined for all sites and allows an easy comparison of the potential schemes profitability.

13.2.2 Global methodology

The objective is reached after processing data collected during the field mission. These data concern some geometrical information and comments on the site situation. Based on these, the global design of the scheme is defined.

Data are then processed in a dedicated software developed by SHER which allows the definition of energy production and project costs. LCOE is obtained from those results.

13.2.3 Type of schemes designed

Three types of schemes are designed:

- Run of the river schemes,
- Daily operated reservoir schemes,
- Regulation reservoir schemes.

Run of the river schemes are supposed to be operated 24 hours a day while daily operated reservoir are supposed to be operated at least 6 hours a day at full capacity. The sites topography is supposed to enable enough storage volume to run reservoir schemes (daily operated or regulation). Hence, regulation reservoirs are supposed to be operated at full capacity 24 h a day all the year long. Regulation reservoirs with daily fluctuation are not considered.

13.2.4 Hydrology

Hydrological parameters are obtained by regionalization of available hydrological measurements. A theoretical rated discharge curve is defined for each site and different return-period discharge values are extracted from this curve to feed the software.

Discharge values used for installed capacity definition are: $Q_{2.5\%}$, $Q_{30\%}$, $Q_{50\%}$, $Q_{65\%}$, $Q_{90\%}$, $Q_{95\%}$. Discharge value used for flood determination has a return period of 100 years ($Q_{100\ year}$).

Discharge available 95% of the time ($Q_{95\%}$) is called “firm discharge” and is used to determine the firm capacity and the firm energy generation.

13.2.5 Design of Works

Project implementation costs are mainly related to Civil Works. Main civil works comprised in a hydropower scheme are: the

dam, the

spillway, the desilting basin

, the intake and headrace (canal or tunnel)

, the forebay or surge tank, the

penstock and the

powerhouse.

Other elements also essential for a hydropower scheme are: electromechanical equipments, access roads and transmission line. The last two however are often considered separately as they are of public interest (roads and transmission lines are part of a country’s development plan) and might be financed by public institutions.

The following section will highlight the main assumptions used for the design of Works (Civil Works and others).

13.2.5.1 Dam

Several dam types were considered:

- Concrete gravity dam
- Masonry gravity dam (with a maximal height of 20 m)
- Rockfilled embankment dam
- Earthfilled embankment dam

To prevent seepage, embankment dams are planned with a clay core. Other techniques exist (bituminous core, concrete facing,…) but are not considered at this very preliminary stage.

Dam dimensions and type are defined after the field mission observations. If no indication is given about the dam type after the field visit, the choice is made after considering the following elements:

- The shape of the valley:
  - Wide : an embankment dam is preferred
  - Narrow : a gravity dam is preferred
- The overall geology of the dam area:

- Rocky : a gravity dam or a rockfill dam is preferred
- Loose : an earthfilled dam is preferred

When the dam is to be placed on a permeable soil (sand, cracked limestone,…) grout cut off is foreseen.

13.2.5.2 Spillway

For gravity dam, the spillway is ungated and ogee shaped. The spillway might be as large as the dam itself, in which case the dam is called a weir.

Embankment dams are planned with an ungated sill with spillway and stilling basin. Guide walls, spillway and stilling basin will be made of concrete.

Gates will only be foreseen for extremely large flood discharge. For micro-hydropower schemes, shaft spillways are not considered.

13.2.5.3 Desilting basin

Desilting basins are among the most important Works for a hydropower scheme, especially when solid transport in the river is high. The more important the sediment load, the larger the desilting basin. Desilting basins are designed with two tanks so as to keep the turbine running even when a flushing is required. They must be large and long enough to cause settling of solid particles but not too much so as to allow an easy flushing; if sediments stay too long in the desilting basin, they might start to consolidate and flushing becomes extremely complicated (it requires large amounts and velocities of water, or even cleaning by hand).

The water turbidity (expressed in NTU) gives a hint about the global solid transport. The higher the turbidity, the higher the solid transport. Although the field measurement is an isolated measurement, it can be used to define whether a desilting basin is required or not.

It is assumed that a desilting basin is required if the turbidity exceeds 100 NTU. Observations on site will allow the definition of the desilting basin size to be implemented. Similarly, if the turbidity is lower than 100 NTU but field observations indicate high amounts of sediment deposition along the river, it might be decided to design the scheme with a desilting basin. Each tank of the desilting basin is equipped with slide gates at entrance and end as well as with a flushing gate.

