



Hydropower solutions for developing and emerging countries

D3.3 Report on HYPOSO Map Establishment

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Introduction

HYPOSO is a multi-approach project to tackle several objectives; identification and mapping of the European hydropower industry, hydropower stakeholders in the HYPOSO target countries, education of new hydropower experts through capacity-building activities and bringing together relevant actors from the EU hydropower sector with stakeholders in the target countries. Interaction with stakeholders is, therefore, an integral part of the activities, like workshops, capacity building activities and interviews with national/local stakeholders are envisaged in all target countries which are outside the European Union, namely workshops in Bolivia, Colombia and Ecuador in Latin America, and Cameroon and Uganda in Africa. Additionally, capacity building courses will be carried out in Bolivia and Ecuador, and in Cameroon and Uganda.

Executive Summary

This deliverable D3.3 is an outcome of Task 3.3 “**Mapping of potential hydropower hotspots in the target countries**” of the WP3 “**Framework analysis and research needs**” (Task leader: VDU; Partners: IHE Delft, SF, TS, CELAPEH, HPAU, SHW, EPN, UMSS).

The main outcome of task 3.3 is the development of a GIS tool (the HYPOSO Map), a geospatial representation of potential hydropower locations including relevant context features in the five target countries. and freely accessible through an interactive web-based platform. The HYPOSO Map Viewer will be completed at the end of this project.

The present report provides the methodology of the establishment of the HYPOSO Map Viewer and is structured of the following parts:

- Data collection in the target countries for the assessment of hydropower potential and development of the database;
- Assessment of climate change impact on hydropower resource;
- GIS database development for assessment of hydropower resources;
- HYPOSO Map Viewer (programming).

1. Data collection in the target countries for the assessment of hydropower potential and development of database

This chapter describes the gathering of the underlying data in the target countries. The data collected will be supplied, processed, and entered into the database of the HYPOSO Map Viewer Module.

Country codes assigned:

- Bolivia (BO);
- Cameroon (CM);
- Colombia (CO);
- Ecuador (EC);
- Uganda (UG).

1.1. Classification of hydropower schemes

The following hydropower (HP) definition is defined (Table 1).

Table 1. Hydropower definition according to power capacity

No	Short name	Full name	Hydropower size P
1.	M-m	Micro and Mini Hydro	<500 kW to 1MW
2.	S	Small Hydro	>1 to 10 MW
3.	I	Intermediate Hydro	>10 to 50 MW
4.	M	Medium Hydro	>50 to 100 MW
5.	L	Large Hydro	>100 MW
6.	PSP	Pump storage hydro (pure or mixed)	-

Hydropower plant (HPP) scheme types are shown in Figure 1:

- Run-of-river (RoR) plant without Diversion;
- RoR with Diversion - RoR-D;
- Storage (reservoir) without Diversion - S;
- Storage (reservoir) with Diversion - S-D.

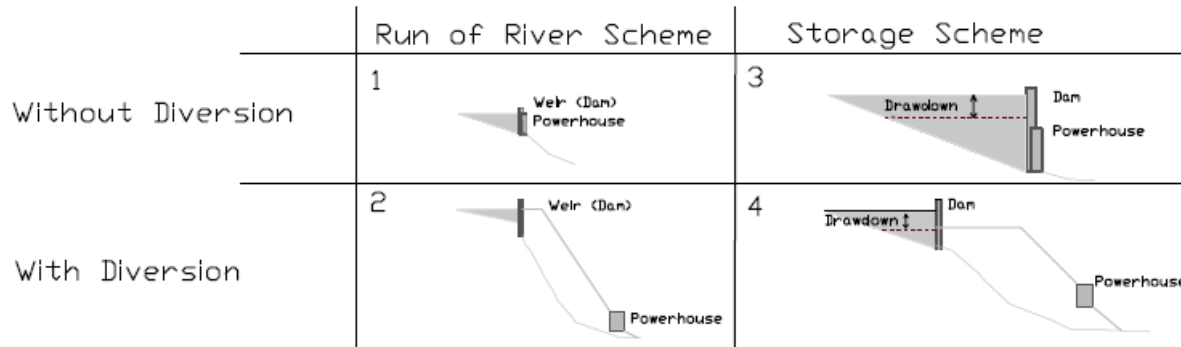


Figure 1. Hydropower schemes

Run-of-river hydropower (RoR): a facility that channels flowing water from a river through a canal or penstock to spin a turbine. Typically, a run-of-river project will have little or no storage facility. Run-of-river provides a continuous supply of electricity (baseload), with some flexibility of operation for daily fluctuations in demand through water flow that is regulated by the facility.

Storage hydropower (S): typically, a large system that uses a dam to store water in a reservoir. Electricity is produced by releasing water from the reservoir through a turbine, which activates a generator. Storage hydropower provides base load as well as the ability to be shut down and started up at short notice according to the demands of the system (peak load). It can offer enough storage capacity to operate independently of the hydrological inflow for many weeks or even months.

Diversion and canal developments (D). The water is diverted from the natural channel into a canal or a long penstock, thus changing the flow of the water in the stream for a considerable distance.

Weir (W) is a barrier constructed across a river to raise the water level on the upstream side. The water is raised to the required height and the water then flows over the weir. In a weir, the water overflows the weir, but in a dam, the water overflows through a special place called a spillway. Weirs have traditionally been used to create mill ponds.

Barrage is a weir that has adjustable gates installed over top of it, to allow different water surface heights at different times.

The dam is a high barrier constructed across a river valley to form a deep storage reservoir. The surplus water is not allowed to flow over the dam, but it flows through the spillways provided at some level built into the dam. The crest of an overflow spillway on a large dam is often called a weir.

Regarding the nature of a site, the physical difference between a dam and a weir or other instream structure will not be considered in the HYPOSO Map.

1.2. Hydrology

Hydrology is crucial in determining hydro scheme feasibility or assessing hydropower resources. To calculate hydropower potential using GIS tools (see Section 3.3.4), the streamflow is needed.

Task: To compile the gauging station streamflow database to derive mean annual flow and specific discharge ($l/s \cdot km^2$ or $m^3/s \cdot km^2$). The flow distribution over seasons or months is required as well.

Data sources: Hydrologic yearbooks, archives of national hydrological/hydrometric services, hydrological publications. Alternatively, the specific discharge maps (in form of isolines or georeferenced) will be most appreciated.

The classic way to determine mean annual flow and its distribution over seasons would be to use streamflow gauging data. The first findings in the target countries revealed that gauged daily flow data collection would be a very difficult exercise due to uneasy access to the data basis, restricted project budget, and lack of human resources. Moreover, in some countries the network of gauging stations is not sufficiently dense, the data series is not long enough to derive reliable flow metrics. Therefore, it was decided to use already available mean annual flow data information without any updating.

Firstly, the list of streamflow gauging stations has to be drawn up (Table 2).

Table 2. List of streamflow/river gauging stations

Gauging station number	Station name	River name (English and local)	Drainage area, km^2	Coordinates, decimal degree		Mean annual flow, m^3/s , specific discharge, $l/s \cdot km^2$ or normal annual runoff depth, mm (any alternative)
				Latitude	Longitude	

The river gauging network is to be exhibited in the HYPOSO Map (only the station locations and names).

The best and most practical way to characterize the mean annual river flow is to have a specific discharge ($l/s \cdot km^2$ or $m^3/s \cdot km^2$). Alternatively, the normal annual runoff depth (in mm) can be used. Then, the flow distribution (monthly step) within the seasons will be needed to be calculated.

In the common hydrologic practice, the specific discharge values are often mapped, represented as isolines (Figure 2), or in colour palette (Figure 3).

