World Hydropower Capacity Evaluation

[1] Theoretical Background

'A Systematical estimation of the World's micro, small and large hydropower capacities based on a new modeling approach'

Author; Lourens Meijer
C1242938 – LJJMeijer@gmail.com

Committee

Prof. Dr. Ir. N.C. van de Giesen	-	Delft University of Technology, CE, Watermanagement
Ir. R. van der Ent	-	Delft University of Technology, CE, Watermanagement
Dr. Ir O. Hoes	-	Delft University of Technology, CE, Watermanagement
Ir R. Pramana	-	Delft University of Technology, CE, Watermanagement
Ir. H. Mondeel	-	WitteveenBos Consultants

Department of Water Management, Faculty of Civil Engineering and Geosciences,
Delft University of Technology, the Netherlands

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Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department of Water Management
Section of Water Resources

WORLD HYDROPOWER CAPACITY EVALUATION

'A Systematical estimation of the World's micro, small and large hydropower capacities based on a new modeling approach'

[1] - THEORETICAL BACKGROUND OF THE MODEL

This Report deals with the theoretical background of the Hydropower Tool. The model structure, processes, input data and variables are clarified here. When modeling hydrologic processes combined with geographical conditions, assumptions and simplifications are inevitable, and they are discussed here. The significance and accuracy of the predicted and simulated hydropower capacities can be found in this report.

For this Master Thesis and research a total of three products will be submitted;

[1] **THEORETICAL BACKGROUND OF THE MODEL**
Clarification of model structure, input data, calculations, assumptions and simplifications

[2] **PRACTICAL USER MANUAL AND THE MODEL & INPUT DATA**
Digital DEM, DIR, RO & Results Data sets, ArcGIS Hydropower Tool & User Manual

[3] **REPORT ON THE RESULTS & CONCLUSIONS**
Report on Hydropower Capacity & evaluation of results

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Abstract

A continuous population growth and increasing energy demand combined with depleting traditional energy reserves puts a pressure on conventional methods of electricity generation. The desire and ambition to create a more sustainable society paves the way for the ‘renewables’.

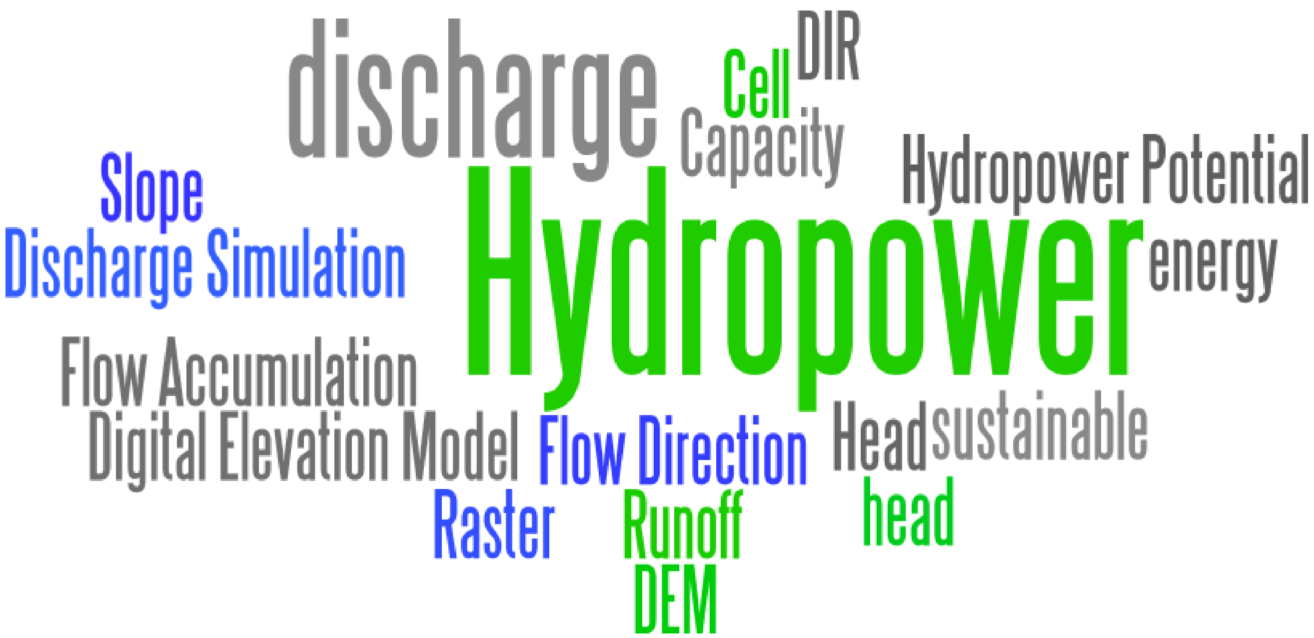
Hydropower or Hydroelectricity already plays a significant role in global energy production, especially the large hydropower plants with giant reservoir lakes.

The contribution of small and micro hydropower however is not really clear. Smaller hydropower plants have some advantages compared to larger plants in terms of sustainability, local benefits and electricity supply in remote areas. The exact location of potential hydropower plants is mostly unknown and the total potential of all combined hydropower capacities for a certain region has not been evaluated as well.

This research aims to give insight in the potential of hydropower for a specific region and distinguishes micro, small and large hydropower. In order to evaluate the global hydropower potential a systematical method has been developed to simulate input data and check whether there is hydropower at a specific location.

The approach is based on a distributed model and raster data. The world is divided into cells with a 3” (three seconds or 92m near the equator) resolution. For each and every cell the hydropower capacity is systematically determined. In order to do this the two basic components for hydropower, head and discharge need to be evaluated for each cell. The discharge is calculated with help of the HydroSHEDS’ DEM and DIR datasets combined with the GRDC Runoff fields’ dataset. Based on the Flow Direction, derived by HydroSHEDS a ‘runoff weighted’ flow accumulation was executed to obtain the accumulated runoff for each cell which is converted into discharge. The head is calculated with the cell size and slope within each cell. The slope was derived from a global 3” DEM which has been modified with the discharge map to obtain a RiverDEM which forms the basis for the slope calculation. Hydropower is calculated within each cell using the Input Variables ‘turbine efficiency’, ‘minimum discharge’ and ‘minimum head’.

The results are filtered into micro, small and large hydropower locations. To give insight in the total hydropower capacity for a specific region the total hydropower is accumulated per category for a region of $0,5^0$ times $0,5^0$ (about $50km^{2}$). The final output is a global map of accumulated hydropower per category with a resolution of $0,5^0$.



Keywords; *Hydropower, Runoff, Digital Elevation Model, Discharge Simulation, Flow Accumulation, Flow Direction, Hydropower Potential, Hydropower Capacity, Head, Slope, Raster, Cell, energy, sustainable, DEM, DIR.*

List of Abbreviations

ConDEM	Hydrological Conditioned Digital Elevation Model
DEM	Digital Elevation Model
DIR	Flow Direction
EGM	Earth Gravitational Model 1996
FLOWACC	Flow Accumulation
GIS	Geographic Information System
GRDC	Global Runoff Data Centre
HydroSHEDS	Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales
IDW	Inverse Distance Weighted Interpolation
KW	Kilowatt (10E 3W)
KWh	Kilowatt Hour
MW	Megawatt (10E 6W)
GW	Giga watt (10E 9W)
TW	Terawatt (10E 12W)
NoData	No Data Available for specific grid cell
RO	Runoff
SRTM	Shuttle Radar Topography Mission
USGS	United States Geological Survey
WGS84	World Geographic System 1984

Nomenclature

Area	Cell size (3")^2 or (m^2)
[x]'	Resolution (minutes)
[x]"	Resolution (seconds)
$[x]^0$	Resolution in (degrees)
Δ	Change (Delta) (-)
g	Gravitational acceleration [ms^{-2}] (assumed 9.81m/s^2)
H_{min}	Minimum Head
KW	Kilowatt=Joule/Second (J/s) or ($kg*m^2*s^{-3}$) (W, kW, MW, GW,TW)
P	Power (kW)
PI	Mathematical number π (assumed 3,14).
$P_{low}Large$	Lower Boundary Large Hydropower (10.000kW)
$P_{Low}Small$	Lower Boundary Micro Hydropower (5kW)
$P_{up}Small$	Upper Boundary Micro Hydropower (100kW)
Q	Discharge (m^3/s)
Q_{min}	Minimum Discharge (m^3/s)
RO	Runoff (mm/month)
η	Turbine Efficiency (%)

Definitions

Capacity	Installed potential Hydropower Capacity, determined by hydropower formula.
Cell	Area with certain resolution is divided in cells that together form a raster.
Discharge	The volume rate of water flow
FlowAcc	The accumulation of cells/discharge/runoff located upstream of a specific cell
Flow Direction	The direction to the steepest down-slope neighbor in a square raster.
Head	Difference in height (elevation) within one cell.
Neighbor	Cell adjacent to specific cell. Cell has 8 neighbor cells in a square raster.
Raster	An Area divided into equal (square) units
Resolution	Spatial Resolution; the number off cells/points per degree. Resolution 3" means 1200 cells within 1^0
Runoff	Amount of water that drains from one area to another. The amount of water that leaves the grid cell as 'runoff' in given time frame.
Slope	The gradient between the horizontal and vertical distance covered within a grid cell.

1. Introduction

Research significance

A lot is known about the potential of hydropower, especially the larger locations, concerning big rivers, huge waterfalls and reservoir lakes. Estimations on the cumulative potential of larger hydropower plants have been made, and mostly the locations are known as well, also because they are quite obvious. The summarized contribution of small- and micro hydropower however has not been evaluated exactly, and if estimations are made, the locations are still unknown. Given the world's energy dilemma, fossil fuel limitations and population growth, new energy, and especially sustainable energy production is required and feasible. A map of small hydropower locations has not been produced yet, neither a scientifically based indication of the cumulative potential of these spots. There are different methods to calculate the global solar or wind energy potentials, but for small hydropower there is no systematical approach or tool. Today institutions and governments are determining their energy strategies and a map or a tool that indicates the small hydropower potential of a region might be very useful to decide whether to invest in hydropower, in which region. Companies specialized in developing small hydropower sites might benefit from a tool which is able to indicate locations and capacities in remote or hard accessible areas.

"The absence of a systematical tool or a scientific developed estimation on hydropower combined with the opportunity window for renewable energy forms the validation and the inspiration for this Master Thesis".

Vision

To develop a tool which is able to indicate both the location and potential of hydropower locations and give insight in the regions which are suitable for investments in hydropower development and give insight in the potential contribution of hydropower to the energy dilemma.

Mission

The goal of the project is to give more insight in which regions are suitable for hydropower development. In order to do so a tool or an algorithm needs to be developed. The purpose of such a tool is both to simulate hydropower locations and give the accumulative for a region as to be able to indicate the exact position of these locations.

Objectives

- To develop a tool that indicates potential hydropower locations, both their location as their capacity.
- To simulate input data using the tool and generate data on hydropower locations and capacity.
- To give insight in the accumulated hydropower capacity potential for a certain region.

2. Introduction into Hydropower

Energy Dilemma – Energy Transition

Today, the worldwide installed energy capacity is over 17 TW. In the year of 2050 this will be 32 TW. With depleting fossil fuels it is inevitable that alternative energy resources are going to play a significant role, including the 'renewables' [Fokko Mulder, SET3011 TuD, 2011]. Renewables already deliver 16% of the energy consumption, with 10% coming from traditional biomass.

New renewables such as *small hydropower*, wind, solar geothermal and biofuels are accounted for 3%, and they are growing rapidly [REN21, 2011]. The future energy supply will come from a mix of different sources and techniques. There are a lot of different scenarios of compositions but the common consensus is that renewables will fulfill over 50% of the energy consumption within 40 years from now [Shell Energy Scenarios, 2011].

Hydropower

Hydropower is a relatively old technique among the 'renewables' and already applied for hundreds of years. Since the technique is not new, neither 'high tech', the development in hydropower is not comparable with wind and solar energy for example.

Hydropower supplies over 90% of the electricity use in 22 countries, and over 99% in 13 countries. As a matter of fact, the largest single energy plant in the world is a hydropower plant, the famous Three Gorges Dam. If all economically feasible potential was installed, it could substitute fossil fuelled plants. [WCD, 2000], [A. Bartle, 1999], [van Duivendijk, Lecture Notes 2011, TuD].

For this research the definition of hydropower is the generation of electricity by means of a turbine, derived from the energy of water (m^3/s) over a certain Head difference (m). The general Formula for hydropower that applies here is;

$$Hydropower\ (kW) = \eta(\%) * g\left(\frac{m}{s^2}\right) * Q\ \left(\frac{m^3}{s}\right) * \ \Delta H\ (m) \qquad (1)$$

Hydropower applies to a wide range of applications which differ a lot in practice. Large well-known hydropower dams and home fabricated water wheels both generate hydropower but have little in common. This research aims to give insight in the potential of micro, small and large hydropower. Pico-Hydropower is not relevant to model on a global scale and the accuracy of the model is not large enough to distinguish very small discharges.

Table 1: Hydropower Categories

Capacity	Range	Description
Large	>10 MW	Huge electricity producers, large dams and structures, only a few in the world
Small	<10 MW	Big variety in setup. Most common, large contributor.
Micro	<100 KW	(Remote) Small Community (Off Grid and On Grid)
Pico	<5 KW	Remote small community or single houses (Off Grid)

The hydropower range of interest is divided into three categories as presented in Table 1 above, and all hydropower larger than 5kW will be taken into account. More detail about the hydropower domain which is determined by both head and discharge domains is dealt with in [5.3 Input Variables].