13.2.5.4 Intake and headrace

Intake is equipped with trash rack, trash rack cleaning device (manual or automated) and a slide gate. A gravel trap is planned in the intake vicinity to prevent gravels from entering the headrace. A flushing gate is foreseen through the dam to eliminate debris and prevent them from obstructing the intake. Stop logs slots are planned upstream of the intake to allow its dewatering.

Two headraces are considered: open canal and underground tunnel. They might be combined.

When the ground transverse slope is higher than 45°, it gets risky to pass with a canal. Hence, tunnels will be preferred each time that the mean transverse slope is higher than 45° on the whole projected canal length. In other situations, a canal might be projected. If the canal trace crosses sections with a high transverse slope (>45°), retaining structures and stabilization measures will be planned.

13.2.5.5 Forebay

A forebay tank is the junction between the headrace canal and the penstock. It might also serve as auxiliary desilting basin (and be designed as such, long and wide enough to allow sedimentation). The penstock must be submerged to such a depth that no vortex is formed. The vortex is air that enters the penstock and could cause cavitation. Hence, the forebay is composed of two sections: a settling section (for sediments) and a head pond (where the penstock mouth is located).

The forebay is equipped with slide gates at the end of the settling section to isolate it from the head pond. A flushing gate is foreseen in the settling section. A trash rack and trash rack cleaning machine are also provided before the penstock mouth, to prevent particles from entering the pipe, so as to avoid damaging the turbine.

13.2.5.6 Surge tank

The surge tank is the junction between the headrace tunnel and the penstock. It is open air and built in reinforced concrete. It avoids damages related to water hammer issue when quick opening and/or closing of the turbines.

13.2.5.7 Penstock

The penstock is the link between headrace works and the powerhouse. It is usually a high pressure pipe. It is made of steel and its diameter is defined to keep head losses to a reasonable value. Nowadays, other types of pipe might be used for penstocks (GRP, PEHD). They are not considered at this very preliminary stage.

The penstock might either be aerial, buried or both. Aerial sections are placed on slide blocks. Anchor blocks are placed at each bend in the pipe.

Given the range of hydropower schemes studies (0 to 10 MW), only one penstock is foreseen. If several turbines are foreseen, a bifurcation (or trifurcation) will distribute water to all turbines.

13.2.5.8 Powerhouse

The powerhouse will be above ground. Underground powerhouses are not studied at this stage.

The powerhouse will be equipped with stop logs downstream of the turbines, in the tailrace canal.

13.2.5.9 Electromechanical equipments

Three types of turbines are considered:

- Kaplan turbines: for low heads and high discharges
- Francis turbines: for medium to high heads and high discharges
- Pelton turbines: for high heads an low to medium discharges

In order to ensure a satisfying production curve, at least two turbines are placed in schemes exceeding 1 MW of installed capacity. It ensures redundancy of equipments, economies of scale on spare parts and the possibility of partly operating the scheme, even during maintenance.

The choice of turbine is conducted based on the next figure. It indicates the discharge and head ranges in which a particular type of turbine might be operated. Following criteria [18] were considered:

- Kaplan turbine :
  - $H < 12$ m
  - $Q > 10$ m³/s and $H < 30$ m
- Francis turbine:
  - $30 \text{ m} < H < 60$ m
  - $Q < 10$ m³/s and $H < 30$ m
  - $Q > 0.5$ m³/s and $60 \text{ m} < H < 100$ m
- Pelton turbine :
  - $H > 100$ m
  - $Q < 0.5$ m³/s and $60 \text{ m} < H < 100$ m

[18] These criteria are relevant for small hydropower schemes and must be reviewed if intended to serve for schemes with an installed capacity exceeding 10 MW.

Other types of turbines (presented in the figure above or not) might also be used and must be analyzed in further studies.