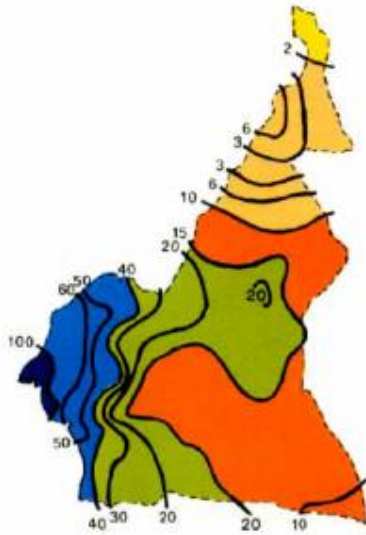


Figure 2. Specific discharge isolines (l/s-km²) of Cameroonian streamflow inventory

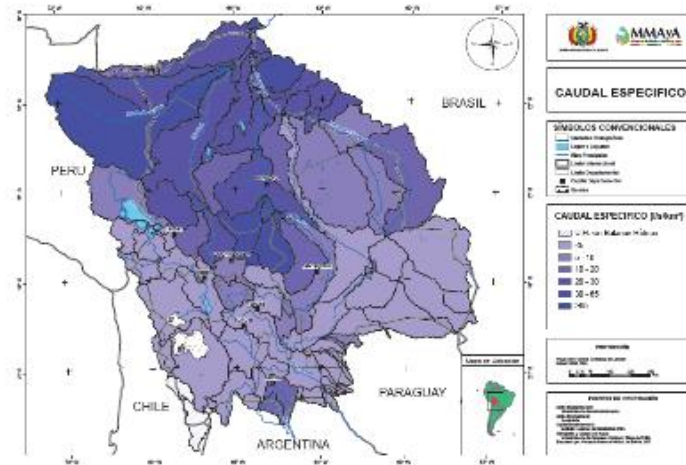


Figure 3. Specific discharge of Bolivian streamflow inventory

The flow distribution (or river regime) over seasons or months is required as well. The seasonality in discharge describes how the long-term mean annual flow is distributed between the twelve months of the year. The best way is to provide their typical graphs for river catchments or hydrologic regions (Figure 4). These seasonal patterns can be given in the normalised form (dimensionless).

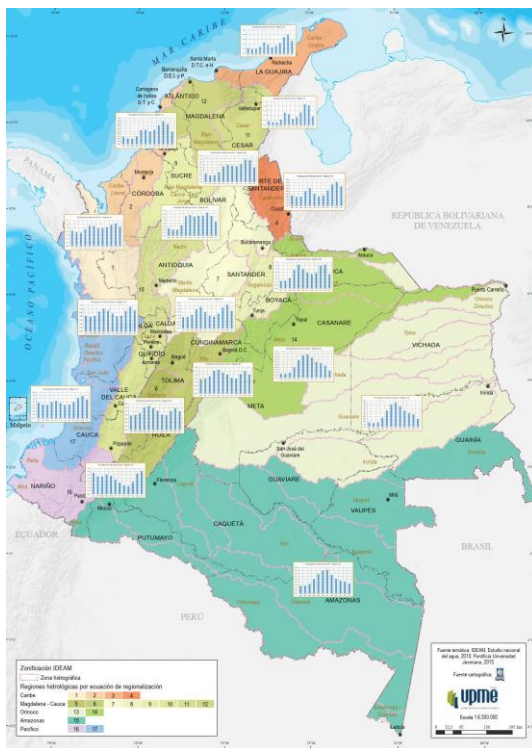


Figure 4. Monthly flow distribution (river regimes) in hydrologic regions of Colombian streamflow inventory

There are some cautions to be considered:

- Reservoir operation at large dams and floodplain impacts modify the natural river regime;
- In many basins, the headwater regions show a different seasonality in the flow than downstream regions;
- Flow routing along with the river network (from the upstream headwater to the downstream river reaches);
- Reservoir and floodplain impacts.

In this study, these factors affecting the river flow distribution over time will not be taken into consideration. Much more effort is needed to account for them.

1.3. Operational Hydropower plants (HPP) and HPP under construction

Specific task: to compile the inventory of existing hydropower plants (with key features) in the target countries to create a GIS layer to HYPOSO Map.

Data sources: National inventories of operational HPPs in the target countries Available GIS shapefiles (attributes of power plants) would be a great supplement for this exercise. In some countries this data is georeferenced (GIS Shapefiles). E. g., in Uganda: Energy Sector GIS Working Group Uganda¹. The so-called Shapefiles “Generation projects” are available in Ecuador.

To facilitate the implementation of this task simple questionnaire built on the previous experience and designated for the project partners and experts in the target countries were drawn up (Table 3).

Table 3. List of operational hydropower plants

No	Country Code	HPP name	River name		Address	WGS84 Coordinates				Installed capacity MW	Discharge m ³ /s	Head m	HPP type	Status		Ownership / Developer	Connection (on grid or off-grid)	Reservoir area, km ² if relevant		Comments	Data Operator	
			English	Local		Dam or intake		Powerhouse (if relevant)						Commissioning year	Under construction or expected year of commissioning			Area, km ²	Storage, hm ³			
			Latitude	Longitude		Latitude	Longitude															

It is structured as follows:

- Country code;
- HPP name;
- River name (English and local);
- Address;

¹ Energy Sector GIS Working Group Uganda: <http://www.energy-gis.ug/gis-data>

- WGS84 coordinates (latitude and longitude, decimal degree, to at least 4 to 6 decimal places, e.g.-78.668675,-1.607612). How to define coordinates is explained in section 3.3.1.:
 - Dam or intake;
 - Powerhouse (if it is far away, say at least 1 to 2 km).
- Discharge, m³/s, Head, m and Installed Capacity, MW;
- HPP type (RoR, RoR-D; S, S-D);
- Commissioning year;
- Under construction (expected year of completion);
- Ownership or Developer;
- Grid connection (on Central grid or off-grid or connected to an isolated-grid);
- Reservoir area, km², and storage hm³ (if relevant);
- Comments;
- Data operator (name, email, if relevant).

All this information in form of attributes will be displayed in the HYPOSO Map Viewer (layer showing existing hydropower plants) (see Figure 25).

1.4. Hydropower potential sites

The main aim of this task is to collect information on 2,425+ hydropower sites (Bolivia - 475, Cameroon - 500; Colombia - 500; Ecuador - 475; Uganda - 475). This data consisting of the list of potential sites with accompanied their key features will be entered into the HYPOSO Map. All available data will be included and made easily accessible in the database.

This hydropower resource assessment is not intended to provide economic feasibility level studies at each site. Only the potential hydropower capacity will be provided. It will be the users' sole responsibility to determine whether, if any site is worthy of further development.

These potential sites consist of:

- new locations and
- existing infrastructure (non-powered dams, weirs, water mills, and other structures) including obsolete plants.

To facilitate the implementation of this task, a simple questionnaire (Excel-based) built on the previous experience and designated for the project partners and experts in the target countries was drawn up (Table 4 and Table 5).

Table 4. Potential new sites identified from prior hydropower assessments or based on visual inspection from Google Maps

1. Potential new sites identified from prior hydropower assessments or based on visual inspection from Google Maps																					
No	Country	Site Name	River name		Address	Coordinates (WGS84)				Based on prior hydropower assessments, if available				HPP type	Site readiness for development	Environmental Sensitivity	Grid Connection, km	Others	Data	Data Operator	
			English	Local		Dam or Intake	Powerhouse (if relevant)	Flow m ³ /s	Head, m	Capacity, MW	Expected flow, m ³ /s	Expected head, m	Installed power (P1 to P4), H, MW								Available power (P1 to P4), if previous data is not available
			Latitude	Longitude																	

Table 5. Potential sites of existing infrastructure identified from prior hydropower assessments or based on visual inspection from Google Maps

2. Potential sites of existing infrastructure identified from prior hydropower assessments or based on visual inspection from Google Maps																					
No	Country code	Site Name	River name	Address	WGS84 Coordinates		Existing infrastructure (non-powered dams, weirs, water mills and other structures), obsolete plants				Historical use	Expected scheme type	Environmental Sensitivity	Grid Connection, km	Physical conditions of dam, powerhouse, if relevant	Others	Data Operator				
					English	Local	Flow Q, m ³ /s	Head H, m	Capacity P, MW	Power available, if previous data is not available (P1 to P4)											
					Latitude	Longitude															

The following categories of potential sites can be distinguished:

- Planned HPPs that have not been yet developed or are still under planning level;
- New sites;
- Non-powered weirs, dams, historic water mills (existing water infrastructure);
- Obsolete HP plants (existing water infrastructure).

To collect the information of some 2,500 potential hydropower sites two different methodologies can be proposed:

- Identification and utilisation of exiting databases, inventories, or registers of national authorities or material available in the literature. In other words, these potential sites will be identified from prior hydropower assessments and adjusted to the current situation.