Current Hydropower Capacity

The total hydropower capacity was about 1050 GW in 2011 [REN21, 2011]. The growth of hydropower compared to other renewables is conservative, see Table 2, where the growth of wind energy is included.

Table 2: Development Hydropower Capacity

Year	Capacity Hydropower (GW)	Capacity Wind Energy (GW)
2007	<950	<121
2008	950	121
2009	980	151
2010	1010	198
2011	1050	240

China, Canada, Brazil and the United States are the world's largest hydropower producers and have the most installed capacity. This is no big surprise since these are huge countries as well. The capacity is unequal distributed over the globe, some countries generate their entire electricity demand on hydropower, and others have none at all.

There is still a lot of hydropower still to be developed. Estimations on the amount of potential to be developed are presented in Table 3 [World Atlas Hydropower and Dams, 1998].

Table 3: Potential Estimations

	Theoretical Potential TWh/year	Technical Feasible Potential TWh/year	Economically Feasible Potential TWh/year	Hydropower Production TW/year	Installed Hydro Capacity GW
World	40500	14320	8100	3000	1010

It is important to realize that these estimations are mainly based on large hydropower installations, not on micro or small hydropower capacity.

3. Modeling Approach

The Hydropower Development Tool is based on a distributed model setup. All data sets are raster data. In Figure 1 the model is presented in its most basic and conceptual form. This model indicates the main input data, processes and results.

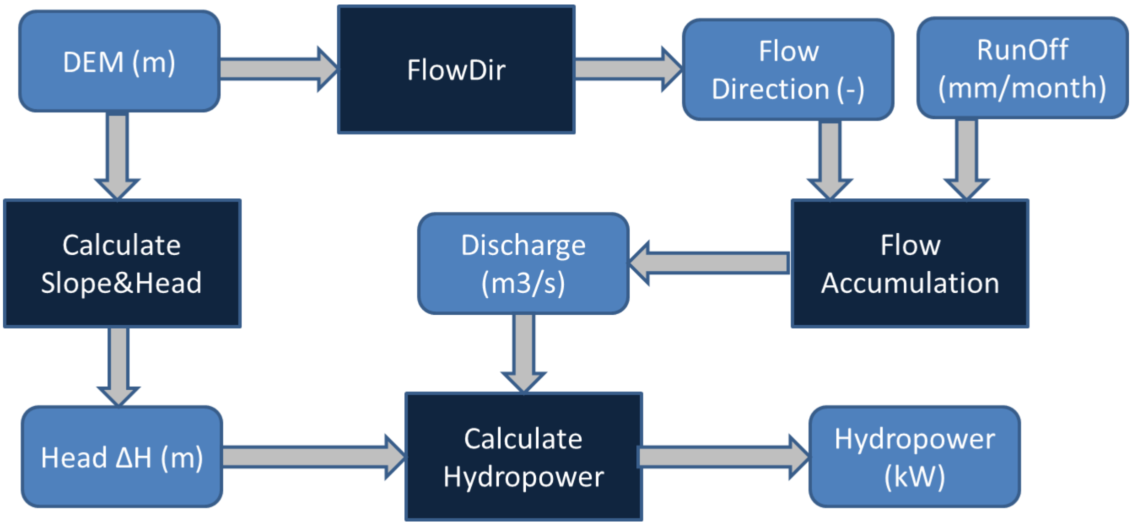


Figure 1; Conceptual Model

System Boundaries

The first level system considered in the model is the single raster cell. The resolution of the data determines the size of the cell. All processes, calculations, parameters and input values apply for a single raster cell.

The second level boundaries are created by NoData Cells. The accumulation of flow is a process depending on the relation between the raster cells. NoData Cells terminate the flow accumulation, and therefore the discharge and hydropower calculation and form a second system boundary. The physical meaning of this boundary is the ocean. This implies that the process of flow accumulation continues until the ocean is reached. This applies both to continents and small Islands.

Model Environment

The model is setup in ArcGIS10 and all datasets will be converted into raster files suitable for ArcGIS10. The area of interest for this thesis is the whole globe in 3" resolution. This involves very extensive raster files and very long calculation times. The data-management and storage for this research is a challenge on its own.

The Hydropower Development Model was created in the ArcGIS10 ModelBuilder and PythonScript.

The process of giving insight in the accumulated hydropower potential for a region is presented in the operational model structure, Figure 2.

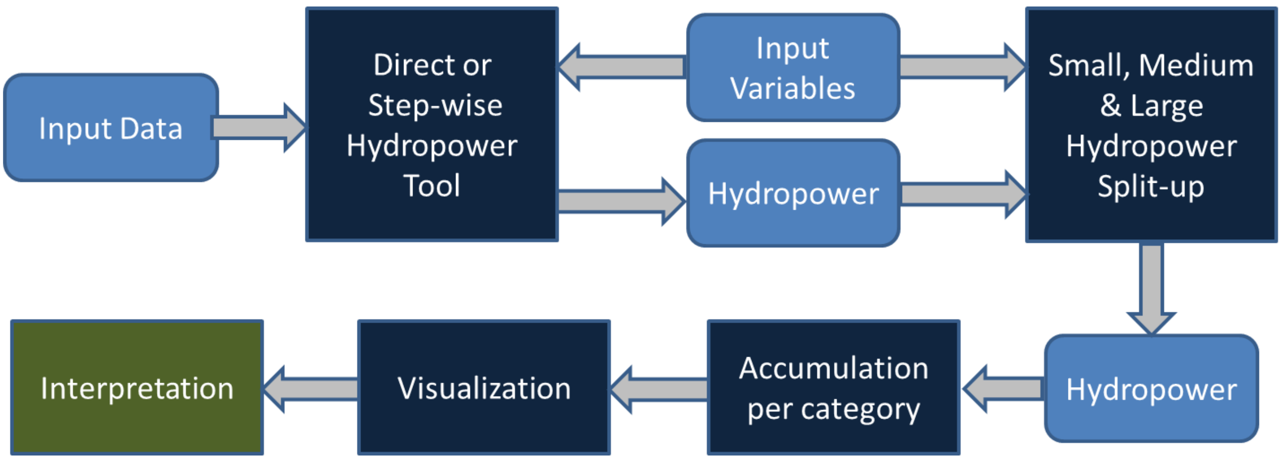


Figure 2: Operetional Model Structure

4. Hydrologic conditions and assumptions

The objective of the Hydropower Development Tool is to indicate interesting locations for hydropower development and estimate regional, continental or worldwide hydropower capacity potential. The aim is not to explain hydrological processes and principles. Like all (hydrological) models assumptions and simplifications are made.

Runoff only hydrologic variable

Only Runoff is considered as input data and hydrologic variable in the model. All other processes as precipitation, evaporation, interception and infiltration are 'included' in the Runoff data. See also 'Runoff Input Data' below.

Time Scale

The time scale of the model is months. All hydrological input data, processes and results are based on monthly averages. Most important, the Runoff is a monthly average, the Discharge (m^3/s) derived from this Runoff is a monthly average Discharge. The initial global hydropower estimation is based on a yearly average discharge month.

Monthly Averages

The Runoff for a specific month is a long term average. Strong fluctuations around this monthly average exist and will occur, resulting in values that can differ significant form the monthly average, both in time and space. Within a monthly average the daily and even hourly based values can fluctuate as well.

For hydropower design and planning these fluctuations are very important but for the estimation of a region's hydropower potential or the indication of hydropower spots the use of monthly averages is valid. However it is and should always kept in mind during this thesis, and when interpreting results that the actual values might differ significant from the simulated data. The aim is to produce data within the expected bandwidth.

Storage and Travel Times and general annotations

Storage and travel times are not considered or included in the model. The Runoff ends up at the catchment outlet instantaneously, within the model time step, which is one month. In reality runoff takes a while to travel through the catchment, and might be temporarily stored.

- Runoff, derived as a fraction from rainfall is subject to large fluctuations in time and space.
- The DEM with a 3" (about 90 meters) resolution provides a valid basis to execute flow direction and flow accumulation calculations but is not exact, small errors in flow path will occur. Chapter 5.2
- Underground heterogeneities are not included in the model. The flow direction is only based on surface elevation differences between raster cells.

The objective of this tool and research is not to predict exact hydropower potential values but to provide insight in the bandwidth of the potential.

Runoff Input Data

The Runoff input data set used in this model and research is produced by the Global Runoff Data Centre (GRDC). The data has a 30-minute resolution and is derived by means of disaggregation of discharge measurements. Discharge is considered as an accurate indicator of integrated terrestrial runoff. An extensive network of long-series averaged discharge measurements has been disaggregated to runoff. [B. M. Fekete, C. J. Vorosmarty, 2004].

A note on the occurrence and risk of circle argumentation using direct GRDC Runoff Data

The author is aware of the fact that the GRDC derived Runoff data grids are produced by disagregation of measured discharge using stream patterns. This model and reasearch aim to derive accurate stream patterns by means of flow direction and accumulation calculations based on Hydrosheds' Digital Elevation Model, which has been intensively contitioned for hydrological purposes by USGS. This research'accumulated runoff is obtained by an 'runoff weighted' flow accumulation. In other words; the runoff, genareted from discharge measurements is again processed to generate 'the same' discharge as from which it originates.

However, new information is generated due the much higher resolution of the data (3") from Hydrosheds. Discharge is now simulated on a much higher resolution resulting in discharge data in more detail. The fact that these two data sets are connected to eachother should always kept in mind.

Binominal Runoff accumulation

The model defines the flow direction for each cell based on the 'steepest slope' principle. All Runoff in the cell flows to its steepest down-slope neighbor. There is no separation of flows within one cell, in time nor in space. The direction of runoff for a specific area is continuous and might even vary in time. The approximation with de discretized raster set on a 3" resolution however is very accurate.

5. Modeling

Essentially the model needs only to multiply the head difference (m) within each cell with it's to discharge (m^3/s) converted runoff (mm/month). The hydrologic assumptions and simplifications already have been dealt with in the previous chapter. The processes of deriving and calculating both discharge and head need some further explanation as well as the input data and the input variables. A schematic overview of these factors is presented in Figure 3.

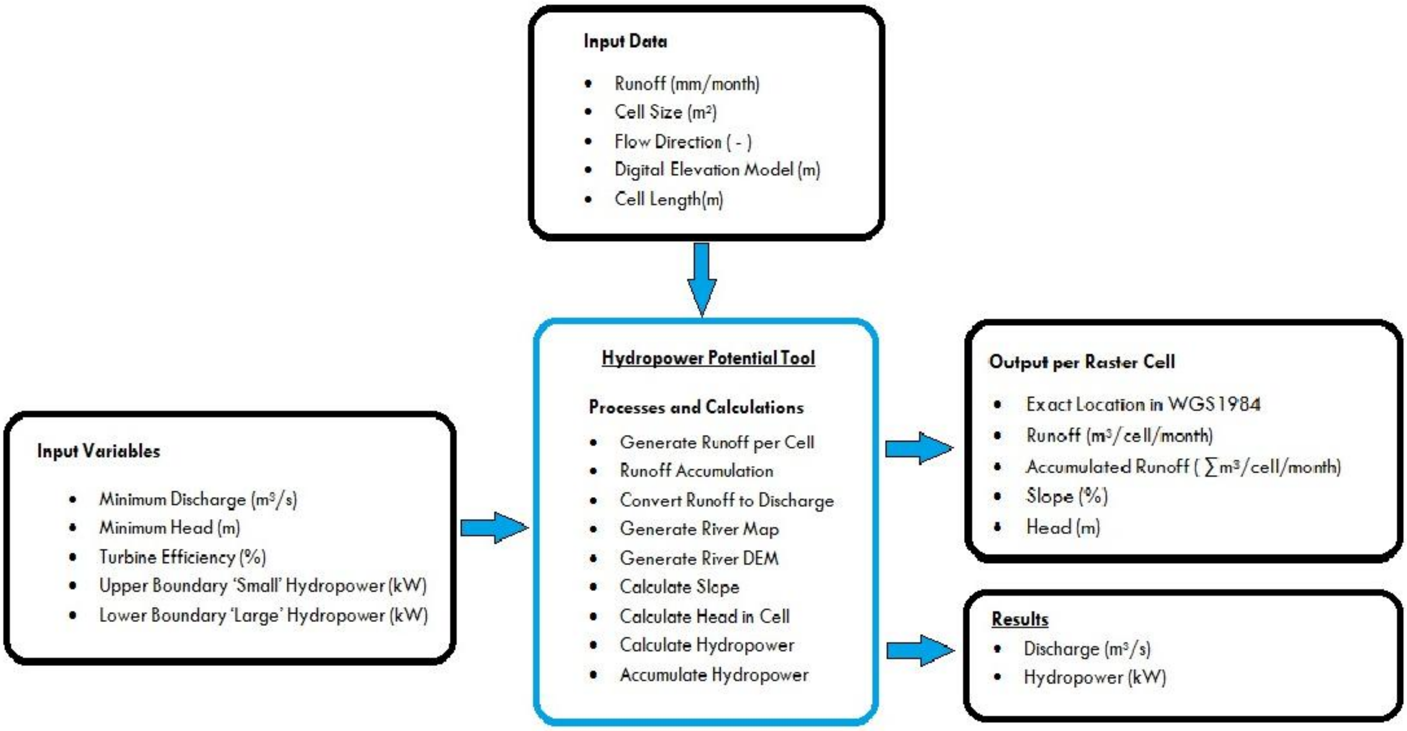


Figure 3: Schematic overview model

The model consists of Input Data, Input Variables and Calculations. The input data sets which are discussed in chapter 5.1 are DEM, DIR, Runoff, Cell size and Cell Length. The main calculations and processes are presented in chapter 5.2. The Input Variables are the minimum discharge, the minimum head, the turbine efficiency and the boundaries that separate micro, small and large hydropower, they are dealt with in chapter 5.3.