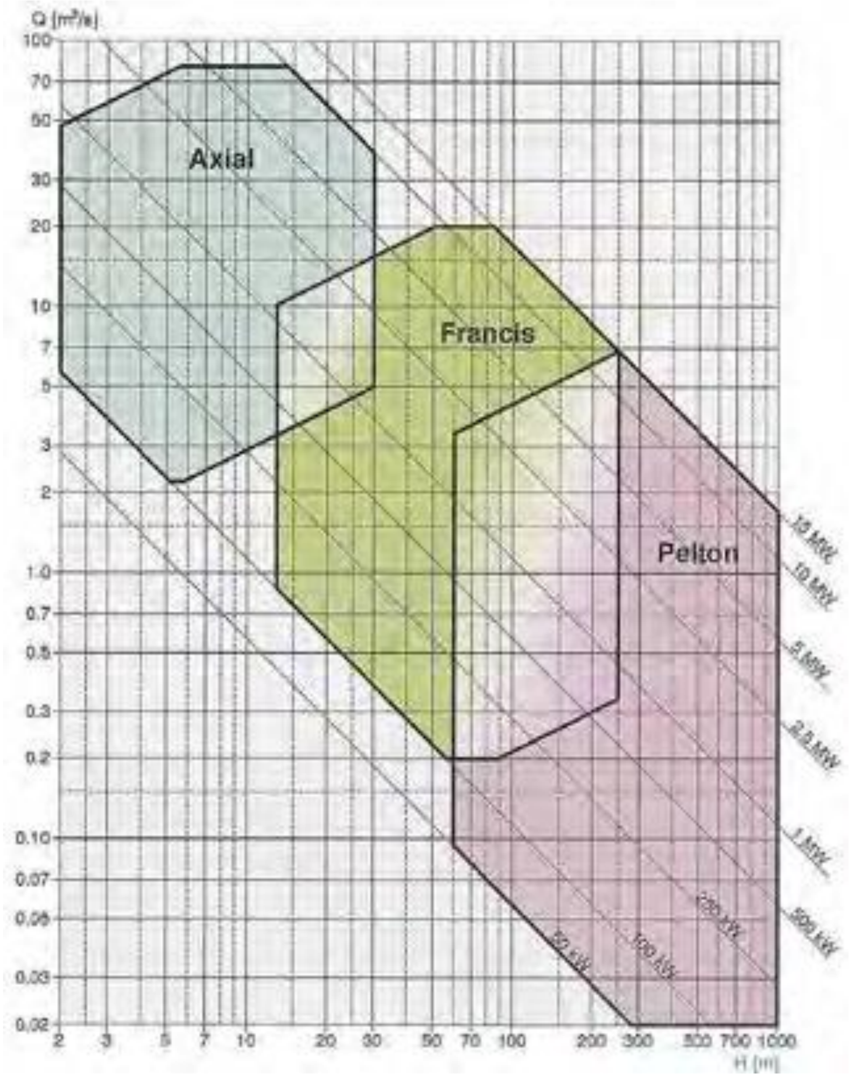


Figure 35. Turbines operating range (Layman. 2005)

13.2.5.10Access road

Access road concerns both sections of road to rehabilitate and sections of road to create to enable access to the scheme (mainly dam and powerhouse sites). Their width is taken to 5m.

In some case, they might contribute to enhance the national network and their costs might be covered by public funds.

13.2.5.11Transmission line

The main objective of transmission lines is to:

- Connect the scheme to the closest grid (national grid or mini grid) if it is supposed to be connected.
- Connect the scheme to final users (hospitals, industries, load centers, households,…) if it is supposed to be isolated.

13.2.6 Cost estimations

Two kinds of works were considerate for cost estimations:

- Dam and transport works (canal, tunnel, penstock)
- Dedicated works (desilting basin, forebay, surge chamber, powerhouse,...)

Quantities required for the first group are easily computed. An estimative bill of quantities is then easily realized, and hence costs might be estimated. Unit prices used for costs estimates are given in the table below.

For the second group however, quantities are more difficult to define, mainly because of the complexity of the works. Costs of dedicated works were then estimated after benchmarking over 50 hydropower schemes in Central Africa and Madagascar. Hence, costs of dedicated works were derived from interpolation on one of the scheme's characteristic (capacity, head, discharge,...), depending on the work treated.

Electromechanical equipments costs were also defined after regressions (cost versus capacity), defined for each type of turbine.

Additional costs were also taken into account. They consist in;

- 20% for Civil Works contingencies
- 15% for Electromechanical equipments contingencies

Engineering and supervision of works is estimated at 10% of the total cost.

13.2.7 Electrical production

Installed capacity depends on the type of scheme and on the demand. Demand is correlated to the connexion that is planned.

Indeed, if the scheme is isolated, the purpose of the hydropower plant is to produce electricity all the year around with as few variations as possible, hence the operating discharge must be close to the firm discharge of the river.

On the other hand, in a connected grid, hydropower plants are often used for peaking. Hence the operating discharge is chosen to provide as much energy as possible over a given amount of time. For example, the plant runs at full capacity during the rainy season, but only at half of its capacity during the dry season.

13.2.7.1 Operating discharge

As highlighted above, operating discharge is chosen according to the demand. Indeed, installed capacity depends mainly on operating discharge and head. Head depends on the site topography and is then a fixed parameter. Operating discharge might be chosen.

Below is a table indicating the operated discharge selected for each case.