The work will rely on the examination of previous studies conducted in the target countries as such Master Plans, Feasibility/Prefeasibility, and other kinds of studies². It should be noticed that when

² E. g., Project for Master Plan Study on Hydropower Development in the Republic of Uganda (JICA, 2011); Hydropower Assessment of Bolivia—A Multisource Satellite Data and Hydrologic Modelling Approach. USGS, 2016. Open-File Report.

using historical records or prior hydropower studies precise data points and locations are not always easily identifiable.

This task in some manner overlaps with the selection of 10 high potential sites (they must be included in the list).

Along with these mentioned data sources, available GIS Shapefiles can be also examined. For instance, the above mentioned available shapefiles in Uganda and Ecuador.

- Identification of potential sites using Google Maps, Google Earth, Google Street View or satellite images of sufficient resolution and good visibility. This „Flyover“ will cover new sites and existing infrastructure (non-powered dams and obsolete HP plants). The operator of this exercise must be aware in advance of the preliminary location of such sites from other available sources. The purpose is to provide a realistic but not necessarily comprehensive list of small hydro sites.

It is obvious, that many aspects of this effort will involve errors and inaccuracies. When using historical records, precise data points and locations using Google Maps and satellite images of the earth are not always easily identifiable. Moreover, accurate hydropower resource assessment requires two critical variables - hydraulic head and design flow. These, without conducting field studies, cannot be automatically obtained.

Where satellite or Maps views resolution is adequate, and groundcover is not too obscuring one can 'Fly' up or down a river and tributaries by clicking and dragging the mouse to pan through the map. Once a potential site is being identified, one can zoom in to validate and add the site with a single click.

Where possible the small human figure (pegman) can be selected from the Google Maps slider bar and be dropped onto a nearby road. This will allow identifying additional features, validate the site, and estimate the power capacity classification (Street View --functions via standard Google Maps interface).

This assessment to be conducted can claim to be a “first pre-reconnaissance level”. It is clear, that site visiting cannot be implemented on the ground due to prohibitive financial and human resources to be allocated for this project. But if any opportunity to do so was presented, it would be a great added value to this assessment. The analysis is not intended to consider the economic feasibility of developing each site.

It is structured as follows:

- Country code;
- River name (English and local);
- Address;

- WGS84 coordinates (latitude and longitude, decimal degree, to at least 4 to 6 decimal places, e.g. -78.668675, -1.607612):
 - Dam or intake;
 - Powerhouse (if it is far away, say at least 1 to 2 km).
- Expected flow, m³/s, expected head, m, capacity, MW, or Power availability (P1 to P4);
- Expected scheme type (RoR, RoR-D; S, S-D);
- Historical use (M, W, O, U);
- Site readiness for development;
- Environmental Sensitivity;
- Grid connection (distance, km);
- Physical conditions of the dam, powerhouse, if relevant (A, M, D);
- Comments;
- Data operator (name and email, if relevant).

Mean Flow Q, m³/s, **Head** H, m, and **Capacity** P, MW, typically used only if these estimates have been made by other authoritative sources.

Expected potential capacity can be calculated by the operator, providing that the mean flow and head values are available:

$$P = 0.008 * Q * H, MW$$

The approximate head can be estimated with the tool provided by Google Earth (View a path's elevation profile). Mean flow can be evaluated from the normal annual runoff maps providing contributing drainage basin area is known. The computed potential hydropower capacity is an estimate based on non-directly measured flow and head and hence does not represent the actual numbers for engineering design.

If the above assessment is not possible, **the power availability** can be determined based on an expert evaluation (or rule of thumb):

- **P1** is estimated to be up to 0.5 MW;
- **P2** is estimated to be between 0.51 MW and 1 MW;
- **P3** is estimated to be between 1 and 10 MW;
- **P4** is estimated to be above 10 MW.

A site readiness for development (or under planning):

- short term (1 to 3 years)
- medium-term (4 to 9 years)
- long term (+ 10 years)
- Not known

Environmental Sensitivity. National parks, protected areas, forests, etc. (to be complemented by GIS tools);

Grid connection (distance, km).

Historical Use, the following definitions are used:

- **M** indicates a watermill, sawmill, and any attendant dam or weir that may have been used for mechanical power generation;
- **W** is indicative of a weir, dam, barrage, or other lateral structure or river obstruction that was used for purposes other than power generation;
- is indicative of an obsolete hydro plant (historical electrical power stations in need of restoration);
- **U** is indicative of unknown or other. This classification is to be used when it is not clear that a site is **M** or **W** or **O** or if the site is degraded to a condition that makes identification impossible. This classification may also include historical electrical power stations in need of restoration.

Physical conditions of existing infrastructure, if relevant:

- **A** indicates an advanced condition. The site is a substantially complete weir or another river or stream blockage;
- **D** indicates a degraded condition. The stream or river is free-flowing with few or no visible remnants. Historical records or other indicators suggest the site existed;
- **M** indicates a moderate condition. Some visible remnants remain. These remnants may be a ruin or other historical building. River obstructions may exist that need for restoration or re-creation to bring the site back into service.

Comments or Remarks. Optional data that might help in facilitating a beneficial harnessing a site. Suggestions include but are not limited to:

- data source, e.g. data registers, authority source, other web sites;
- comments about the quality of information, or other points that may be of concern to public, agencies, or site developers.

Data Operator: name of the data partner who will be assigned credit against their data point quota as agreed by the EU contracts.

All this information in form of attributes will be displayed in the HYPOSO Map Viewer (layer showing existing hydropower plants).

Responsibility for Data Accuracy: Every partner is responsible for its data quality including the accuracy, completeness, validity, and verification of their data points supplied or entered. No in-depth data verification will be done, this is outside the scope of this study.

2. Assessment of climate change impact on hydropower resource

2.1. Objective

Hydropower plants are characterized by heavy investments with a long life lasting up several decades, therefore regional hydropower development needs to be based on long-term strategic planning. The anticipation of long-term trends in climate change, and the related impact on hydropower potential, can, therefore, be essential for thorough planning of hydropower development. In other words, to derive climate change impacts on the potential capacity in the river basins in the context of changing hydrology.

The objective of the climate change scenario analyses is therefore to assess possible future climate trends and their impact on future river flow and hydropower potential.

The assessment is to be based on climate projections for the 21st century from Regional Climate Models (RCMs) of the CORDEX Africa and South America, representing the most detailed climate simulations currently available for these continents

2.2. Data sources

There are plenty of studies to assess the sensitivity of hydropower generation to uncertain water resource availability driven by future climate change in Ecuador (Carvajal et al, 2017), climate impacts on hydropower in Colombia (Arango-Aramburo et al, 2019), climate risk assessment for hydropower generation in Cameroon (Grijnsen, 2014), proposal to integrate climate change in hydropower development in East Africa (Jjunju, 2016). Water balance projections for medium- and long-term periods (2020-2050 and 2050-2090) are available under MPI-ESM-MR scenarios for main river basins in Bolivia.

Several publications are dealing with regional climate change modelling in South America (Solman, 2013) and Africa (Giorgi et al., 2009). Climate change projections are available for Africa and South America based on Global Climate Models (GCMs) and Regional Climate Models (RCMs). RCMs provide climate simulations in higher spatial resolution than GCMs, with better representation of regional climate peculiarities. Application of RCM data in climate change impact studies therefore yields more precise regional analyses.

For the climate change scenario analyses RCM data of the Coordinated Regional Downscaling Experiment in Africa and South America (CORDEX) is intended to be used, which were the result of

the most recent research with RCMs for these continents. These data were published in 2015 and this study is one of the first to use CORDEX Africa (Region 5) and South America (Region 1) data.

2.3. Methodology

Precipitation data from the available RCM runs need to be processed for the defined sub-catchments derived for a particular layer (this exercise is still ongoing). Time-series of annual precipitation have to be calculated from the gridded monthly RCM data for each sub-catchment. The historic annual time-series data will be smoothed to enable a more robust calculation of long-term trends. Climate change signals in each RCM run are to be computed between the long-term mean values for the reference period 1998-2014 and two future periods (2026-2045, 2046-2065). Based on their results, the change in mean annual runoff and hydropower potential can be derived.

2.4. Expected outcomes

Near future (period 2026 to 2045) and far future (period 2046 to 2065) scenarios will be considered. The baseline or reference period for such comparison will be the period 2000 to 2015.

After climate change study the following information will be exhibited in HYPOSO Web Map:

- Change in future mean annual runoff or specific discharge in %;
- Change in future hydropower potential in %.