5.1 Input Data

Digital Elevation Model (DEM)

The DEM is produced by the United States Geological Survey (USGS) and presented as HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales). HydroSHEDS is based on high-resolution elevation data obtained during a Space Shuttle flight for NASA's Shuttle Radar Topography Mission (SRTM).

The Digital Elevation Model is processed for Hydrological purposes before the Flow Direction dataset is generated. Local depressions (Sinks) are removed and other hydrologic improvements are executed resulting in a DEM which is optimized for hydrologic purposes [Bernhard Lehner, Kris Verdin, Andy Jarvis, 2006]. DEM raster sets are available at several resolutions with (3") as the highest resolution, which is the resolution used for this research.

It is beyond the scope of this research to deal with the hydrologic conditioning of DEM's in detail but it is important to be aware of the modifications of the DEM executed in HydroSHEDS. The main purpose of all these modifications is to obtain the most realistic drainage pattern as possible. The modifications are;

- Deepening of Open Water Surfaces (make sure accumulated flow stays within these water bodies)
- Weeding of Coastal Zone (remove objects that block flow into oceans)
- Stream Burning ('Burn' known river courses into the DEM)
- Filtering of DEM (remove local spikes and depressions to allow better stream flow)
- Modeling of Valley Courses (remove small objects in shallow valleys to improve flow)
- Sink Filling (fill local depressions in DEM to allow continuous flow)
- Carving Trough Barriers (remove barriers in Original DEM when a river path is known)
- Manual Modeling (modify conDEM manually if a river path is known to be incorrect)

Most modifications are neighborhood operations, or Kernel modifications to modify an incorrect or undesirable cell value based on the values of its surrounding cells. An example is presented below in Figure 4.

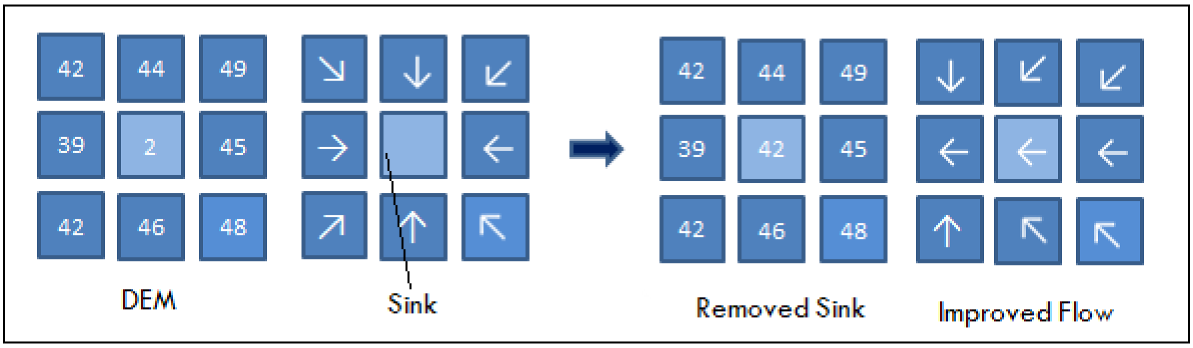


Figure 4: Sink Removal

In Figure 5 below the DEM of the island of Papua is presented as a DEM map in ArcGIS. Ocean cells are assigned a NoData value. The 3 second resolution results in a very accurate DEM on large scale.

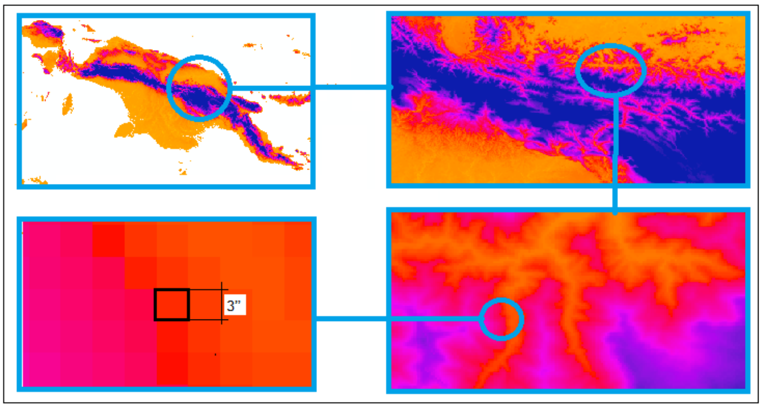


Figure 5: DEM resolution

Flow Direction (DIR)

The DIR file is derived from the hydrologic conditioned DEM described above. The DIR-principle requires a brief introduction. The DIR map defines the direction of flow from each cell in the DEM to its steepest down-slope neighbor. First the steepest down-slope neighbor is determined. The location of the neighbor determines the code for the specific cell. The coding is indicated in the figure below. Each cell in the DEM raster is coded using this algorithm.

- Pits or Sinks already have been removed in de conDEM from HydroSHEDS but could otherwise be filled up or be assigned a NoData value.
- Cells that outlet to the ocean are flagged with value 0 in HydroSHEDS.
- It is important to realize that the steepest slope determines the flow direction
- Cells are assigned a value between 1 and 128 (both ESRI&USGS).

[D. Greenlee, 1987], [Bernhard Lehner, Kris Verdin, Andy Jarvis, 2006], [S.K. Jenson, J.O. Dominique, 1988]

The DIR map is distributed as a HydroSHEDS file by the USGS and is available in 3" resolution. Both HydroSHEDS and ESRI use the same coding for the flow directions as indicated in the figure. For this research the DIR map from HydroSHEDS is used instead of manual generated DIR maps because the USGS took a lot of effort improving the DEM for hydrological purposes, this is why DIR is considered as Input Data, not as a model process but understanding the process of creating a DIR map is required for the right interpretation of further results.

The principle of Flow Direction is presented in the right figure. The conDEM is used as input. The DIR algorithm determines the steepest neighbor slope or the neighbor cell with the largest difference in elevation. In a raster the position of the steepest downslope neighbor is one of the eight directions as presented in Figure 6. This algorithm is executed for each cell in the raster. A map with drainage directions is obtained, see Figure 7.

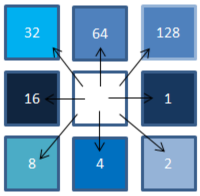


Figure 6: DIR coding

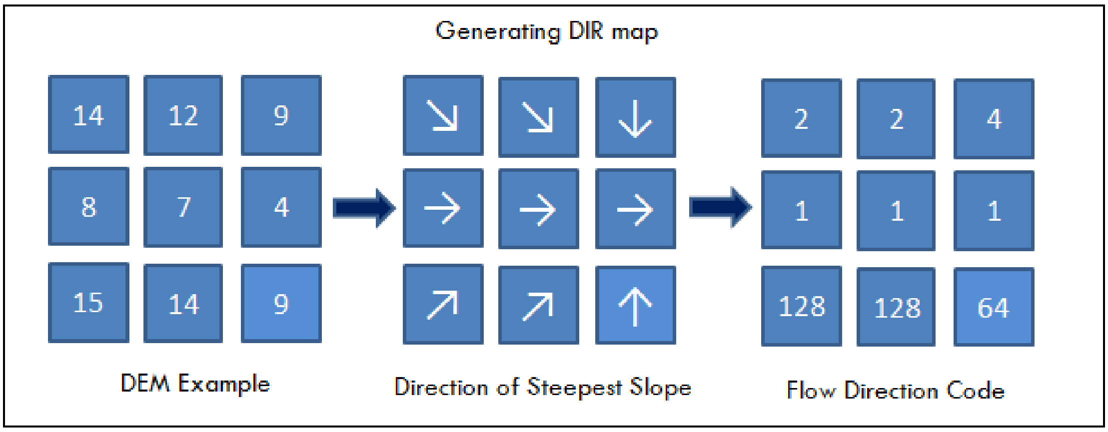


Figure 7: DIR-Map Coding

On a larger scale, a raster is created containing only the values that indicate the drainage direction. An impression of such a map is presented in the Figure 7.

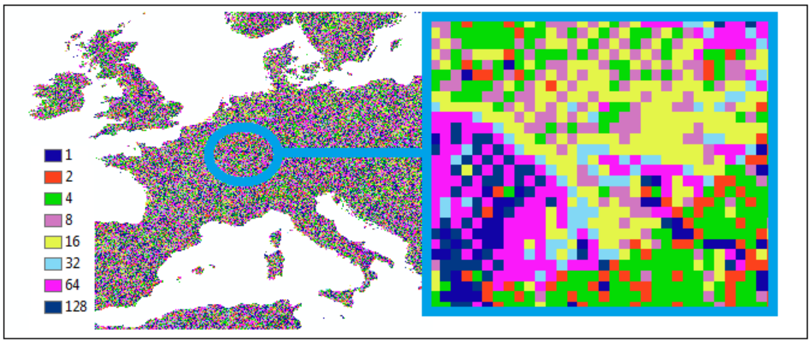


Figure 8: DIR map Europe

Runoff (mm/month)

The Runoff has been mentioned already in chapter 3 and is produced by the UHN/GRDC. The data is available at a 30 miniutes (0,5⁰) resolution and covers the globe from N(83⁰) till S(55,5⁰). The time scale is months. The Runoff is derived from river discharge measurements. The annual average runoff is presented in Figure 9.

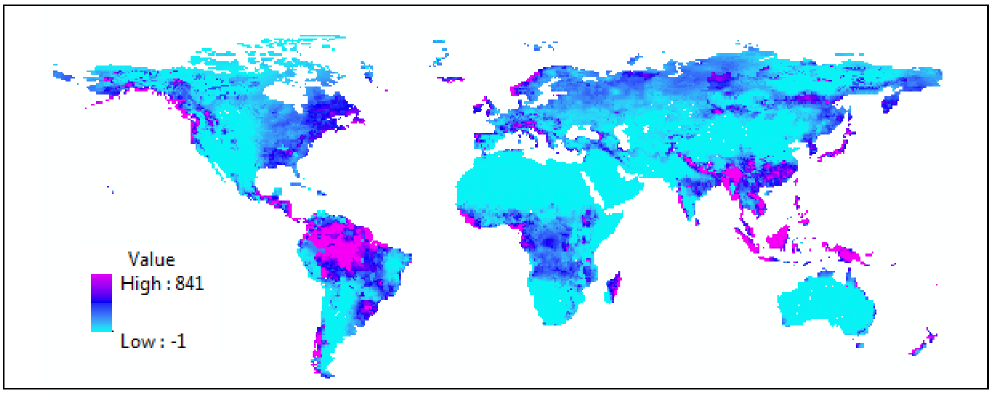


Figure 9: Annual Average Runoff (mm)

An extensive description of the runoff dataset generation principle is presented in the article 'Global, Composite Runoff fields based on Observed River Discharge and simulated Water Balances' [Balazs M. Fekete, Charles J. Vorosmarty, 2004].

The data set from GRDC demonstrates the potential of combining observed river discharge information with a climate-driven Water Balance Model in order to develop composite runoff fields which are consistent with observed discharges.

- Combined runoff fields preserve the accuracy of the discharge measurements as well as the spatial and temporal distribution of simulated runoff, thereby providing the **"best estimate" of terrestrial runoff** over large domains.

The method applied in the preparation of this data set utilizes a gridded river network at 30-minute spatial resolution to represent the riverine flow pathways and to link the continental land mass to oceans through river channels. Selected gauging stations from the Global Runoff Data Centre data archive were co-registered to a simulated topological network (STN-30p) developed at the University of New Hampshire. Inter-station regions between gauging stations along the STN-30p network were identified. Inter-station discharge and runoff were calculated to compare observed runoff with outputs from the water balance model (WBM) simulation. Correction coefficients based on the ratio of observed and simulated runoff for inter-station areas were calculated and applied against simulated runoff to create composite runoff fields.

For the scope of this research it is interesting to know that the GRDC intends to improve the runoff dataset and more important to generate a discharge database. The GRDC intends to develop an algorithm to convert the improved runoff database into a river discharge database. For this research a discharge map is derived from the runoff as well with help of flow accumulation (chapter 4.2) but a separate developed and extensive discharge database would really improve the results of the hydropower estimation tool.

Compared to the DEM the runoff dataset is quite rough (3" versus 0,5⁰ = 30' = 1800"). Therefore the Runoff dataset will not exactly meet the DEM surface dataset. This is presented in Figure 10.

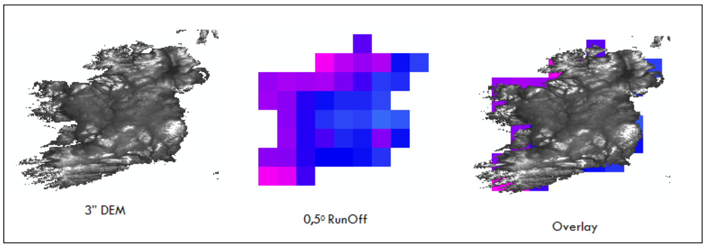


Figure 10: DEM-Runoff overlay

Runoff Interpolation

The DEM and DIR maps are available at a 3" resolution and the RunOff data at 0,5⁰ resolution. Since 60 seconds make 1 minute and 60 minute makes 1⁰ , one runoff cell contains 600 times 600 DEM or DIR cells. Since the model is based on raster data the RunOff needs to be resampled to 3".

Near the shorelines the difference in resolution causes problems. The runoff raster does not cover the complete DEM. For large continents this is no problem since the discharge is approximately not influenced by the contribution of the last shoreline cells. But for small catchments and islands this might cause significant problems and the runoff therefore needs to be interpolated in some occasions.