	Isolated	Connected
Run of the river scheme	$Q_{90\%}$	$Q_{30\%}$
Daily reservoir scheme	4 $Q_{90\%}$	4 $Q_{30\%}$
Regulation reservoir scheme	$V_{Storage}/(365 \cdot 24 \cdot 3600)$	

13.2.7.2 Firm capacity, firm energy and installed capacity

Run of the river scheme

The capacity [kW] of a hydropower run of the river scheme is determined from the following equation:

$$P = \eta \rho g H Q_{operating}$$

with η the global efficiency (estimated at 85%), ρ the water density (1000 kg/m³), H the net head and $Q_{operating}$ the scheme operating discharge (m³/s).

The firm capacity [kW] is the capacity reached with the firm discharge ($Q_{95\%}$) : $P_{firm} = \eta \rho g\ H\ Q_{firm}$

The firm energy [kWh] is the amount of energy produced on one year if the scheme works at firm capacity. It is then obtained by multiplying the firm capacity by 8760h : $E_{firm} = P_{firm} \cdot 8760\ h$

Daily reservoir scheme

The capacity [kW] of a hydropower daily reservoir scheme is determined from the following equation:

$$P = \eta \rho g \left(H - \frac{H_u}{3}\right) Q_{operating}$$

with η the global efficiency (estimated at 85%), ρ the water density (1000 kg/m³), H the net head, $H_u$the width of active storage volume and $Q_{operating}$ the scheme operating discharge (m³/s).

As daily reservoir are supposed to be operated 6 hours a day, the firm discharge is $Q_{firm} = \frac{24}{6} \cdot Q_{95\%}$ The firm capacity is the power delivered by the turbines under the lowest operating conditions (when the water level is the lowest). In such case, turbines are not working at their best efficiency. This effect is taken into account by modifying the discharge according to the new head conditions $Q_{adm} = Q\sqrt{\frac{H_{new}}{H}}$. For the firm capacity, $H_{new} = H - H_u$. The firm capacity [kW] is then given by :

$$P_{firm} = \eta \rho g\ (H - H_u) Q_{firm} \sqrt{\frac{H - H_u}{H}}$$

The firm energy [kWh] is the amount of energy produced on one year under the lowest operating conditions[19]. It is given by:

[19] The head considered is the mean head because a daily reservoir is only operated part of the day, so it has time to re-fill up to maximum level during non-functioning periods.

$$E_{firm} = \eta\rho g \left(H - \frac{H_u}{3}\right) \cdot 4 \cdot Q_{firm} \cdot 6 \cdot 365 \qquad [kWh]$$

$$= \eta\rho g \left(H - \frac{H_u}{3}\right) \cdot Q_{firm} \cdot 8760 \qquad [kWh]$$

13.2.7.3 Regulation reservoir scheme

The installed capacity is calculated the same way as for daily operated reservoir. The firm capacity [kW] is calculated based on the same formula as for daily operated reservoirs:

$$P_{firm} = \eta\rho g\,(H - H_u)Q_{operating}\sqrt{\frac{H - H_u}{H}}$$

The only difference is that the firm discharge is the operating discharge. It is due to the fact that the storage volume is considered sufficient to allow a regulation all over the year. Turbines will thus be operated all the year round at the same discharge; the operating discharge.

The firm energy [kWh] is the amount of energy produced on one year under the lowest operating conditions:

$$E_{firm} = \eta\rho g\,(H - H_u) \cdot Q_{firm} \cdot 8760$$

13.2.7.4 Energy production

Run of the river schemes

The energy production [kWh] is calculated based on the "operation flow duration curve". It is defined by the union between the operating flow and the flow duration curve.

The operation flow discharge curve is then multiplied by $\eta\rho g H$, so as to obtain an "operational power duration curve". The energy production is obtained by integrating the area under this last curve.

Daily reservoir schemes

The principle is the same as for run of the river schemes, except that the flow duration curve must be multiplied by a factor corresponding to the opposite of the portion of time during which the scheme is supposed to be working:

$$Factor = \frac{24\ h}{T_{operating}}$$

As the hypothesis was taken that the plant is supposed to be working at full capacity at least 6h a day, the factor value is 4.

Regulated reservoir schemes

For regulation reservoir, the available discharge is defined based on the total storage volume. Here, we suppose that storage is enough to absorb all discharges, except discharges higher than $Q_{2.5\%}$. The total volume of water is obtained by integrating the area under the flow duration curve, from 2.5% to 100%.

The available operating discharge [m³/s] is then

$$Q_{operating} = \frac{V_{tot}}{365 \cdot 24 \cdot 3600}$$

The yearly energy output [kWh] is given by :

$$E_{annual} = \eta \rho g \left(H - \frac{H_u}{3}\right) \cdot Q_{operating} \cdot 8760$$

13.2.8 LCOE estimation

As explained earlier, the LCOE is defined based on investment costs (Capex - Capital Expenditure), Operational costs (Opex - Operational expenditure) and the annual energy production.