3. GIS database development for assessment of hydropower resources

3.1. Objective

The main purpose of this study is to provide a complete and comprehensive assessment of the hydro resources and computation of hydropower potential in the target countries. To achieve this, the river network and sub-catchment GIS layers shall be created with relevant attributes showing the hydropower potential. The objective of the data layers is to provide a regional overview and to enable the identification of sub-catchments and rivers with attractive theoretical hydropower potential along with the potential location of real sites.

It needs to be noted, that apart from the operational hydropower plants and potential sites (new sites, not powered dams, weirs, and obsolete plants) layers identified by expert evaluations, all of

the data published in the GIS layers are based on modelling results. This provides the basis for follow-up studies to proceed with pre- or feasibility studies.

3.2. Data sources

Spatial data for GIS data layers consist of three categories:

- Observed data (collected by partners of target countries);
- Existing open-source data (free available);
- Derived data using observed and existing data.

The main data sources used for deriving the theoretical hydropower potential in this study are:

- Digital elevation models and derived products;
- River specific discharge data based on observed river flow data.

The other context features needed to perform preliminary feasibility assessments are the following:

- Climate zones;
- Mean annual precipitation;
- Protected areas, etc.

3.3. Methodology

3.3.1. Online data collection

Some GIS layers are created by collecting data manually e.g. potential hydropower sites or using existing tabulated data (see Section 1.4). Tabulated data must have a coordinate of the site (Table 6).

Table 6. A hypothetical site in Ecuador

Country	River name	Nearest settlement or town	Site number	Coordinates	
				Latitude	Longitude
Ecuador	Rio Guano	Guano	01	-78.668675	-1.607612

The Google Maps coordinates (or sometimes called GPS coordinates) are intended to be used for the HYPOSO Map and other project outcomes.

Before the coordinates of potential hydropower site are determined, the approximate location of the object must be known to find the location on the screen of Google Maps. Any site location must be represented by its geographical coordinates using the World Geodetic System - WGS 84³.

Coordinates of each site shall be expressed as geographic coordinates to the best resolution (maximum zoom in) provided by Google Maps, for example, 43.262464,-2.050720. The minimum resolution needed for data entry is five (5) decimal places giving an approximation of the location sufficient to be able to identify it by others.

There are many ways to show a place on a map. For example, the latitude and longitude of the St. Lawrence University in Kampala can be expressed as:

- Degrees, minutes and seconds 0° 18' 6.62'', 32° 33' 41.80''
- Degrees and decimal minutes 0° 18.1103', 32° 33.6966'
- Decimal degrees (DD) 0.301838, 32.561601

Decimal degrees are the most convenient to be used for finding the coordinates of an address or a place.

Use periods as decimals, not commas. Incorrect: 41,40338, 2,17403. Correct: 41.40338, 2.17403.

How to Get Coordinates in Google Maps?

Find the object for which you need to determine coordinates. It can be done by typing the address, the name of the settlement or the name of the river in the search box (Figure 5). If you do not know any of them, then you manually find the location of the object. Try using the example with St. Lawrence University in Kampala. Enter the name of the university and city name in the search box. You will get a list of schools with the same name. Click the mouse on the right one.

³ The parameters of that system: GCS_WGS_1984 WKID: 4326 Authority: PSG Angular Unit: Degree (0.0174532925199433) Prime Meridian: Greenwich (0.0) Datum: WGS_1984 Spheroid: WGS_1984 Semimajor Axis: 6378137.0 Semiminor Axis: 356752.314245179 Inverse Flattening: 298.257223563

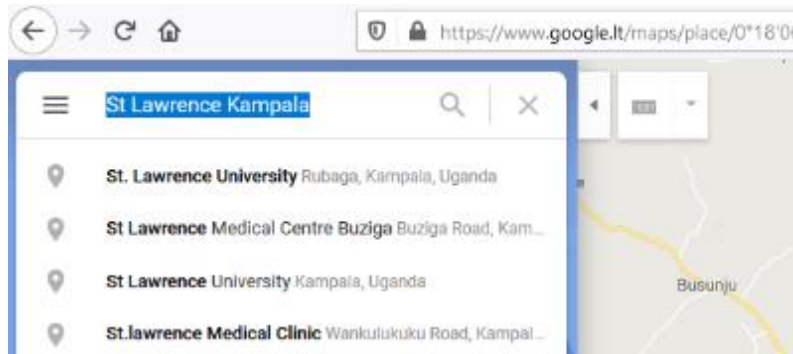


Figure 5. Search tool

You will be navigated to the right place and see the red marker on the map (Figure 6). Now you zoom in to get the best map resolution (Figure 7).



Figure 6. Navigation to object location



Figure 7. Zooming to the highest resolution

To see more details, you can switch the map background to the satellite image (Figure 8), but do not move the map.



Figure 8. Object location on the satellite image

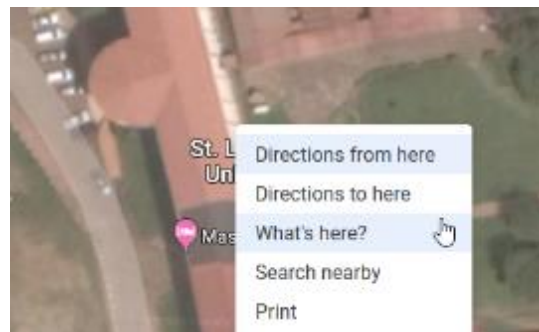


Figure 9. Asking of object coordinates

Now at the bottom of the screen (Figure 10), you will see the small window with coordinates in decimal degree. When you move the mouse on it, coordinates become blue colour. You can read the coordinates and include into your table.



Figure 10. Reading the coordinates

A better option is to click the left mouse button on the coordinate and look in the top left corner of the screen (Figure 11). In the search box, you see the coordinates in degrees, minutes and seconds, and below in decimal degrees.

Highlight the decimal degree coordinates (Figure 12), copy them and paste to the right place in your table.

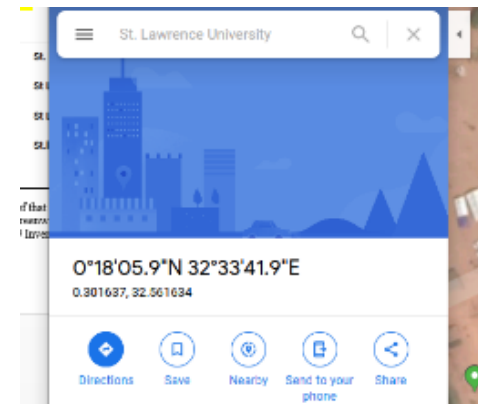


Figure 11. Search tool

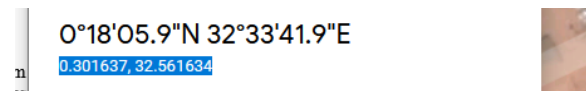


Figure 12. Selecting and copying coordinates

More about Google Maps coordinates can be found at the support website⁴.

3.3.2. Digital Elevation Model

Digital Elevation Model (DEM) is an array of regularly spaced elevation values referenced horizontally either to a Universal Transverse Mercator (UTM) projection or to a geographic coordinate system (Figure 13). The grid cells are spaced at regular intervals along south to north profiles that are ordered from west to east. For DEM based catchment and stream network

⁴ Find or enter latitude & longitude:

<http://support.google.com/maps/bin/answer.py?hl=en&answer=2533464&topic=1687353&ctx=topic>

delineation is used UTM projected DEM, and results are converted to the geographic coordinate system.

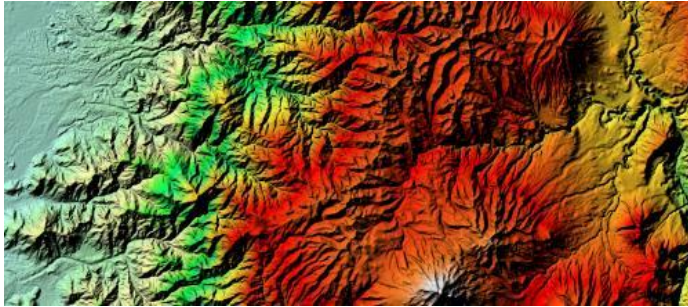


Figure 13. A fragment of the digital elevation model represented as shaded relief

The digital elevation model used for river network and catchment delineation is MERIT Hydro (used with CC-BY-NC 4.0 license). It is a global hydrography dataset, development of which is based on the MERIT DEM. The MERIT DEM was developed from the existing spaceborne DEMs (SRTM3 v2.1 and AW3D-30m v1) and represents the terrain elevations at a 3 arcseconds resolution (~90 m at the equator).