The runoff data can be interpolated using several interpolation algorithms. For this research Inverse Distance Weighted Interpolation (IDW) was used. The intention of the interpolation is just to enlarge the area of the dataset. The extra data points need to be assigned about the same value as the surrounding runoff values. The IDW interpolation can be adjusted to the desired result. In this case not many cells need to influence the value of the interpolated point but just the 2 or 3 neighbor cells need to determine the interpolated value. For ArcGIS IDW interpolation the following parameters need to be specified;

- Power (N) Controls the significance of surrounding points on the interpolated value. A higher power results in less influence from distant points. It can be any real number greater than 0, but the most reasonable results will be obtained using values from 0.5 to 3. The value used for this research is 2.
- Search Radius.(Defines which of the input points will be used to interpolate the value for each cell in the output raster). A 'fixed' number of points is used here.
- For this research a 'fixed' number of points is used to execute the IDW interpolation. This number of points is 3.

For interpolation the raster dataset needs to be converted into points first. The points are then interpolated. The interpolated points dataset is converted back to a raster, and resampled to 3" to meet the DEM. ImageFigure 11 presents the interpolation of Indonesian runoff data. This is especially interesting because Indonesia exists of small Islands.

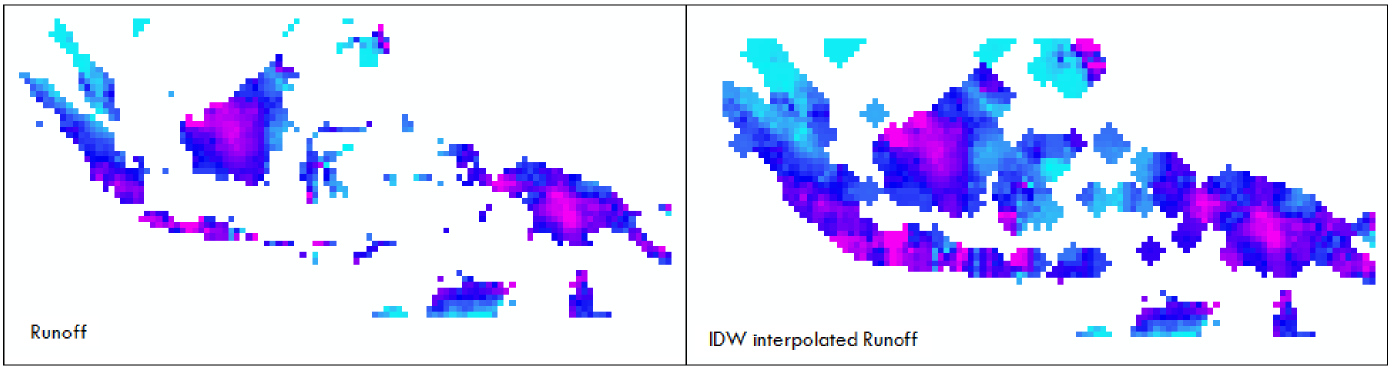


Figure 11: Indonesia Interpolation RO

The impact and importance of interpolation for small areas is presented in Figure 11. The Island of Bali is only covered by two runoff data points. About half the Island has no runoff. The river discharge simulation is really affected.

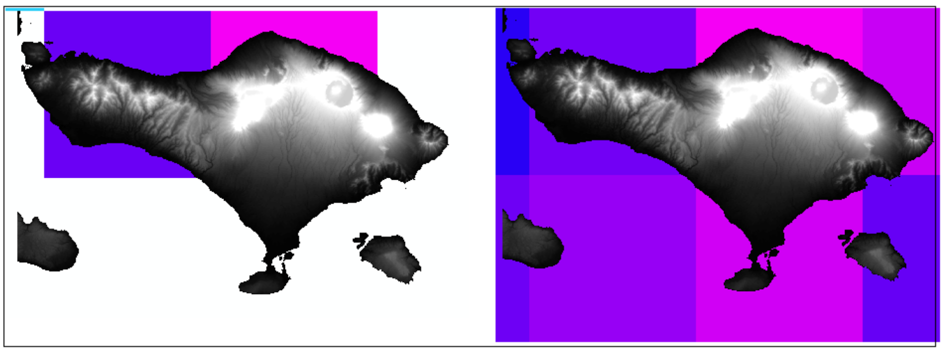


Figure 12: Bali Interpolation

Geo Referencing

All HydroSHEDS data are horizontal geo referenced with the WGS84 datum and EGM96 vertical datum. For the global positioning Figure 13 shows the longitude and latitude map of the world in degrees. In this reference each cell has a square surface of its resolution, in this case 3" times 3".

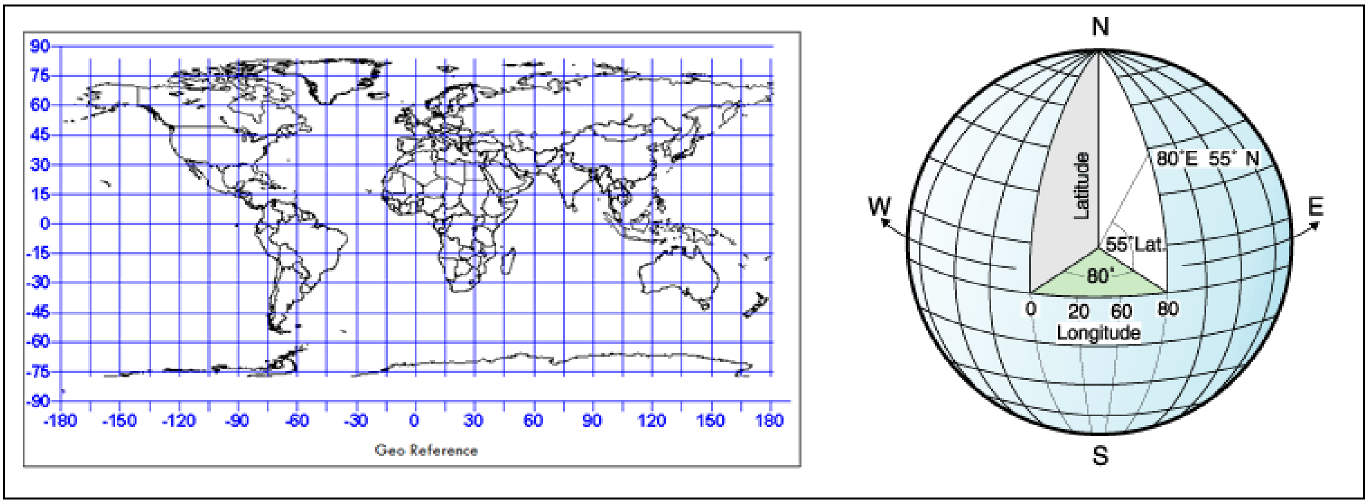


Figure 13: Geo Referencing and decreasing cell size near poles

Near the equator 3" implies about 92 meters but near the poles this is much less. The right side of Figure 14 shows the decreasing latitude when moving away from the equator. For runoff calculations this needs to be corrected.

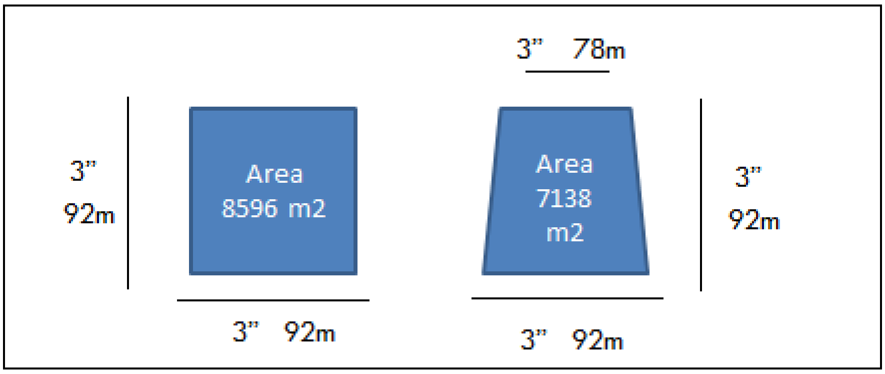


Figure 14: Surface Area Cell (equator; left, north, right)

Cell Size (m^2) and Cell Length (m)

To obtain accumulated runoff (m^3) the runoff (m) needs to be multiplied with the surface area (m^2). The highest resolution is (3") which is about 92 meters near the equator, assuming [1^0 = 111089.56m] and this value decreases when traveling away from the equator and this needs to be corrected with (2).

$$Area\ (m^2) = \left(0{,}5 * \frac{m}{degree}\right) * \left(0{,}5 * \cos\left(\ lattitude * \frac{pi}{180}\right)\right) * \left(\frac{m}{degree}\right) \quad (2)$$

Both a surface area (m^2) and length (m) raster file have been created using (2) at a 3" resolution and later multiplied with the runoff.

5.2 Processes & Calculations

Generate Runoff per Cell

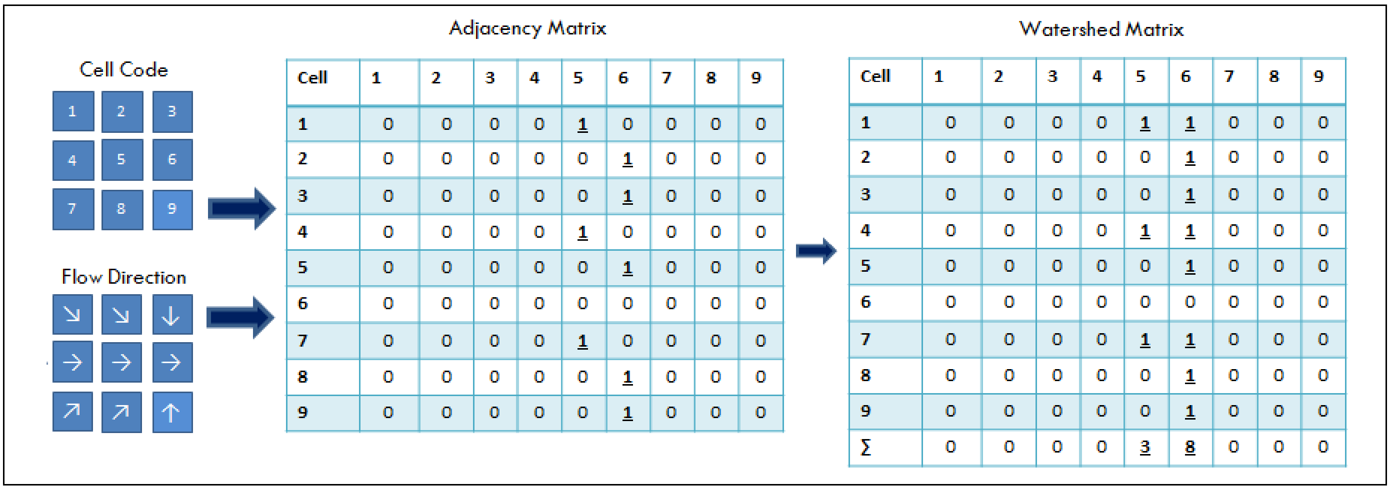
In preparation of the weighted flow accumulation the runoff is multiplied with the corresponding surface area as described on the previous page.

$$Runoff\left(\frac{m^3}{month}\right) = Cellsize\,(m^2) * \left(\left(Runoff\left(\frac{mm}{month}\right)\right)/1000\right) \quad (3)$$

Flow Accumulation

Based on the input flow direction or DIR map a flow accumulation calculation can be executed. Flow accumulation accumulates the weighted flow into each downslope cell. When no weight raster input is involved the weight for each cell is 1 and the accumulation is the absolute number of cells flow into a downstream cell. [D.G. Tarboton, R.L. Bras, I. Rodriguez, 1991].

The example below is based on a 3x3 matrix. The input for the calculation is the DIR map. See Figure 15. First an adjacency matrix is generated. This is a 'connectivity' matrix. When a specific cell drains into another, a 1 is noted in the matrix (not vice versa). This matrix indicates when a cell in the row is one step removed (or drains directly to) a cell in the column. Matrix theory allows us to derive a matrix which shows the first and second derivatives. These are the connections within 2 or 3 steps. In this example all cells connect within 2 steps maximum, so only the first derivative of the adjacency matrix is required. These matrices are summarized yielding the actual 'watershed' matrix. This matrix indicates the cells threw which cells in the column a cell in the row flows. See Figure 15. [N.C. van de Giesen, 2009]



Adjacency Matrix

Cell	1	2	3	4	5	6	7	8	9
1	0	0	0	0	1	0	0	0	0
2	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	1	0	0	0
4	0	0	0	0	1	0	0	0	0
5	0	0	0	0	0	1	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	1	0	0	0	0
8	0	0	0	0	0	1	0	0	0
9	0	0	0	0	0	1	0	0	0

Watershed Matrix

Cell	1	2	3	4	5	6	7	8	9
1	0	0	0	0	1	1	0	0	0
2	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	1	0	0	0
4	0	0	0	0	1	1	0	0	0
5	0	0	0	0	0	1	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	1	1	0	0	0
8	0	0	0	0	0	1	0	0	0
9	0	0	0	0	0	1	0	0	0
Σ	0	0	0	0	3	8	0	0	0

Figure 15: Matrix Calculations

Figure 16 below presents the process of flow accumulation. The summarized values for each column in the watershed values indicate the total number of cells that drain to the specific cell. Optional the unity matrix can be added, which implies that each cell drains also to itself. This is not the case in this example.