Capex are related to:

- Engineering and supervision of works (10% of total investment costs)
- Investment costs specific to Civil and Electromechanical Works
- Relocation and environmental mitigation measures (10% of total investment costs)

Access roads and transmission lines are not considered in the Capex.

Opex are annual costs and are related to

- Replacement costs for spare parts : 0.25% of investment costs specific to Civil and Electromechanical Works
- Operation and maintenance costs : 10 $/installed kW
- Insurance costs : 0.1% of investment costs specific to Civil and Electromechanical Works

The LCOE is defined as :

$$LCOE = \frac{NPV(Capex + Opex)}{NPV(Energy\ production)}$$

The NPV is the "Net Present Value" and is calculated as $NPV(value) = \sum_i \frac{value_i}{(1+n)^i}$ with n the "actualization rate", taken at 10%.

The levelized cost of energy might be calculated over whatever period of time, here 50 years. Decommissioning costs at the end of the economic life are taken to 10% of investment costs specific to Civil and Electromechanical Works.

13.3 BIBLIOGRAPHY

2014	SITES AYANT FAIT L'OBJET AU MOINS D'ETUDE DE RECONNAISSANCE POUVANT ETRE AMENAGES EN SITES HYDROELECTRIQUES	
2014	Centres d'exploitation de la JIRAMA	JIRAMA
2014	Sites JIRAMA	JIRAMA
2014	ETUDE SUR L'ENERGIE A MADAGASCAR	CENTRE DE RECHERCHES, D'ETUDES ET D'APPUI A L'ANALYSE ECONOMIQUE À MADAGASCAR
2014	DIAGNOSTIC INSTITUTIONNEL ET JURIDIQUE DU DOMAINE DE L'EAU ET DE L'ASSAINISSEMENT TOME III : DIAGNOSTIC ET PISTES D'ORIENTATION	TONTOLO MAHARITRA
2014	DE L'ÉLECTRICITÉ VERTE POUR UN MILLION DE RURAUX À MADAGASCAR	Fondation Énergies pour le Monde
2013?	Projet d'électrification rurale sur la côte Est de Madagascar, village d'Ambodirafia	Solidarité Entraide Madagascar
2013	Carte de localisation des sites potentiels à Madagascar	JIRAMA
2013	Etude de préfaisabilité du grand aménagement hydroélectrique pour les réseaux interconnectés à Madagascar - Phase 2 : Présaisabilité de l'aménagement d'Antetezambato	Artélia
2013	PLAN DIRECTEUR POUR L'ELECTRIFICATION RURALE DE LA REGION ALAOTRA MANGORO	ADER
2013	ENERGIES DURABLES POUR TOUS / les ménages, les collectivités et les entreprises	Amédée Mamy Tiana Randrianarisoa
2012	Aménagement hydroélectrique de Talaviana sur la rivière Manandona	Artelia
2012	APPUI A L'ADER POUR L'ETABLISSEMENT D'UN PLAN REGIONAL D'ELECTRIFICATION RURALE DANS 6 REGIONS DE MADAGASCAR Activités réalisées et activités à poursuivre	IED
2012	Diagnostic du secteur énergie à Madagascar	WWF
2012	PLAN DIRECTEUR POUR L'ELECTRIFICATION RURALE DE LA REGION ITASY	ADER
2012	BASELINE RENEWABLE ENERGY DATABASE FOR THE COMESA REGION	COMESA Secretariat
2011	Elaboration de plans directeurs pour électrification rurale Boeny, Sava, Sofia - Rapport n°4: Plans régionaux d'électrification	IED
2011	PLANS REGIONAUX D'ELECTRIFICATION RURALE - Régions BOENY, SAVA & SOFIA	IED / GTZ
2011	BASE DES DONNÉES DE RÉFÉRENCE SUR LES ÉNERGIES RENOUVELABLES POUR LA RÉGION COMESA	Secrétariat du COMESA,
2011	PROJET D'AMENAGEMENT DU SITE HYDROELECTRIQUE DE MANDIALAZA RIVIERE NANANGAINA - APS	B.E.T.C Nanala SARL Unip
2011	PROJET D'AMENAGEMENT DU SITE HYDROELECTRIQUE D'ANDRIANA - ANKARINARIVO - Rivière IMADY - APD	B.E.T.C Nanala SARL Unip
2011	PROJET D'AMENAGEMENT DU SITE HYDROELECTRIQUE DE MAHERIARA - Rivière DE MAHERIARA - APD	B.E.T.C Nanala SARL Unip
2011	PROJET D'AMENAGEMENT DU SITE HYDROELECTRIQUE DE MANDIALAZA RIVIERE NANANGAINA - APS	B.E.T.C Nanala SARL Unip
2011	PROJET D'AMENAGEMENT DU SITE HYDROELECTRIQUE DE SAHATONA - RIVIERE FANINDRONA - APD	B.E.T.C Nanala SARL Unip
2010	ETAT D'INVENTAIRE DES SITES SUSCEPTIBLES D'ALIMENTER LA PROVINCE DE FIANARANTSOA	JIRAMA
2010	ETAT D'INVENTAIRE DES SITES SUSCEPTIBLES D'ALIMENTER LA PROVINCE DE MAJUNGA	JIRAMA
2010	PROJET D'AMENAGEMENT D'UNE CENTRALE HYDROELECTRIQUE SUR LA RIVIERE DE IHAZAFOTSY-RANOHIRA-IHOROMBE - Site ANGONDONGODO - APD	B.E.T.C Nanala SARL Unip
2010	PROJET D'AMENAGEMENT D'UNE CENTRALE HYDROELECTRIQUE SUR LA RIVIERE DE MANDALO-CR MARITAMPONA-TSIROANOMANDIDY - Site MANDALOBE - APS	AIDER
2010	ETUDE A.P.D Site MANDALOBE	B.E.T.C Nanala SARL Unip
2010	PROJET D'AMENAGEMENT D'UNE CENTRALE HYDROELECTRIQUE SUR LA RIVIERE D'ANDRIAMIHAVANA-AMBINANINDRANOATSINANANA - Site ANDRIAMIHAVANA - APS	B.E.T.C Nanala SARL Unip