MERIT HYDRO has hydrologically adjusted DEM and is available as a component of MERIT Hydro dataset⁵ (Table 7). It contains flow direction, flow accumulation, river channel width, and hydrologically adjusted elevations. The latter is used in this study.

For comparative analysis, HDMA database is used⁶. It is widely applied in the world and has a certain reference value, which was used for visually based accuracy comparison.

⁵ Yamazaki et al., 2019. MERIT Hydro: A high-resolution global hydrography map based on latest topography datasets. *Water Resources Research*, v.55,.5053-5073.

⁶ Verdin, 2017, *Hydrologic Derivatives for Modelling and Applications (HDMA) database: USGS data release.*

Table 7. The list of digital terrain models

Product	Source	Spatial resolution	Description	Comment
DEM	MERIT Hydro	3s (~90m)	Hydrologically adjusted elevations*	Used as an input for further processing of longitudinal river profiles and catchment delineation.
DEM	HDMA	3s (~90m)	Hybrid of three datasets: HydroSHEDS, GMTED2010 and SRTM	Used for comparative analysis

* the DEM is ready for procedures described in section 3.3.3.

3.3.3. River network generation and catchment delineation

To solve this task, a well known gravitation-based model developed by D.G. Tarboton was applied. The DEM used for this procedure was MERRIT HYDRO and ArcGIS Pro with ArcHydro toolset employed for data processing.

A digital elevation model must be free of sinks. The presence of sinks may result in an erroneous flow-direction raster. It is important to understand the morphology of the area well enough to know what features may truly be sinks on the surface of the earth and which are merely errors in the data. As it was mentioned before, in this study the pre-processed DEM without sinks and depressions was used.

The next most important procedures are flow direction and flow accumulation including both new raster layers derived from pre-processed DEM.

The direction of flow is determined by the direction of steepest descent, or maximum drop, from each cell to its downslope neighbour, or neighbours, using D8, Multiple Flow Direction (MFD) or D-Infinity (DINF) methods. Flow accumulation grid is derived from flow direction. It estimates area draining into a grid cell (Figure 14).

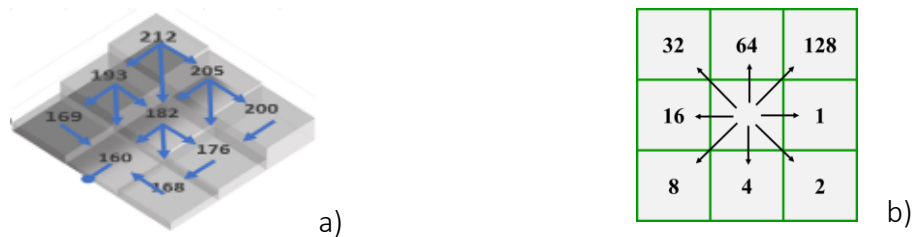


Figure 14. Flow direction estimation (a) and coding by D8 method (b)

Flow accumulation grid is derived from flow direction and represents the number of cells that converges from upstream into the current cell. Any DEM cell area (in this case 8,464 m²) multiplied by this number results on the lowest sub-basin area draining to this cell (Figure 15, left). Flow accumulation grid then is converted to the river network, but before that the minimums the threshold area parameter must be selected. This parameter defines the minimum catchment size and number of catchments when converting flow accumulation (Figure 15) into the river network. The 25 km² was applied in this project. Both grid layers – flow direction and accumulation are used for that. The first iteration gives the river network grid, and the second one the catchment grid.

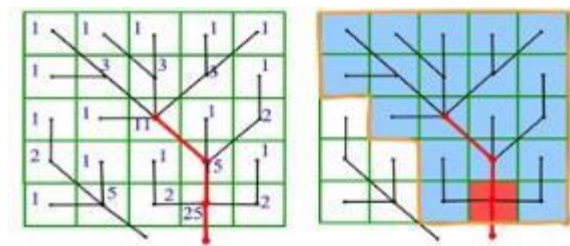


Figure 15. River network and catchment delineation scheme

Both generated raster layers then are converted to vector layers. The fragments of the generated river network and catchment layers are presented in Figure 16 and Figure 17.

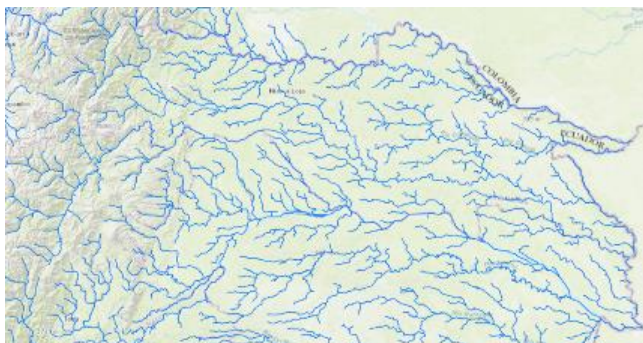


Figure 16. Generated theoretical river network (a fragment from Ecuador)



Figure 17. Generated catchments (a fragment from Ecuador)

3.3.4. Generation of theoretical hydropower potential for river segments and sub-catchments

The river network generated in the previous step created river segments of different length. Each catchment has one river segment. For the HP potential calculation, segments of 2.5 km were generated (Figure 18). Rivers are divided into segments from downstream to upstream. All these above discussed procedures are joined into one tool (Figure 19).



Figure 18. Splitting rivers into segments of 2.5 km

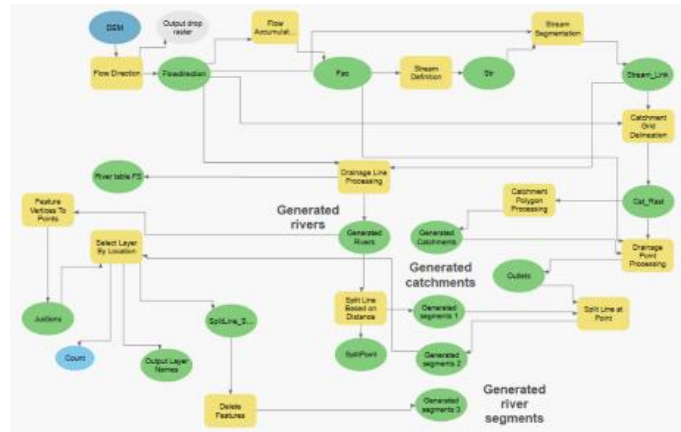


Figure 19. ArchHydro tools joined by the model builder into one tool

For each river segment at the start and end are calculated theoretical hydropower potential. River flow for each segment was estimated using specific discharge raster layer values (Figure 20) and flow accumulation raster values give catchment area at the start and end of the segment. Multiplied specific discharge values by drainage area to the calculated point give river flow. The elevation at the start and end of segment estimated from DEM, and then the difference of upstream and downstream elevation gives the drop down height. Having a river flow and drop-down height for any segment, the theoretical hydropower potential was obtained. The sub-basin layer generated from catchment layer using a threshold area of 3,000 km² (in coastal regions was reduced to 1,000 km², see Figure 21). This layer will be used to display the spatial distribution of generated theoretical HP potential.

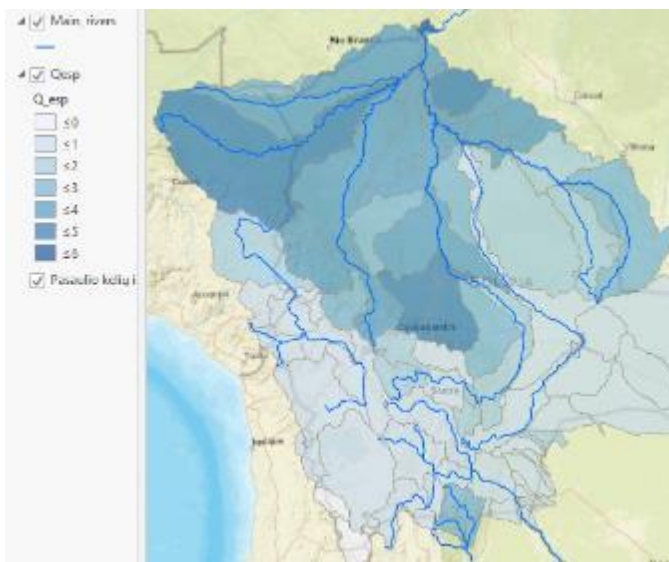


Figure 20. Specific discharge (l/s km²) map for Bolivia



Figure 21. Generated basins in Ecuador

Manual adjustments of sub-catchments were made at existing major reservoirs to ensure that the whole reservoir lake is included solely in one sub-catchment.