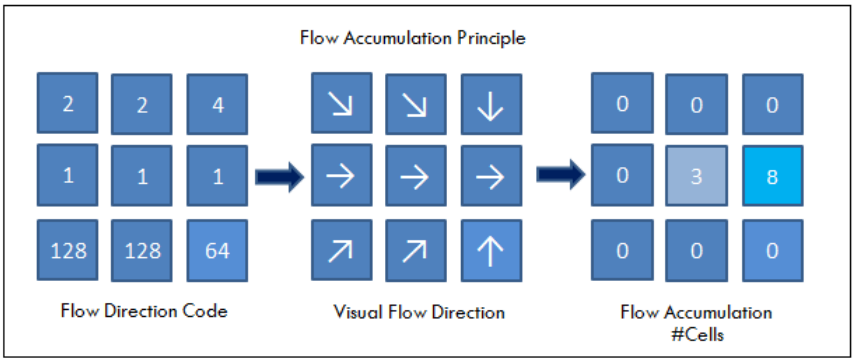


Figure 16: Flow Accumulation Example

Weighted Flow Accumulation

For this research the weight raster is the Runoff (m^3/month) as described earlier. The accumulation therefore results in the amount of Runoff that flows into a specific cell. The required input DIR-map determines how much and which cells drain to a specific cell and the Runoff map determines the amount of Runoff.

In practice it is possible that some cells have a very high number of absolute cells draining into it but if the runoff of those cells is small or zero the weighted flow accumulation will be small or zero and vice versa. An example is presented in Figure 17.

The earlier described accumulation describes the watershed as an accumulation of absolute cells. To generate a map which contains the accumulated runoff, the watershed matrix needs to be multiplied with the corresponding discharge.

The previous example (Figure 16) is generated without a weight input raster. The accumulation exists only of the number of cells that drain into a cell. Lower Cells in the DEM have higher values than cells with a higher elevation. Cells with a high flow accumulation can be defined as rivers. In this model the output of the flow accumulation is a map which indicates the amount of Runoff (m^3/month) which flows into each cell.

Cells with very high flow accumulation indicate rivers, and cells with no flow accumulation indicate ridges, or watershed boundaries. Higher resolution DEM and thus DIR maps result in more accurate the flow patterns.

To obtain a weighted runoff accumulation, the rows of the watershed matrix need to be multiplied with the discharge for each cell. The ones of the 'connectivity' (DIR) are multiplied with the 'weight' (Runoff).

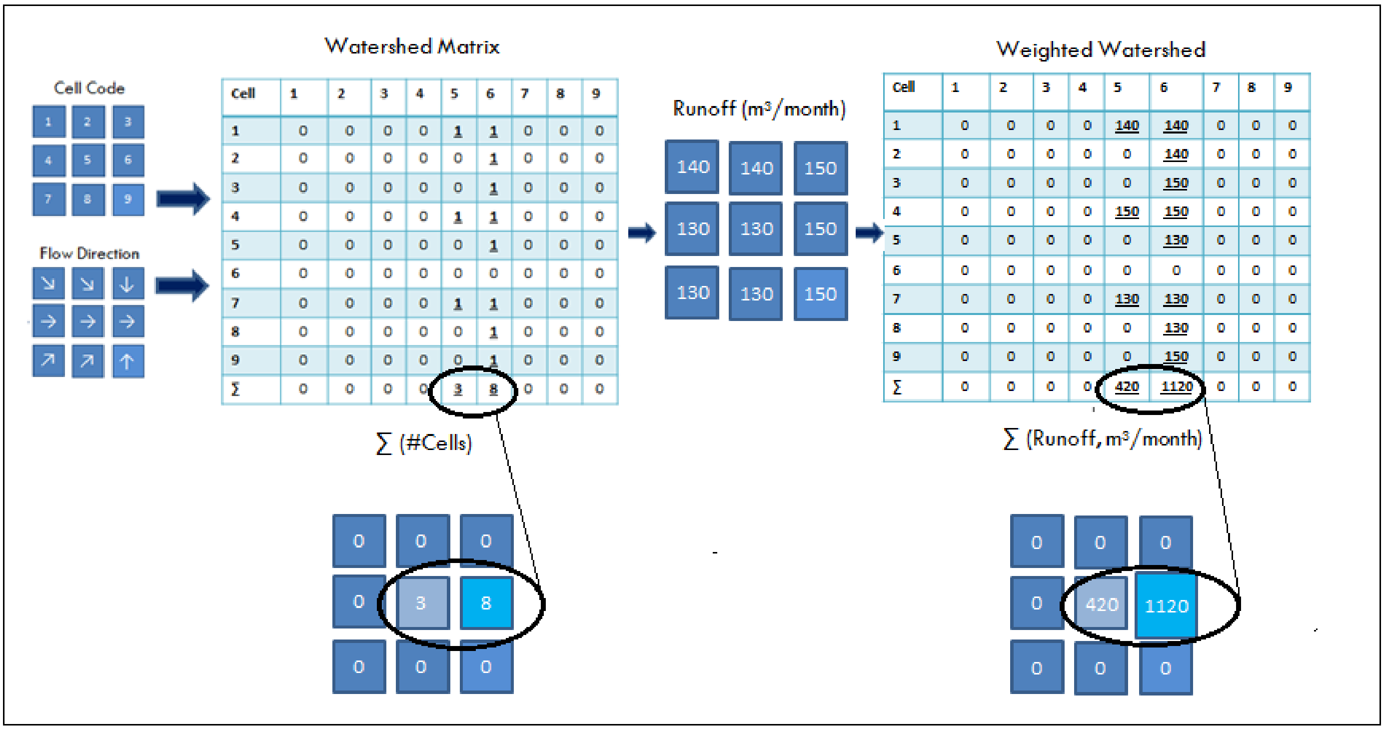


Figure 17; Weighted Runoff Accumulation

In Figure 17 above the multiplication of a watershed matrix with the runoff is presented. Final output is a raster which contains the amount of runoff in m^3/month per cell. The process of flow accumulation is a standard tool in ArcGis but for full comprehension and interpretation of the model and the results the process is evaluated here.

Convert Runoff to Discharge

The output from the flow accumulation is accumulated Runoff (m^3/month). For hydropower development we are interested in the Discharge (m^3/s). Therefore the Runoff is converted into Discharge using (3).

$$Discharge\left(\frac{m^3}{s}\right) = Runoff\left(\frac{m^3}{month}\right)/(\#days * 24 * 3600) \qquad (4)$$

Generate River Map & River DEM

The obtained discharge map now needs to be evaluated. The discharge map yields the amount of discharge for each single cell. The difference in discharge between cells is huge. The previous chapter on flow accumulation already discussed the occurrence of concentrated flow. Cells with a very concentrated flow are likely to appear as physical rivers in reality. The challenge here is to determine wheatear a cell is a river or not. Here the first input variable is involved, the 'select minimum discharge' variable. Cells with a discharge smaller than the minimum discharge are assigned a NoData value, and cells equal or larger are assigned the original Discharge value, formula (6), Figure 18.

$$River = Con(Discharge >' minimum\ discharge', Discharge, NoData) \quad (5)$$

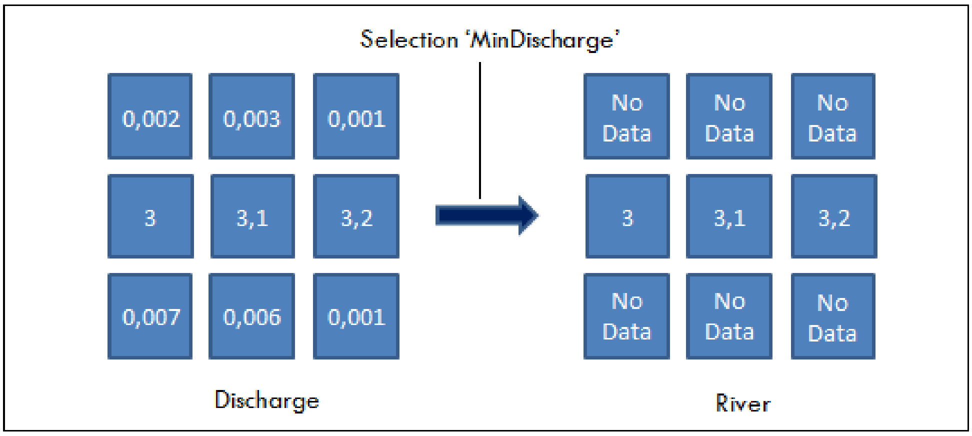


Figure 18: Select Discharge

Besides discharge we are also interested in the Slope and Head of a river. To be able to calculate the slope of a river the original DEM needs to be modified so only elevation values of the river are obtained, and not-river cells are assigned a 'NoData' elevation, so the slope of river cells will only be based on elevation values of river cells themselves see Figure 19.

$$RiverDEM = \left(\frac{River}{River}\right) * DEM \quad (6)$$

$$Con(RiverDEM > 0, RiverDEM, NoData) \quad (7)$$

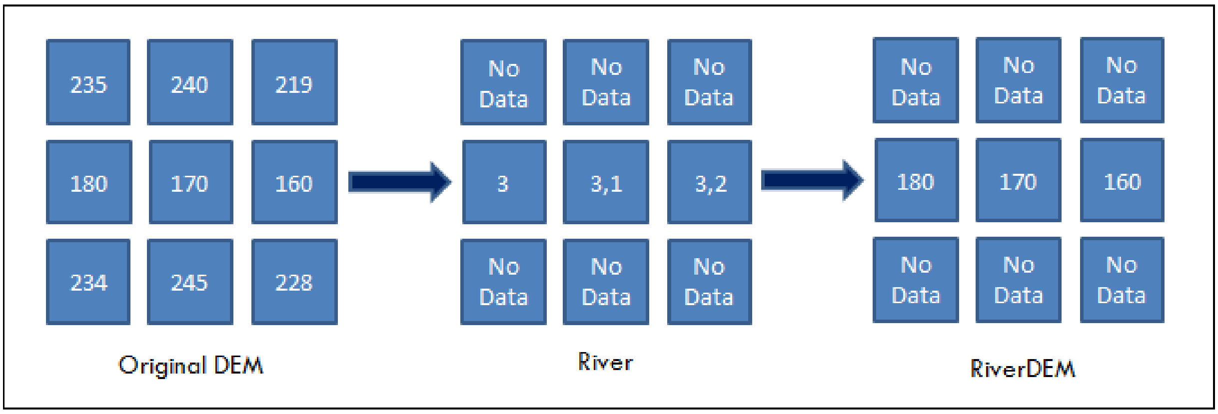


Figure 19: RiverDEM

Calculate Slope & Head

The slope needs to be calculated in the river cell. A cell needs to be a river, and the slope is to be calculated in reference to the up- and downstream river cell. For this calculation we use the RiverDEM map as described on the previous page. A RiverDEM map contains the elevation value of a cell, in case the cell is a river cell, otherwise it contains NoData. If the regular DEM is used, the slope calculation also involves the elevation of the levees. In the case one levee is must higher than the other; the steepest slope direction could be perpendicular to the river and would not be relevant because the head would be calculated perpendicular to the river instead of within the river.

The slope calculation is not as straightforward as would appear on first sight. The first reason for this is that there are different river configurations possible in a raster, Figure 20.

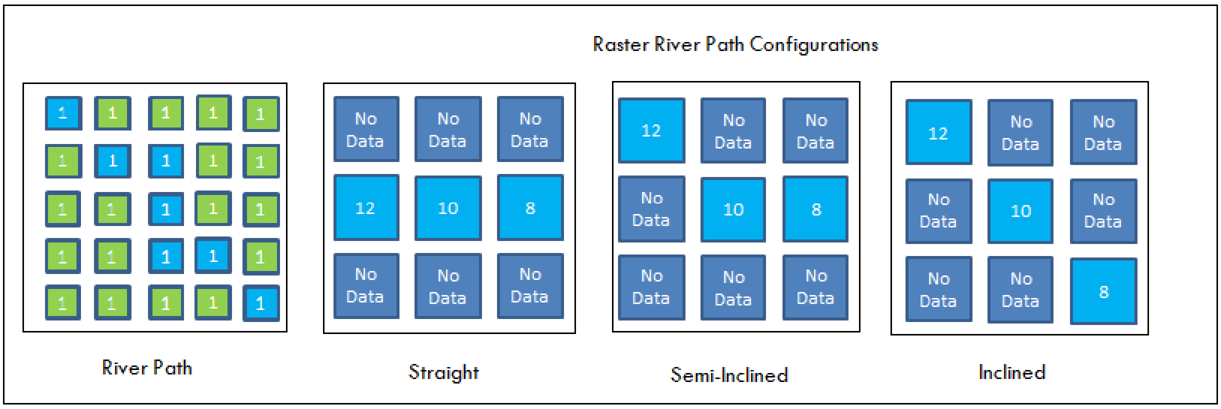


Figure 20: River in Raster

Figure 20 shows a river path in a raster, and three different configurations of neighbor cells that form a river.