2010	PROJET D'AMENAGEMENT D'UNE CENTRALE HYDROELECTRIQUE SUR LA RIVIERE D'ANDRIAMBOLA-ANTOBY EST-MIARINARIVO II - Site ANTOBY EST - APS	B.E.T.C Nanala SARL Unip
2010	ETUDE HYDROLOGIQUE D'ANDRIAMIHAVANA à MAHANORO en vue d'un Aménagement hydroélectrique	?
2010	AMENAGEMENT HYDROELECTRIQUE D'ANDRIAMIHAVANA a MAHANORO	?
2010	Mission hydrologique dans la région de Sofia	Razafindrabe Simon
2010	Des potentiels naturels à exploiter	Expansion Madagascar
2010	PROGRAMME RÉGIONAL DE DÉVELOPPEMENT RURAL (PRDR) Région ITASY	Groupe de Travail pour le Développement Rural (GTDR)
2009	Preliminary study for expansion of Manandona Hydroelectric power plant in M/car	newjec inc.
2009	PROJET D'AMENAGEMENT HYDROELECTRIQUE DU SITE D'ANGODONGODO SUR LA RIVIERE D'IHAZOFOTSY - APS	B.E.T.C Nanala SARL Unip
2009	ETUDE DE PREFAISABILITE D'UN GRAND AMENAGEMENT HYDROELECTRIQUE POUR LES RESEAUX INTERCONNECTES A MADAGASCAR DANS LE CADRE DU PLAN DE RESTRUCTURATION ET DE RENOVATION DU SECTEUR DE L'ENERGIE ET DE L'ELECTRICITE - Phase 1 : COMPARATIF DES AMENAGEMENTS ET PROPOSITION DU SITE POUR LA PREFAISABILITE DE PHASE 2	SOGREAH
2009	MICP Programme National de Renforcement de la Compétitivité des Industries de Madagascar	Ministère de l'économie, du commerce et de l'industrie
2009	Erosion Rates and Sediment Sources in Madagascar Inferred from Be Analysis of Lavaka, Slope, and River Sediment	Cox et al.
2009	Madagascar Industrial Competitiveness Plan (MICP)	Ministère de l'économie, du commerce et de l'industrie
2008	Valorisation des Potentiels hydroélectriques pour l'Electrification rurale à Madagascar	ITECO Ingénieurs SA
2008	Électrification de 7 communes rurales par énergies renouvelables dans la région de ANDROY	Fondation Energies pour le Monde
2008	Tableau de bord environnemental - Région Atsinanana	Ministère de l'environnement, des forets et du tourisme
2008	PROGRAMME D'ENGAGEMENT ENVIRONNEMENTAL (PREE) AUDIT D'IMPACT ENVIRONNEMENTAL ET SOCIAL DU P R O J E T „RIANAN'I LEMANA" OU LEMENA, POUR L'ELECTRIFICATION D'UNE ZONE RURALE A PARTIR D'UNE RESSOURCE HYDRO-ELECTRIQUE REGION DU VAKINANKARATRA	ADER
2008	DIAGNOSTICS DES INFRASTRUCTURES NATIONALES EN AFRIQUE	WB SSATP
2007	Etat d'inventaire des sites susceptibles d'alimenter la région de Tuléar	ORE
2007	Forest Management in Madagascar Logging within Marojejy National Park Mining & Conservation – Contested Spatial Coincidence Velondriake Community Project	Madagascar Consrevation and Development
2006	Potentiel de développement de Micro/mini centrales hydroélectriques (max 200 KW)-Etude régionale, district d'Andapa	INTEGRATION Environnement & Energie
2006	Country energy information MADAGASCAR	Developing Renewables
2006	PNAT Politique Nationale de l'aménagement du territoire	UNDP Madagascar
2006	LES ENERGIES RENOUVELABLES A MADAGASCAR	MINISTERE DE L'ENERGIE ET DES MINES
2006	PROGRAMME DE DEVELOPPEMENT REGIONAL POUR LA REGION VAKINANKARATRA	DSRP
2006	PROGRAMME RÉGIONAL DE DÉVELOPPEMENT RURAL (PRDR) Région ATSINANANA	Groupe de Travail pour le Développement Rural (GTDR)
2006	POWER/WATER SECTORS RECOVERY AND RESTRUCTURING PROJECT	WB
2005	Étude énergétique des sites du Plan d'expansion au moindre coût	Hydro Québec
2005	Plan d'expansion au moindre coûts des réseaux Plan de développement du parc de production	Hydro Québec International