3.4. Climate, Hydrology and Protected Areas

3.4.1. Climate Zones

The objective is to create a GIS layer that shows the regional distribution of the diverse climatic conditions in the target countries. Considering the location of the target countries in the different world continents the aim is to select a simple climate classification scheme. On the other hand, this dataset is not intended for local studies but only for regional comparison.

For the climatic zones layer, the updated World Map of the Köppen-Geiger climate classification is to be used (based on temperature and Mean Annual Precipitation - MAP)⁷. The updated Köppen-Geiger map provides a higher resolution of 5 arc minutes using the downscaling algorithms. It is representative for the more recent 25-year period 1986-2010.

An example of climate zones developed in a GIS environment is shown in Figure 22.

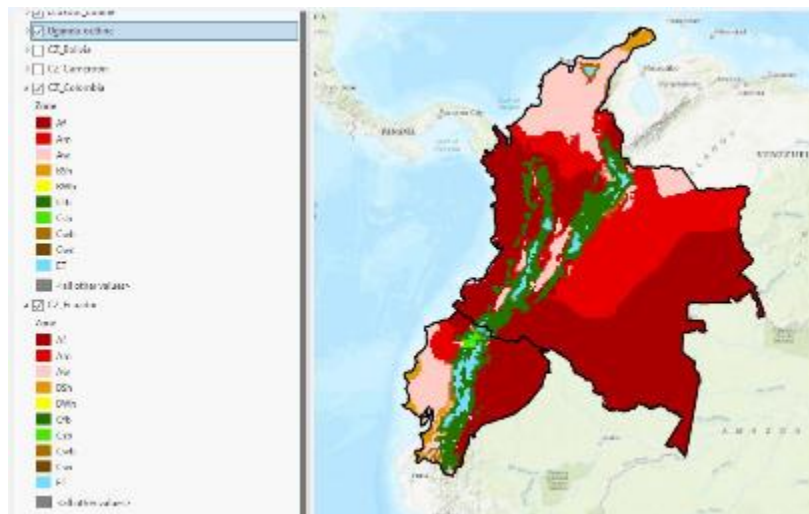


Figure 22. Climatic zones of Colombia and Ecuador in a GIS environment

⁷ Köppen-Geiger climate classification <http://koeppen-geiger.vu-wien.ac.at/present.htm>.

As an alternative, the regional climatic zones classification of Central and Western Africa will be considered (L'Hôte et al. (1996)). Here the climatic zone limits are based on mean annual and seasonal precipitation:

- Desert: Mean Annual Precipitation < 100 mm;
- Semiarid desert: MAP < 400 mm;
- Semiarid tropical: MAP < 700 mm;
- Pure tropical: MAP < 1000 mm;
- Transitional tropical and equatorial: MAP > 1000 mm, one wet season or two wet seasons.

The results will be published as a polygon shapefile in the HYPOSO Map viewer. Before that, the resulting polygons are to be generalized (smoothing of polygon boundaries, removal of islands).

3.4.2. Mean Annual Precipitation

The data of the mean annual precipitation (MAP) of the Global Precipitation Climatology Centre (GPCC) is to be used⁸. Other available data sources will be tested as well (e.g., the Tropical Rainfall Measuring Mission⁹, RFE - Rainfall Estimate for Continental Africa¹⁰ and WorldClim (Historical climate data)¹¹).

For each defined sub-catchment area (<3,000 km²), GIS shapefiles reflecting the long-term mean annual precipitation (mm) are to be developed for inclusion into the HYPOSO Map (Figure 23).

⁸ Global Precipitation Climatology Centre: <https://www.dwd.de/EN/ourservices/gpcc/gpcc.html>

⁹ Tropical Rainfall Measuring Mission: <https://trmm.gsfc.nasa.gov/>

¹⁰ Rainfall Estimate for Continental Africa: <https://earlywarning.usgs.gov/fews/product/48>

¹¹ WorldClim: <https://worldclim.org/data/worldclim21.html>

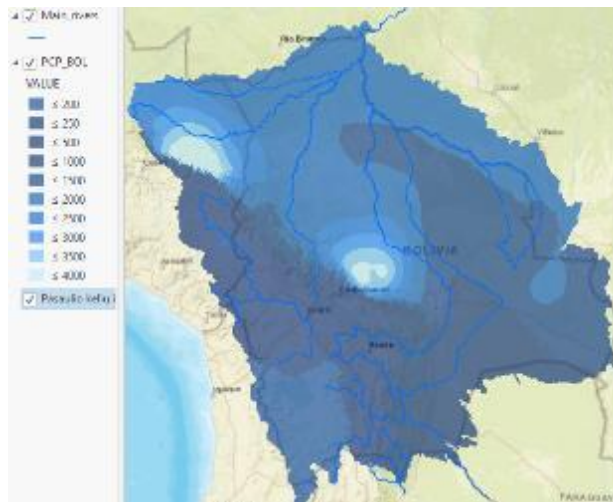


Figure 23. Mean annual precipitation for Bolivia

3.4.3. Mean Annual Specific Discharge

Based on the collection of data of specific discharge (see Section 1.2), GIS shapefiles are to be developed for inclusion into HYPOSO Map (Figure 20).

3.4.4. Protected Areas

Protected areas (PA) are dedicated to preserving the biological diversity and natural, recreation, and cultural resources that are managed through legal means. When planning a hydropower scheme the first step is to exclude any resource that is unlikely to comply with these legal provisions.

In different countries the status of PA varies as per country as inside the country, therefore very different constraints related to HPP development may be in any single PA. Also, many PAs (e.g. national and local level) are overlapping each other. To simplify their mapping task, there will be developed a generalized GIS layer “Protected areas” without a detailed attribute table (Figure 24).

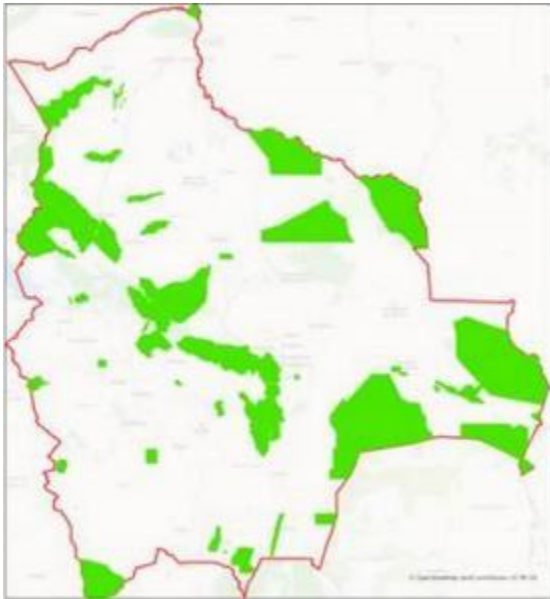


Figure 24. The map of protected areas of Bolivia (based on data provided by partners)

For further details about any single PA in which potential hydropower site is to be located the user will be redirected to the original database¹². This database provides the GIS data of the world's protected areas.

The results are to be published as a generalized polygon shapefile in the HYPOSO Map. A copyright policy laid down by this source of information will be respected in the HYPOSO Map.

3.5. Theoretical hydropower potential

There are different definitions of hydropower potential, as listed below.

Gross theoretical hydropower potential: The annual energy potentially available in the country if all-natural flows were turbined down to sea level (or the water level of the border of the country if the watercourse extends into another country), with 100 % efficiency. It is estimated based on atmospheric precipitation and runoff. The power can be calculated:

$$\text{Power [kW]} = 9.81 * \text{Flow [m}^3\text{/s]} * \text{Height [m]},$$

where,

¹² UNEP-WCMC and IUCN (2018), Protected Planet: www.protectedplanet.net

Power is the gross theoretical hydropower potential [kW];

9.81 is the specific weight of water ($g=9.81 \text{ kN/m}^3$);

Flow is the long-term mean annual discharge [m^3/s];

Height (head) is the elevation difference from start to end of a river reach [m].