Figure 21 shows the extremes. Since the slope is a function of the difference in elevation and the horizontal length, the positioning of the cells affect the calculation. For a regular slope calculation in a cell formula (8) applies.

$$Slope\ (\%) = \frac{dy}{dx} * 100 = \frac{\Delta\ Elevation}{Cellsize\ (2x)} \qquad (8)$$

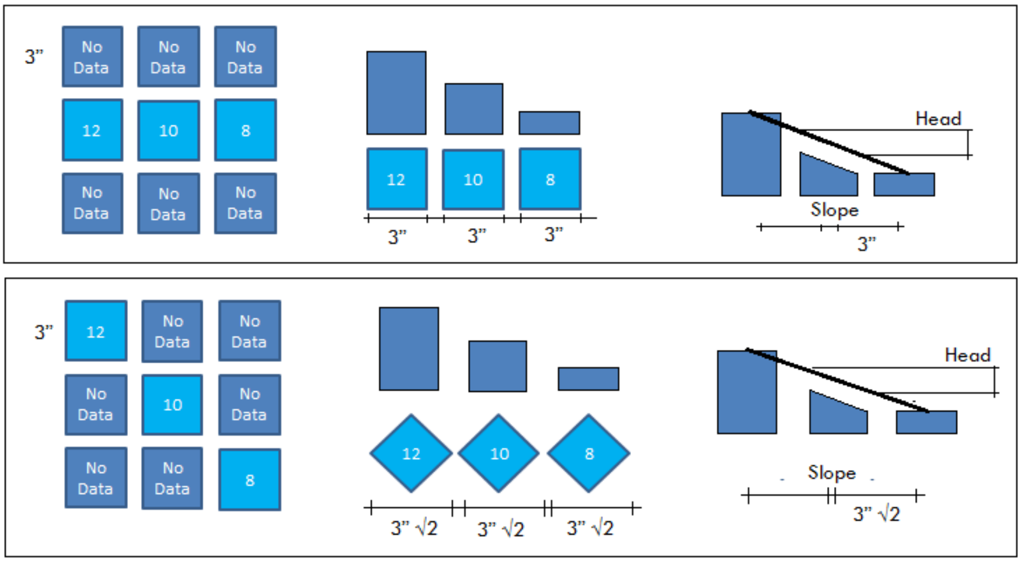


Figure 21: Slope in Raster

In a raster the slope in a cell is the difference in elevation between 2 neighbor cells divided by the distance between the centers of those 2 neighbor cells, which is usually 2 times the cell size. The head is then simply obtained by multiplying the slope percentage of the specific cell with the cell length of the cell, see formula (9).

$$Head\ (m) = Slope(\%) * Cellsize\ (m) \qquad (9)$$

For systematic ArcGIS slope calculations there are some algorithms to determine the slope in each cell. Because a raster contains of multiple neighbor cells the calculation is more complicated then presented on the previous page. This is why the RiverDEM raster has been created, see chapter on River Map and River DEM.

Slope calculations depend on the following parameters;

- Cell size or resolution. (3")
- Number of cells involved in calculation (usually 8, including NoData cells)
- Z-factor: Converts horizontal degree cell size into vertical elevation (m) (depends on latitude).

The basic ArcGIS slope calculation for a 3x3 raster is given by formula (13), see Figure 22 for further explanation. The slope to be calculated is always the slope in the center of a 3x3 raster, in this case cell e.

$$\frac{dz}{dx} = \frac{(c+2f+i)-(a+2d+g)}{(8*[Resolution])} \quad (10)$$

$$\frac{dz}{dy} = \frac{(a+2b+c)-(g+2h+i)}{(8*[Resolution])} \quad (11)$$

$$RiseRun = \sqrt{(\left(\frac{dz}{dy}\right)^2 + \left(\frac{dz}{dy}\right))^2} \quad (12)$$

$$Slope\ (\%) = RiseRun * [\,Zfactor] * 100 \quad (13)$$

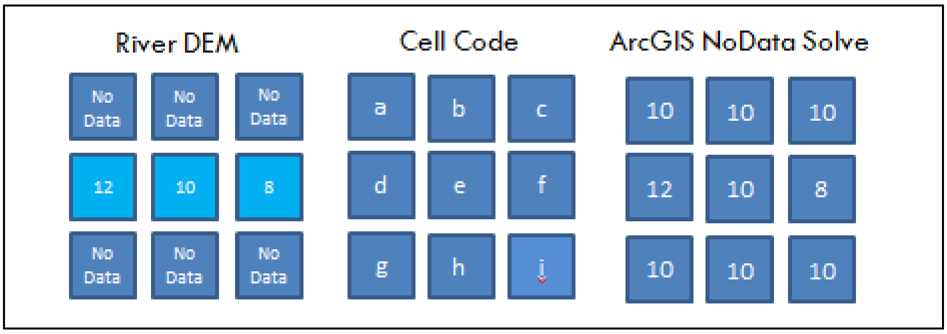


Figure 22: Slope Coding

ArcGIS automatically assigns the value of the central cell, cell e, to all NoData cells. In the case of a straight alignment this is no problem since the values are subtracted anyway. The obtained value needs to be multiplied with a factor 2 since there is a factor 2 in the formula, and the value is divided by 8.

Using the ArcGIS Slope algorithm with a RiverDEM, NoData values as input and corrected with a factor 2, this method results in the correct slope for *cell* e in a straight alignment. For other alignments this method is incorrect since the horizontal distance is not 2 cells, but due the inclined traces the distance might be √2*[cell size], see figure 21.

Depending on the configuration, the slope formula (13) should multiply the obtained head with 1,5, √2, √2/2 or 1 if only looking at the raster configuration. First of all it is hard to systematically describe the configuration because there are a lot of combinations. Besides that it is not a real accuracy because the river path is not equal to the raster approximation, see Figure 23.

For practical reasons the head available for hydropower will be less than the potential head due head reduction caused by friction and structure configurations. For a potential estimation we aim for a ***conservative*** head because in reality the head will be reduced. Therefore the head formula for this research is given by;

$$Head\ (m) = Slope(\%) * 2 * [cellsize] \quad (14)$$

This formula (14) gives the exact slope in straight configurations, and underestimates the slope a little in inclined and semi-inclined combinations.

The 3” resolution, about 92 meters near the equator, is relatively large for small rivers, which implies that for smaller rivers only a fraction of the area of the cell is actually a river. Even in straight alignments the river course can be longer than 2 times the cell size due meandering. The exact river length is hard to determine within a cell and so is the exact location. See Figure 23. This is the reason why the head formula is modified by a conservative factor.

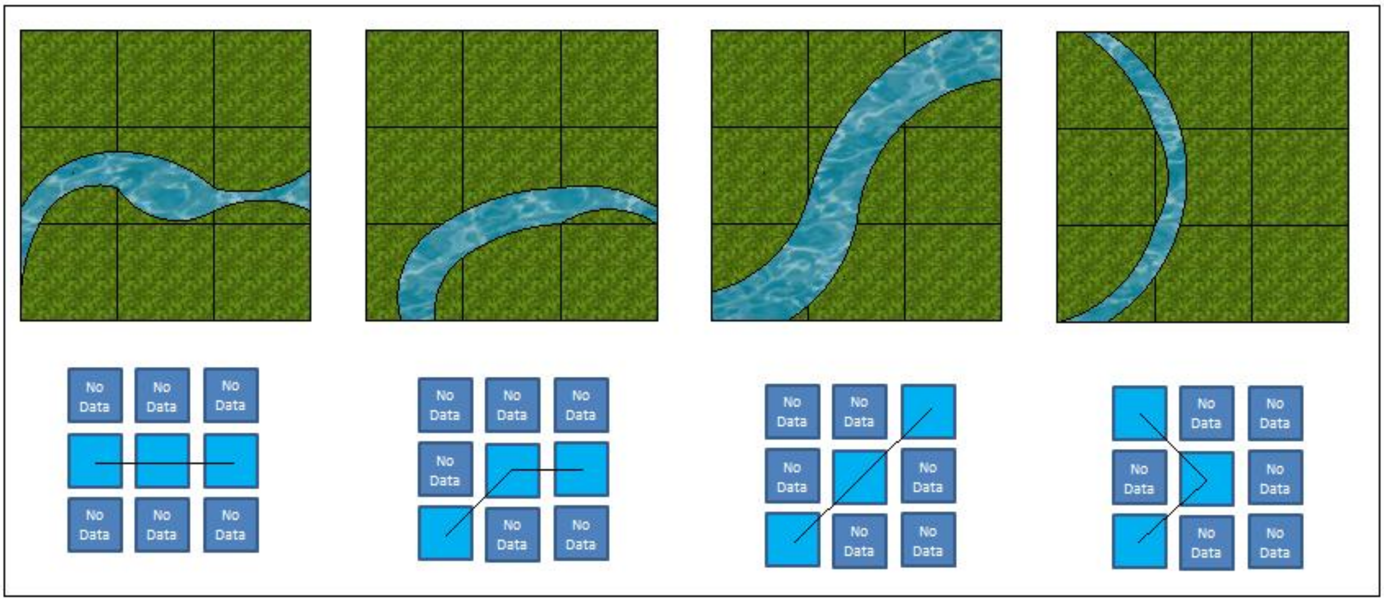


Figure 23: Raster and actual river paths

Calculate Hydropower

The hydropower potential (kW) for each cell is calculated regarding the general hydropower formula as presented in the introduction and given by (15). The input values for the calculation are the minHead and minDischarge map, the gravity acceleration (assumed constant; 9,81m/s²) and the input variable ‘turbine efficiency’, a value between 0 and 1, is discussed under ‘input variables’.

$$Hydropower\ (kW) = \eta(\%) * g\left(\frac{m}{s^2}\right) * Q\left(\frac{m^3}{s}\right) * \Delta H\ (m) \quad (15)$$

$$Hydropower\ (kW) = minHead * minDischarge * 9{,}81 *' turbineefficiency' \quad (16)$$

As explained in the introduction the hydropower output needs to be divided into micro, small and large hydropower determined by the boundary limits.

$$microHydropower\ (kW) = Con(Hydropower < upperBoundaryMicro, Hydropower, NoData) \quad (17)$$

$$preselectSmall(kW) = Con(Hydropower < lowerBoundaryLarge, Hydropower, NoData) \quad (18)$$

$$smallHydropower\ (kW) = \\ Con(preselectSmall > upperBoundaryMicro, preselectSmall, NoData) \quad (19)$$

$$LargeHydropower\ (kW) = Con(Hydropower > lowerBoundaryLarge, Hydropower, NoData) \quad (20)$$

The calculations and filters above result in a separate raster for micro, small and large hydropower. This map contains the amount of potential yearly average capacity (kW) per grid cell, so all individual spots.

Accumulate Hydropower

The hydropower potential in kilowatt has been calculated for each cell. Since the resolution is 3" which implies a cell size varying between about 70 and 92 meters all 'locations' are regarded as single, independent spots. The occurrence of multiple spots in a row or the fact that longer penstocks than the cell size exist is discussed in chapter 4.2. The hydropower maps are maps which contain individual hydropower locations with their corresponding capacity in kilowatt, all other cells that don't meet the hydropower filter, or the required minimum head or discharge are assigned 'NoData'. Now we are interested in the hydropower capacity of a certain region. This means that the capacities of all hydropower spots in that region need to be accumulated, an example is presented in Figure 24.

For this research the minimum region of interest is an area of $0{,}5^0$ by $0{,}5^0$. Since 1^0 is about 111089.56m, the $0{,}5^0$ resolution results in an area of about 55,5 km by 55,5 km or 3080km^2.

The reason for this resolution is that on a global scale this gives a good impression of areas with a lot of hydropower potential. Higher resolutions result in higher peak values but less visibility on global scale. Smaller resolutions are to rough and don't show enough detail in the distribution of hydropower potential. For specific smaller regions other resolutions can be implemented. Regardless the size of the area of interest, the individual hydropower spots always need to be accumulated in order to give insight in the total hydropower capacity of that area of interest.

In ArcGIS the neighborhood function 'block statistics' executes the accumulation of hydropower within the specified area.

- The input raster is the selected hydropower map which contains Hydropower (kW) or NoData
- The neighborhood needs to be selected, for this research a square area is considered
- The size of the neighborhood needs to be selected in number of cells. The resolution of the input map is 3"or $0{,}00083333^0$ the desired resolution is $0{,}5^0$. The number of cells of the neighborhood is thus 600 by 600.
- The calculation that needs to be executed within this specified neighborhood is an accumulation or 'SUM'.
- The output of the calculation is the total value of the hydropower spots within the neighborhood. Each cell within the $0{,}5^0$ *$0{,}5^0$ (600*600 cells) area is assigned this total value.

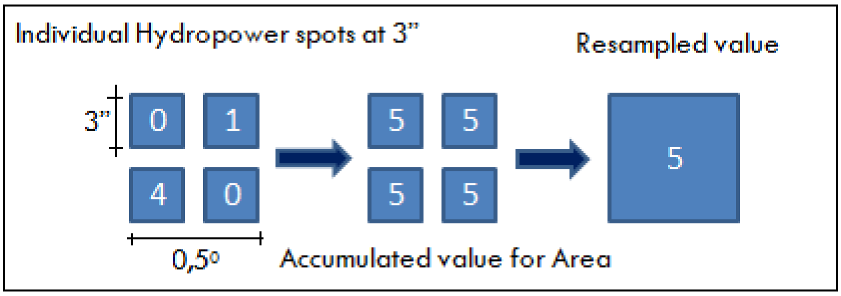


Figure 24: Example Hydropower Accumulation

5.3 Input Variables

[1] Minimum Discharge (m^3/s)

The minimum discharge has two functions in the model. The first is to define when accumulated discharge is to be regarded as a river and the second is to filter rivers with insufficient discharge to be of interest for hydropower development. There is a wide range in turbines which handle different discharges, for this research the occurrence of river flow is prevailing.

The river definition is of importance for selecting the riverDEM which is processed to generate the slope in River map, which should only consist of slopes in rivers with sufficient discharge for hydropower, so one value for minimum discharge determines both the riverDEM and the filter for hydropower.

Each cell with a Runoff > 0 contains a certain discharge in this model for each cell drains to another cell. The question is when a cell is a river (or at least contains surface stream flow on its surface area). Each natural flow trying to reach the sea is in fact a river. No minimum discharge is required, some rivers are ephemeral. A condition for this research is that if there is any flow it is surface runoff in the form of river or creek discharge.