2003	ETUDE D'AVANT PROJET SOMMAIRE DE L'AMENAGEMENT HYDROELECTRIQUE DU SITE DE BEANDRAREZONA SUR LA RIVIERE BEANDRAREZONA	?
2003	MONOGRAPHIE DE LA REGION DE SOFIA	Ministère de l'agriculture, de l'élevage et de la peche
2002	Etat d'inventaire des sites susceptibles d'alimenter la région de Toamasina	JIRAMA
2002	Etat d'inventaire des sites susceptibles d'alimenter le réseau interconnecté TANA et la province d'Antananarivo	JIRAMA
2001	Aménagement hydroélectrique d'Antafofo	EDF
2001	Aménagement hydroélectrique d'Antetezambato	EDF
2001	Aménagement hydroélectrique de Lohavanana	EDF
2001	Aménagement hydroélectrique de Volobe	EDF
2001	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R3-0 ETUDE PRELIMINAIRE DES CANDIDATS HYDROELECTRIQUES	EDF Sogreah
2001	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R3-1 PEMC du Parc de Production	EDF Sogreah
2001	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R3-2A ETUDE DU RESEAU CIBLE 2015	EDF Sogreah
2001	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R3-2B PEMC DU RESEAU	EDF Sogreah
2001	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R4 PLAN D'INVESTISSEMENT A COURT TERME	EDF Sogreah
2001	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R5 ELABORATION DES COUTS DE FOURNITURES	EDF Sogreah
2001	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R6 SYNTHESE GENERALE	EDF Sogreah
2000	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R1 ETUDE DU MARCHE	EDF Sogreah
2000	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R2-1 IDENTIFICATION DES CANDIDATS HYDRAULIQUES	EDF Sogreah
2000	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R2-2 IDENTIFICATION DES CANDIDATS THERMIQUES	EDF Sogreah
2000	Mini centrale hydroélectrique de la "Lokoho aval" à Andapa - étude de faisabilité	Tractebel Engineering
2000	La dynamique du secteur privé à Madagascar	AFD
1999	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT RM Mesures d'urgence	EDF Sogreah
1999	PLAN D'EXPANSION AU MOINDRE COUT DU RESEAU INTERCONNECTE D'ANTANANARIVO RAPPORT R0 DONNEES D'ENTREES DU PROJET	EDF Sogreah
1998	Données hydrologiques de la rivière Vohitra	JIRAMA
1993	Inventaire de la ressource en eau et mini-centrales	ORSTOM