Technically Feasible hydropower potential: The total hydropower potential of all sites that could be, or have been, developed within the limits of current technology, regardless of economic or other considerations. Calculated based on an inventory of sites, unless otherwise specified.

Economically feasible hydropower potential: That portion of the gross theoretical hydropower potential that could be, or has been, developed within the limits of the current technology and under the present and expected local economic conditions. The figure usually includes economic potential that would be unacceptable for social or environmental reasons

This part of the study focuses only on the **theoretical hydropower potential** which takes approximately into consideration energy losses due to turbine efficiency and hydraulic losses (penstock, etc.) and is computed as follows:

$$\text{Power [MW]} = 0.0085 * \text{Flow [m}^3/\text{s]} * \text{Height [m]}$$

where,

0.0085 is a coefficient for considering unit conversion and power plant efficiency/hydraulic losses.

The theoretical hydropower potential gives the upper limit of mean power that could be produced in the river reach under the following assumptions:

- The full head (elevation difference from start to end) of the reach is utilized;
- The full river discharge is turbinated (no spillway losses);
- The efficiency of turbines, generator and transformer as well as hydraulic losses (penstock, etc.) are already approximately considered.

The theoretical hydropower potential is by definition higher than the technical or economic, which will not be assessed in this study.

Based on GIS modelling the following potential will be derived:

- Specific hydropower potential, MW/km;
- Total sub-catchment theoretical HP potential, MW.

Specific hydropower potential will be grouped into at least 5 categories:

- to 0.1 MW/km;
- 0.2 to 1.0 MW/km;

- to 10.0 MW/km;
- 10.1 to 30.0 MW/km;
- 30.1 to 200 MW/km.

Total sub-catchment theoretical HP potential, MW will be grouped into at least 6 categories:

- to 10.0 MW;
- 10.1 to 50.0 MW;
- 50.1 to 100.0 MW;
- 100.1 to 200.0 MW;
- 200.1 to 300.0 MW;
- 300.1 to 1000.0 MW.

Classification of preferred hydropower plant size. Four classes are considered for the preferred plant size (Table 8).

Table 8. Classification of preferred hydropower plant size

Class	Description of preferred hydropower plant size
0	None. No attractive theoretical potential for hydropower.
1	Attractive theoretical potential for micro and mini HPP with an installed capacity of less than 1 MW.
2	Attractive theoretical potential for small HPP with installed capacity 1-10 MW.
3	Attractive theoretical potential for intermediate HPP with installed capacity 10 - 50 MW.

4. HYPOSO Map Viewer (programming)

The above described collected, processed, generated and stored in the database information will be exhibited concisely in the HYPOSO Map Viewer. It will be the geospatial representation of potential hydropower locations including relevant context features in the five target countries. It will be accessible through an interactive web-based platform providing as well as visual and digital information for users.

The HYPOSO Map Viewer for an individual target country consists of the following key layers shown in Figure 25.

No	1st layer	2nd layer	3rd layer
1	Base map	1.1 Open Street Map	
		1.2 Digital Elevation Model	
		1.3 Terrain map	
2	Background	2.1 Population Distribution	
		2.2 National Boundaries	
		2.3 Land Cover	
		2.4 Natural Protected Areas	
		2.5 Water bodies	
		3.1 Transmission Grid	
3	Infrastructure	3.2 Road Networks	
		4.1 Large Hydro	4.1.1-4.5.1. Operational
4	Operational Hydropower plants (HPP) and under construction	4.2 Intermediate Hydro	4.1.1- 4.5.1. Under construction
		4.3 Medium Hydro	
		4.4 Small Hydro	
		4.5 Micro and Mini Hydro	
		5.1 Climate Zones	
5	Climate and Hydrology	5.2 River Network	
		5.3 Catchments and Sub-Catchments	
		5.4 Gauging Stations	
		5.5 Mean Annual Precipitation	
		5.8 Mean Annual Specific Discharge	
		6	Hydropower (HP) Resources (Potential)
6.1.2. New site			
6.1.3. Non-powered Dam, Weir, Mill			
6.1.4. Obsolete HP plant			
6.2 Theoretical hydropower potential (MW)			
6.3 Catchment (Sub-) theoretical HP potential (MW)			
6.4 Specific HP potential MW/km			
7	Climate change impact on Hydropower resources	7.1 Near Future HP potential at catchment level (short term)	
		7.2 Far Future HP potential at catchment level (long term)	

Figure 25. Structure of key layers

4.1. Objective

The work aims to design and implement an interactive web-based HYPOSO Map Viewer capable of displaying various georeferenced objects such as point, line and polygon reflecting the structure of key layers shown in Figure 25. This HYPOSO Map Viewer will also have a structure that would allow access to publicly available and hosted information, as well as information for logged-in users (administrators).

4.2. Tools and technologies used

The software (HYPOSO Map Viewer) as well as the database will be hosted on a Windows server.

The technical parameters of the server are not worse than:

- Processor: Intel XEON Gold 5118 CPU @ 2.30Ghz;
- RAM: 8 GB;
- Disk capacity: 100 GB SSD.

Software requirements:

- Server operating system -Windows server 2016 standard or equivalent;
- The project user interface is created using Microsoft Visual Studio .NET Community 2019;
- The program code is created using the VB.NET programming language;

- The database uses Microsoft SQL Server 2017 Express;
- Microsoft SQL Server Management Studio 18 is used to manage the database.

4.3. Structure of the HYPOSO Map Viewer

4.3.1. General view of the Viewer

The HYPOSO Map Viewer is planned to be publicly available at www.hyposomap.eu (Figure 26.).

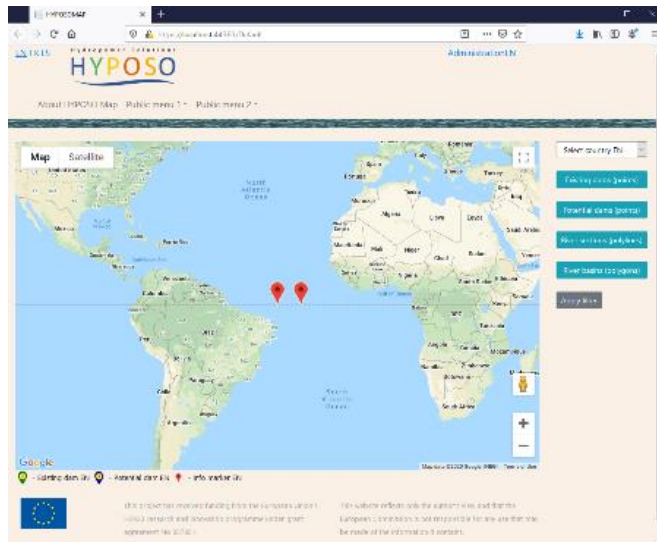


Figure 26. The default view of the HYPOSO Map Viewer

- **Base map**

The base map menu of the HYPOSO Map Viewer toolbar will allow selecting a background map for the HYPOSO Map window.

Google maps are used for the map layer (base). It has the following standard sections (layers) represented in Figures 27-31.



Figure 27. Standard map



Figure 28. Surface relief map



Figure 29. Satellite view without labels (location names)

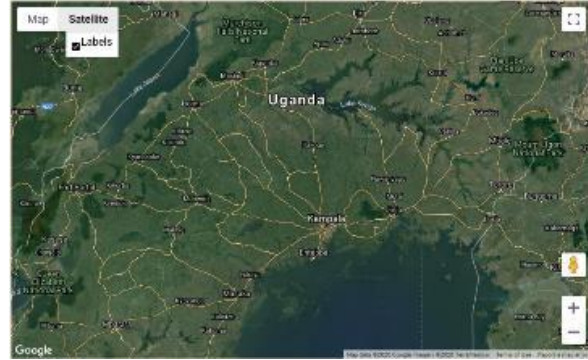


Figure 30. Satellite view with a location name



Figure 31. Google street view layer

4.3.2. Data type

On the main layer of the Google maps map, the Viewer will display three types of graphic elements: points, polylines and polygons.