The physical scientific relation between the amount of discharge for a specific area and the occurrence of surface runoff is a little unclear. There is Hortonian overland flow but this doesn't apply to monthly average flows. The process of groundwater flow is complex and for this research scope we are just interested in an assumption which allows us to regard a certain amount of discharge as surface or river flow.

This is likely when a specific cell is located in a depression or a valley. Surrounding cells with higher elevations and groundwater tables will drain to the specific cell creating a wetland or in this case stream flow since every cell drains into another.

Another way to approach this problem is to look at the velocities of groundwater flow. Given the discharge for a single cell, assume the depth, gradient, k-value and effective porosity of the aquifer and calculate the groundwater velocity. When this value appears to be unrealistic large there probably is surface runoff.

For example a cell with a 90m resolution, a 90m aquifer depth, and a 0,3m^3/s discharge has a 3,2m/d groundwater flow velocity. Even for rough sand layers this is much higher than average groundwater flows and surface runoff is likely to occur [DWR, 2012].

When selecting a '*minimum discharge*' the following aspects should be considered;

- Minimum discharge required for feasible turbine operation (in combination with head).
- Simulated discharge for specific cell by model should in reality be surface runoff or river flow. Minimum discharge required, otherwise likely to be groundwater flow (not suitable for hydropower).

[2] Minimum Head (m)

The minimum head as an input variable filters the head required for hydropower development. This minimum head is determined by the type of turbine. Both low- and high head turbines exist. Low-Head Turbines deal with a head in the range between 2m and 35m [D. Krompholz, 2008]. Only Archimedes Screws and Hydraulic Wheels deal with smaller heads but these techniques are not suitable for global modeling.

The DEM as described earlier is measured with certain errors and uncertainties and the derived slope and head have uncertainties as well. This error becomes larger in flat areas where the slope direction to its steepest neighbor becomes less clear than in steep mountain areas where this usually is obvious. Steeper slopes and higher head differences in for example valleys are more accurate and strongly indicate that there is significant drop in the river flow path and are therefore more reliable.

The minimum head is the difference in elevation within the cell resolution!

When selecting a '*minimum head*' the following aspects should be considered;

- Different turbines require a different minimum head (low- and high head turbines).
- The head resulting from the model is more reliable when the head is larger (>10m), in other words; areas with steep slopes are modeled more accurate.
- In general; the higher the head, the more accurate, thus the higher the minimum head, the more accurate the results will be. Real large head differences are quite obvious (waterfalls, riches).
- The head only applies to one cell. It is the difference in elevation over the cell resolution.

The issue of head over one cell

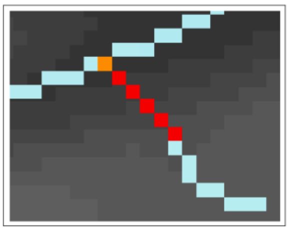


Figure 25: multiple Hydropower location in a row

The head is only calculated over one cell. The resolution determines the head over one cell. The question might arise that in practice hydropower configurations exist of long penstocks that cover much more than one cell (about 90m). In specific hydropower spots this might cause trouble. The model only calculates spots over one cell size while in fact one spot can be based on a penstock that covers 4 cells. In most cases the model will come up with 4 spots in a row with a quarter (depending on the head per cell) of the capacity (Figure 25: multiple Hydropower location in a rowFigure 25). The accumulation of the capacity will be approximately equal. Complex penstock configurations will not be accounted for.

[3] Turbine Efficiency

The turbine efficiency is a variable depending on many parameters. The highest efficiency is obtained when a turbine is used in an optimal design configuration. Different turbines are designed for different configurations, which are mostly influenced by the head and discharge (low head, high discharge, high head, low discharge). The efficiency typically ranges between 60% and 90% [O. Paish, 2002].

Figure 26 presents the different turbine efficiencies plotted against different proportions of design flow. The optimum design flow range results in an average efficiency between 75% and 85 %. Figure 26 gives insight in the application of different turbines for different combinations of head and discharge as well.

This research is based on monthly average discharges, derived from monthly averaged runoff and yearly averages. It is therefore unlikely to assume that the turbine will operate at the optimal design flow, on the other hand are out-of-date techniques with low efficiencies excluded from the potential estimation. An average annual efficiency of 70% is a quite conservative assumption for capacity estimation. It is important to realize that capacity (kW) and production (kWh) are different definitions. For kWh estimations the monthly fluctuations and actual efficiencies need to be accounted for. For the capacity calculation an efficiency of **70%** is valid.

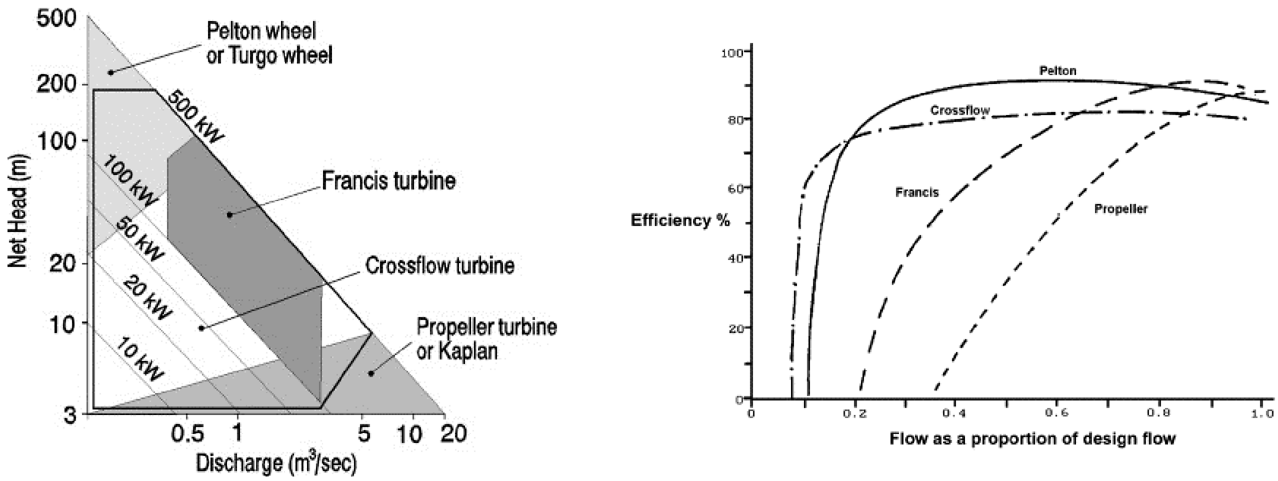


Figure 26

[4] Hydropower Category Boundaries

The three types of hydropower as defined in the introduction are micro hydropower (5kW – 100kW), small hydropower (100kW – 10.000kW) and large hydropower (>10.000kW or 10MW). The model defines small, medium and large hydropower. To separate three categories, two input variables are required as boundaries. The unit for hydropower in the model is kW, so all boundaries are defined in kW. Accumulation values might be in MW.

- Micro Hydropower (5kW – 100kW)
- Small Hydropower (100kW-10.000kW)
- Large Hydropower (>10.000kW)

For this research the variable input boundaries are therefore 5kW, 100kW and 10.000kW.

6. Research Area

The input variables have been discussed in the previous chapter. Together these input variables determine the research area. For this research the input variables are assigned the following values;

- *Grafity Acceleration* — g — 9,81 — (m/s^2)
- *Minimum Discharge* — Q_{min} — 0,1 — (m^3/s) or (100L/s)
- *Turbine* Efficiency — η — 70 — (%)
- *Minimum Head* — H_{min} — 4 — (m)
- *Lower Boundary MicroHydropower* — $P_{Low}Small$ — 5 — (kW)
- *Upper Boundary MicroHydropower* — $P_{up}Small$ — 100 — (kW)
- *Lower Boundary Large Hydropower* — $P_{low}Large$ — 10.000 — (kW)or (10 MW)

The research area is presented in Figure 27. The minimum head and discharge result in a green marked area that is by defenition excluded as a hydropower outcome area. The grey triangle in the lower left corner is the area lower than 5kW, or pico hydropower and is therefore excluded as well. The 100kW and 10.000kW separate micro, small and large hydropower. The areas indicate all possible combinations between head and discharge.

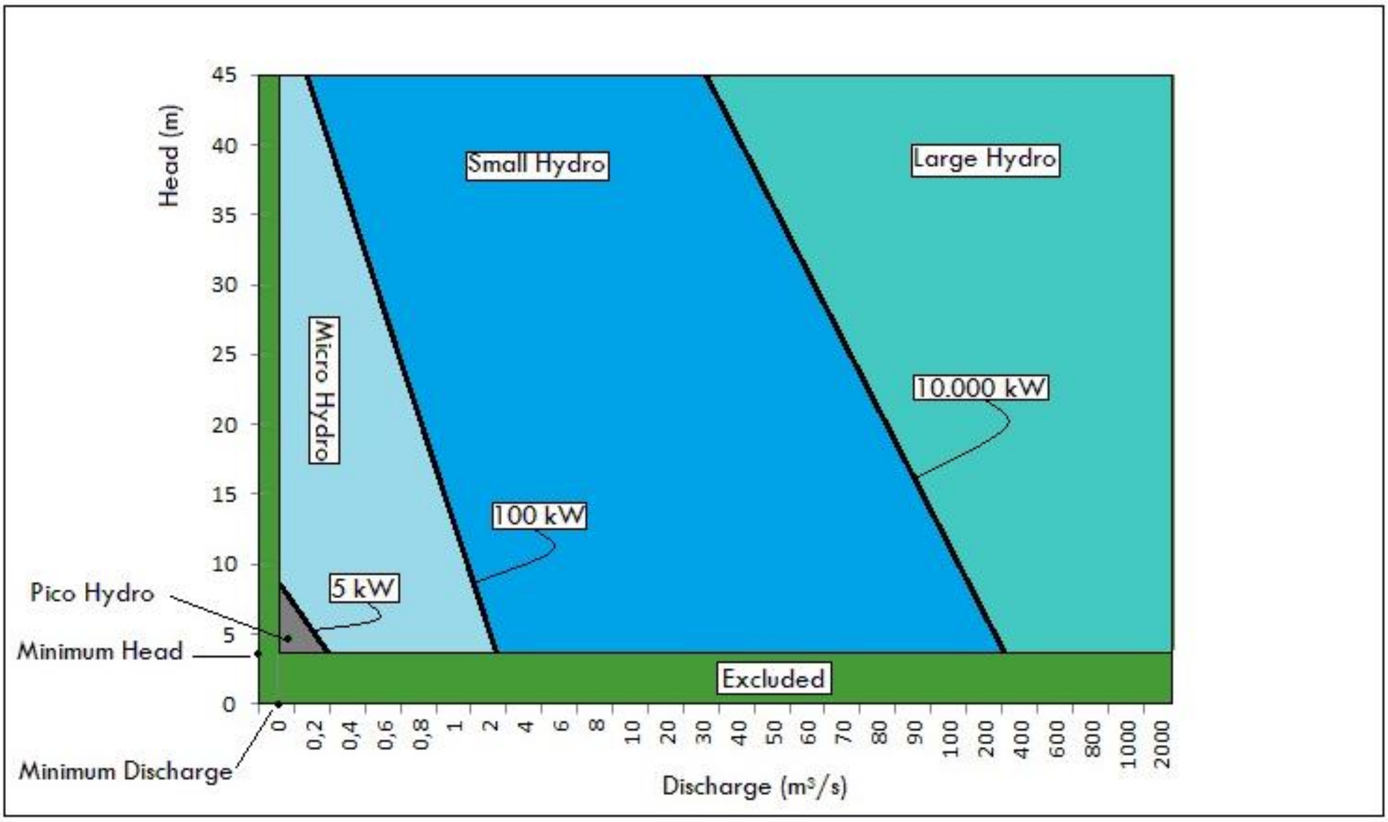
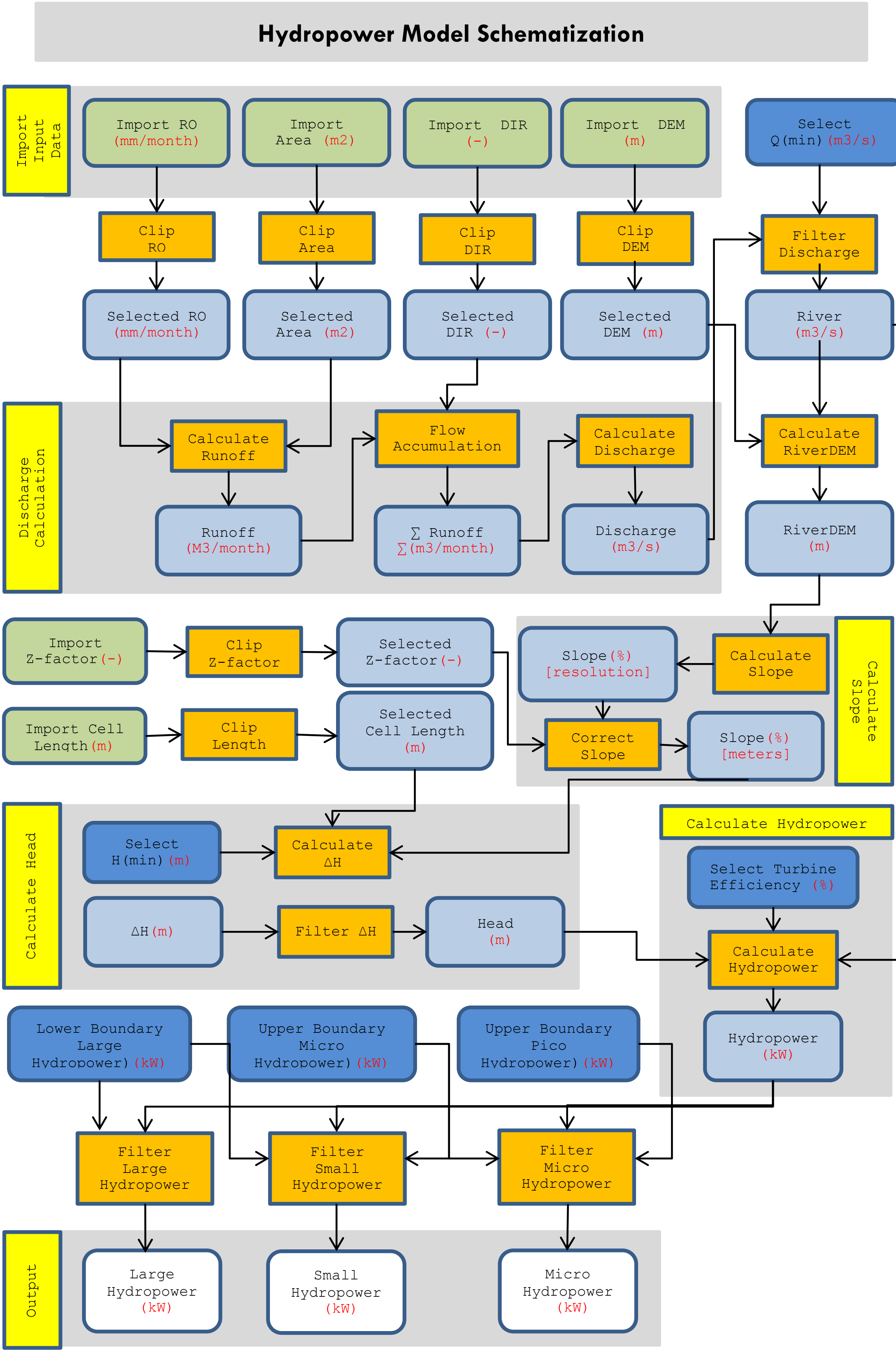