1993	Fleuves et rivières de Madagascar	ORSTOM Pierre Chaperon, Joël Danloux, Luc Ferry
1992	Actes des Journées de l'Eau Gestion des ressources en eau	ANDRIAMBOAVONJY et al.
1991	Etude des crues: Les données d'observations et estimation des débits maximums	ORSTOM
1989	Etude d'inventaire de sites pour aménagements hydroélectriques - Recensement des sites	Someah
1988	Mini et microcentrales hydroélectrique à Madagascar TOME 2	COYNE et BELLIER
1988	Etudes de mini et micro centrales hydroélectriques à Madagascar	Coyne&Bellier
1986	Aménagements connexes à la construction du barrage réservoir d'Ankarahotra	APD - Note hydrologique
1986	Réhabilitation de l'aménagement Hydroélectrique du Grand Volobe	Coyne&Bellier
1984	Etude d'hydrologie à usage agricole	ORSTOM
1982	Etude hydrologique de la Vohitra supérieure : Ankorahotra	Direction de la Météorologie
1981	Aménagement Hydroélectrique du Grand Volobe	Etude Préliminaire - Annexes
1981	Plan d'Equipement de la Zone Interconnectée Volume 1 - Tome 1 - Eléments de base	Coyne&Bellier
1981	Plan d'Equipement de la Zone Interconnectée - Vol 2 Aménagement hydroélectrique de Sahofika sur l'Onive	Coyne&Bellier
1981	Plan d'Equipement de la Zone Interconnectée - Vol 3 Aménagement hydroélectrique de Mahavola sur l'Ikopa	Coyne&Bellier
1981	Etude d'hydrologie à usage agricole Rapport d'installation et premières mesures	ORSTOM
1980	Barrage réservoir d'Ankorahotra - Rapport de factibilité	DAFECO
1978	Cyclones intéressant Madagascar (puis Saison cyclonique)	Direction de la Météorologie
1976	Etudes hydrologiques dans l'Ankaizina 1974-1976	ORSTOM
1972	Aménagement de la Vohitra - Chute d'Andekaleka	DAFECO
1972	ANNUAIRE HYDROLOGIQUE DE MADAGASCAR ANNEE 1968 -1969	ORSTOM
1971	Annuaires hydrologiques	ORSTOM
1971	BIOLOGIE COMPARÉE DE TILAPIA RENDALLI (BOULENGER) (Pisc. Cichl.) AU LAC ITASY ET AU LAC DE MANTASOA	ORSTOM, J. Moreau
1971	Propriété des Andosols de l'Itasy et de l'Ankaratra	ORSTOM
1970	Annuaire hydrologique de Madagascar	ORSTOM - Ministère des Mines et de l'Industrie de Madagascar
1969	Annales de Géologie Contribution à l'étude des surfaces d'aplanissement sur les Hautes Terres centrales malgaches	ORSTOM (Bourgeat et Petit)
1969	Application de la méthode de dilution (Jaugeages chimiques) sur les rivières de Madagascar	ORSTOM
1968	CARACTÈRES DES SURFACES D'APLANISSEMENT SUR LES HAUTES TERRES MALGACHES	ORSTOM (Bourgeat et Petit)
1967	Données hydrologiques de base	ORSTOM
1966	Données hydrologiques préliminaires pour 3 aménagements de Madagascar (Rogez/VOHITRA, Ranomafana/IKOPA, Volobe/Ivondro)	ORSTOM
1965	Etudes hydrologiques et programme de la décennie	UNESCO
1965	Bassins versants expérimentaux de l'Ankaboka	ORSTOM
1965	Etude des étiages des rivières Onilahy, Linta, Ménarandra et Manambovo en 1963 et 1964	ORSTOM
1965	NOTE HYDROLOGIQUE sur les RIVIERES des HAUTS-PLATEAUX de MADAGASCAR	ORSTOM
1965	L'Efaho à Fanjahira - Note Hydrologique	ORSTOM

1964	Monographie Hydrologique de l'Ikopa et de la Betsiboka	ORSTOM
1964	TENDANCES ACTUELLES DES i' ETUDES HYDROLOGIQUES DE LA RECHERCHE SCIENTIFIQUE ET TECHNIQUE OUTRE-MER	ORSTOM
1962	Annales de Géographie	René Battistini
	Le massif volcanique de l'Itasy (Madagascar)	
1959	Annuaire hydrologique de la France d’Outre-Mer	ORSTOM
1954	Mémoires de l'insitut Scientifique de Madagascar	Riquier
	ETUDE SUR LES "LAVAKA"	
?	Aménagement hydroélectrique au site d'Ampandriambazaha sur le Mahavavy nord	Hydelec SA
?	Inventaire des sites	JIRAMA
?	ASSESSING THE IMPACTS OF CLIMATE CHANGE ON MADAGASCAR’S BIODIVERSITY AND LIVELIHOODS	Conservation International & WWF
?	Chute de l'Onibe à Andriamamovoka	EDF
?	Etude d'inventaire de sites pour aménagements hydroélectriques - Etude de reconnaissance de sites - rapport définitif	Someah
?	Listing de sites potentiels (hydro)	ADER
?	Sites hydroélectriques potentiels ORE	ORE