- **Points**

The coordinates of the points are taken from the information in the database. If the scale of the map is large and there are many concentrated points in one place, they are grouped into groups. Clicking on the group map automatically zooms in and displays the previously grouped points (see Figure 32). The map has a feature that when you click on a specific point, a pop-up window displays information about the specific selected point (Figure 33).



Figure 32. Points displayed on the base map

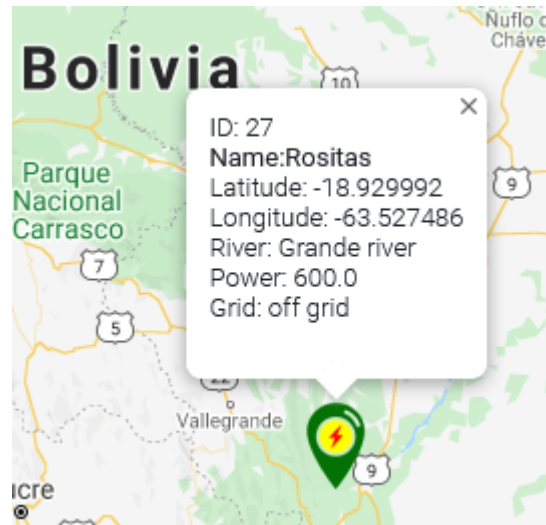


Figure 33. A pop-up window with information of the point

Both coordinates of the point are needed to display the point on the map, and the information displayed in the pop-up window is taken from the information stored in the database (Figure 34).

SQID	CountryCode	Country	Title	F4	F5	F6	lat1	Inq1	lat2	Inq2	Power	F12	F13	F14	F15	F16	F17	F18
2	1	Bolivia	Misicuni	Misicuni river	Rio Misicuni	Provincia Quilla...	-17.097174	-66.328954	-17.313674	-66.262292	80.0000	9,8	1035.5	S	2018		ENDE - ...	On grid
3	1	Bolivia	Corani	Malaga river an...	Rio Malaga y ot...	Provincia Chap...	-17.227732	-65.892759	-17.212145	-65.875779	54.0000	n/a		S	1966		ENDE - ...	On grid
4	1	Bolivia	Santa Isabel	Discharae from...	Descaraa desde...	Provincia Chao...			-17.191557	-65.823164	93.0000	n/a		RoR-D	1973		ENDE - ...	On arid

Figure 34. Sample fragment of the data table containing information of the points

It is planned that the points will show the location of existing and potential hydropower plants on the map. For this purpose, two separate tables with all the necessary information have been created.

- **Polylines**

Polylines represent sections of rivers (Figure 35) and other sections with a beginning and an end. Their coordinates are stored in GeoJSON type files. To increase the speed of the HYPOSO Map Viewer, the accuracy of the coordinates is reduced to 5 decimal places. For our tasks, such accuracy is quite sufficient. Original (not reduced) source data for downloading will be available. Polyline elements also have the property that clicking on it with the mouse button displays the information contained in the attributes of the GeoJSON file (Figure 36).



Figure 35. River section displayed on the base map

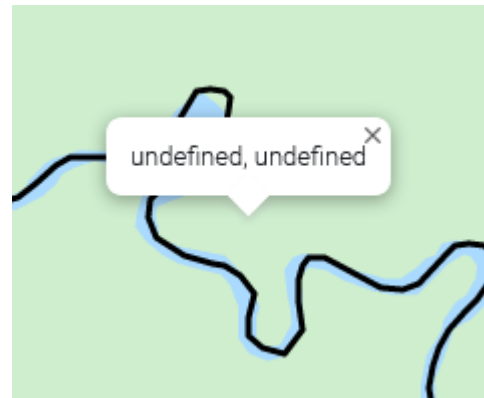


Figure 36. A pop-up window of the polyline

- Polygons

Polygons represent objects such as river basins, state borders, and so on (Figure 37). Any object that is not a point and which start point coincides with the endpoint can be displayed. Their coordinates are stored in GeoJSON type files. To load quickly the Map Viewer the accuracy of the coordinates is reduced to 5 decimal places. This accuracy will not affect the performance of displaying data. The original data source will be available for download. Under the property function of any polygon element, there will be the information in the attributes of the GeoJSON file (Figure 38).



Figure 37. Polygon on the base map

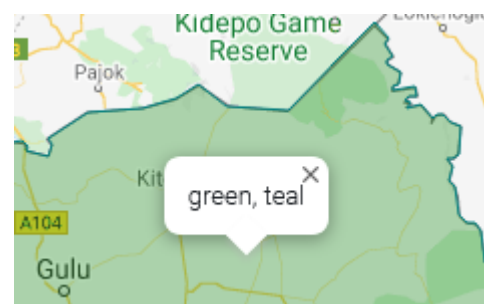


Figure 38. A pop-up window of the polygon

The full GeoJSON specification can be found at the GeoJSON website ¹³.

- **Navigation Tools**

The navigation tools can be accessed from the HYPOSO Map toolbar to easily view and explore features displayed in the HYPOSO Map window. From left to right, the navigation tools allow users to zoom in, zoom out, zoom to a full extent, pan left, pan right and pan by clicking and dragging the map.

The users will be able freely to view, and query geospatial distributions and characteristics of various key datasets. The HYPOSO Map will host publicly available information that can be downloaded by all visitors. It will be accessible through publicly available menu items (Figure 39).



Figure 39. Publicly available menu items

An administrator (with login) user area will be installed on the HYPOSO Map (Figure 40). The logged-in user will only be able to access the admin area with their login details. It will be able to read/download information for registered users.

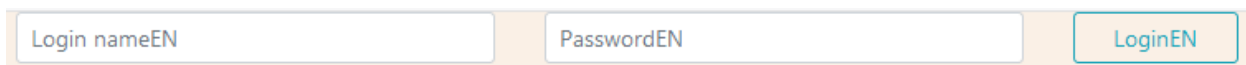


Figure 40. Administrator login window

¹³ The GeoJSON Format: <https://tools.ietf.org/html/rfc7946>

The administrators' menu will be available for logged users (see Figure 41).

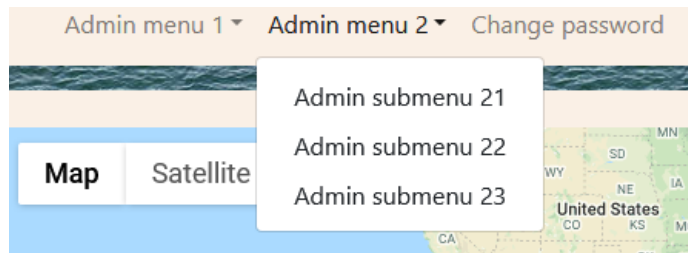


Figure 41. Menu items for logged users (Administrators)

- **Search Features**

The display of the layers (points, polylines, polygons) in the HYPOSO Map Viewer on the main map will be done by filtering the desired elements. The country is selected, the objects and their parameters are selected, and the filter is applied (Figure 42). The HYPOSO Map will be available in three languages - English, French and Spanish (see Figure 43).

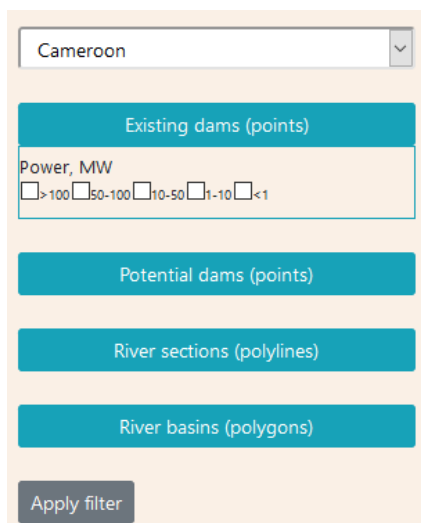


Figure 42. Search (Filter) dialogue of the Viewer



Figure 43. Language selector of the Viewer user interface

The HYPOSO Map will contain a legal disclaimer about the project.

- **Metadata, tutorial and maintenance**

Metadata is a set of data that describes and gives information about other data. This description is crucial to know how the data was created, what is its quality and how to obtain it. The metadata developed for HYPOSO MAP layers is to be stored in a metadata catalogue.

A handy interactive tutorial will be prepared to introduce the users through the HYPOSO Map functionality.

The HYPOSO Map Viewer software will be maintained by VDU during and after project completion (at least 5 years).