Figure 27: Model outcome area

Higher heads and discharges than indicated in Figure 27 above are possible. Since the head is only accounted over one grid cell it is almost impossible to have heads over 100m. Discharges over 2000m^3/s are common but are considered to be large rivers, which usually occur downstream in the catchment in flat areas. The combination of high head (>100m) and high discharge (>2000m^3/s) will seldom occur but is accounted for in the total potential.

Figure 27 presents the possible outcome area in which the results of the simulation will appear.

7. Model structure and appearance



The model on the previous page is a visual schematization of the model procedure steps. All processes and elements of the model have been examined and dealt with in theory and principle. In this chapter a more practical insight is given into the meaning of modeling.

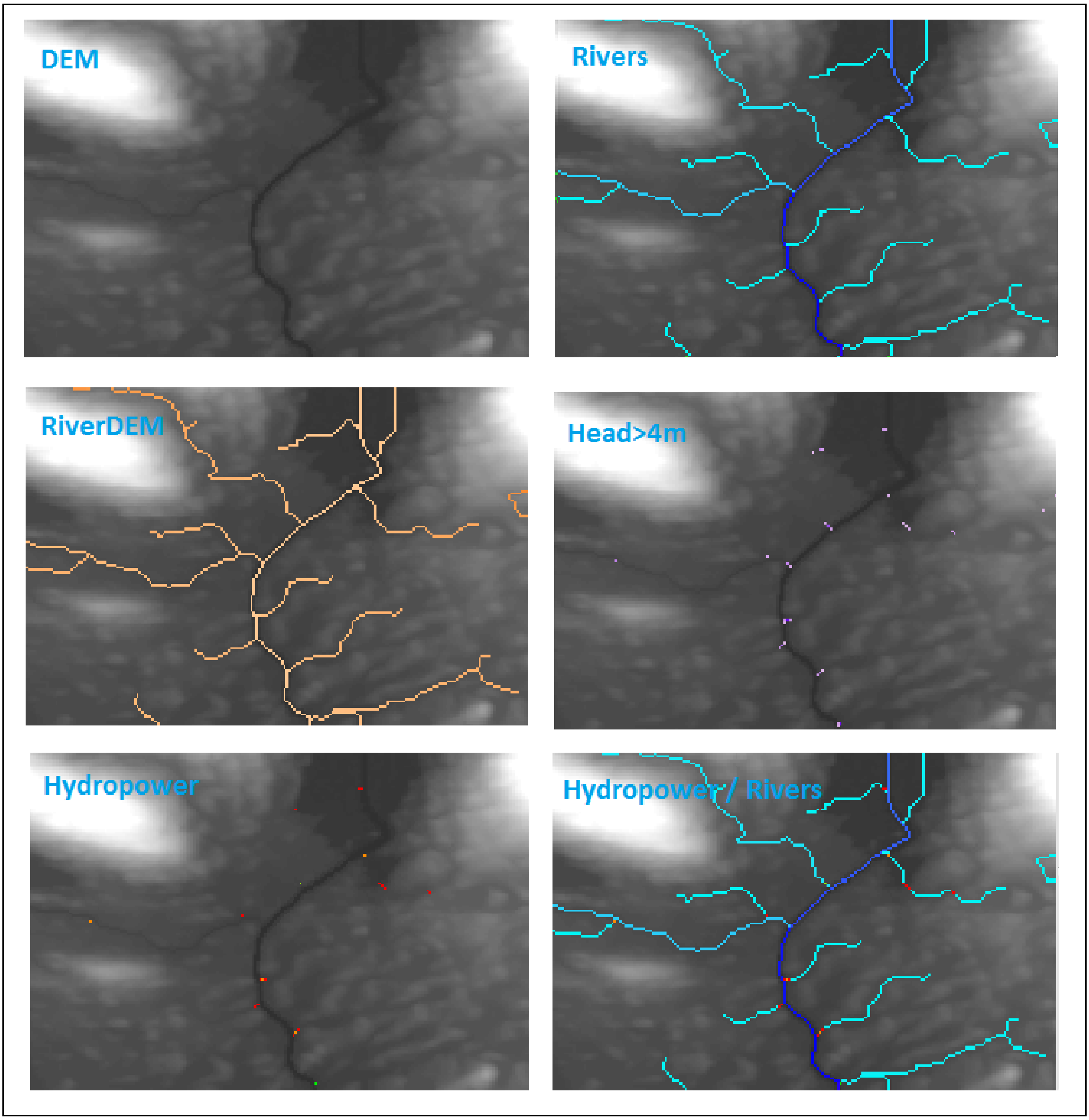


Figure 28: Rivers, RiverDEM, Head and Hydropower projected on DEM

Figure 28 visualizes the modeling steps. Based on the DIR and Runoff data a river layer is generated. A river is a cell that meets the input variable 'minimum discharge'. For each cell that is a river cell, a separate DEM is extracted called the RiverDEM which consists of elevation values for river cells. The head needs to be calculated within the river and therefor the slope is calculated from the RiverDEM. The slope for each river cell is then converted to 'head' with the cell length map and afterwards filtered with help of the 'minimum head' input variable resulting in a head map for river cells. The head and river layers are than combined to calculate the hydropower for each cell. Each cell that contains hydropower potential is thus automatically a river cell and has a certain head.

All layers contain of equally sized cells and it becomes clear that only a fraction of the DEM is a river cell as well and an even smaller fraction is both a river and a hydropower cell as well.

8. Model Output Example & Interpretation

The individual hydropower spots are accumulated for an area of 0.5^0. In contradiction to individual locations, the accumulated potential gives a quick insight in the hydropower potential of a region. This potential is the annual average hydropower potential for Ireland Figure 29.

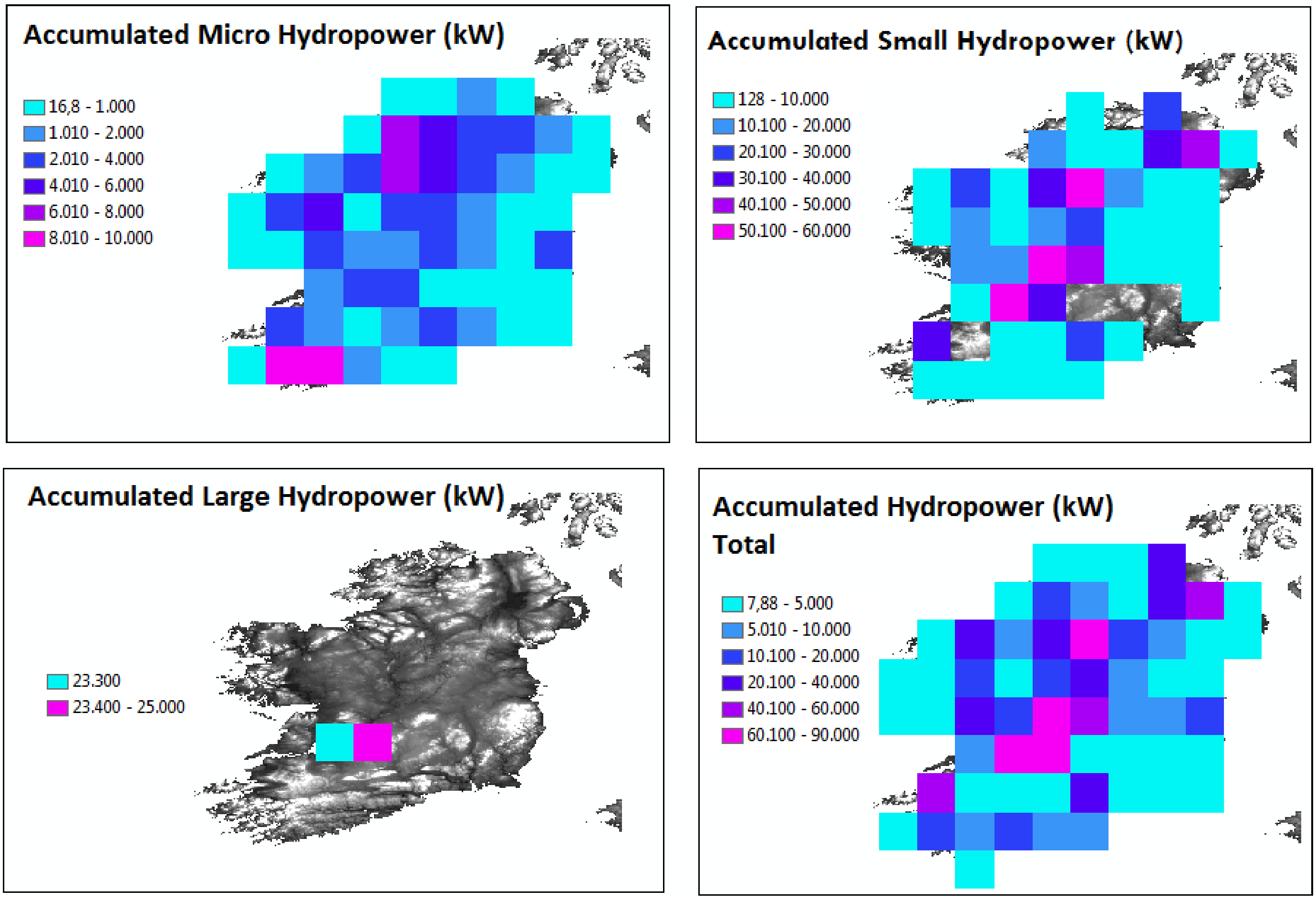


Figure 29: Accumulated Hydropower (kW) for Ireland

A quick analysis of the image above lead to the conclusion that large hydropower (>10.000kW) is rare in Ireland and that small hydropower is the largest potential contributor, while micro hydropower is distributed quite equally over the Island. Ireland has regular precipitation periods and moderate hills or small mountains. Ireland is not a perfect location for hydropower development but still there is some potential.

Table 4: Hydropower breakdown Ireland

Hydropower Breakdown Ireland			Individual		Accumulated	
	Number	Total (kW)	min (kW)	max (kW)	min (kW)	max (kW)
Total Hydropower	8112	827600				
Micro Hydropower	7387	112812	5	99	16,8	8617
Small Hydropower	721	650700	100	9818	128	63500
Large Hydropower	4	47700	10500	13800	23400	24400

From Table 4 can be concluded that the annual average potential hydropower capacity is about **827MW** which is the equivalent of 2 moderate coal power plants.

9. Quality Evaluation

In order to be able to simulate the world hydropower potential, simplifications and assumptions need to be made. The hydrologic restrictions already have been dealt with, and here a further explanation of the possible errors of DEM and DIR data sets are discussed.

The HydroSHEDS datasets based on shuttle elevation data and processed as described earlier gives a good approximation on the actual river paths. HydroSHEDS has been evaluated and compared to other hydrologic databases resulting in the following statements;

- Generally, HydroSHEDS shows significantly better accuracy than HYDRO1k, a global hydrographic data set at 1-km resolution (USGS 2000), due to HydroSHEDS being based on a superior digital elevation model.
- Generally, HydroSHEDS shows significantly better accuracy than the river layer of ArcWorld (even in difficult areas) as ArcWorld has been incorporated in the conditioning process of HydroSHEDS.
- Generally, HydroSHEDS does not reach the accuracy of high-resolution local river networks as depicted in existing maps or remote sensing imagery. The user is thus encouraged to further improve HydroSHEDS through incorporating local information.

The systematical improving of satellite DEM data (hydrologic conditioning) and the systematical deriving of flow direction data includes some errors. First of all the DEM data is subject to surface aspects as vegetation, roughness, wetness and radar shadow [Freeman, 1996].

- Areas of low or not well-defined relief, including lake surfaces.
- Varying vegetation cover, particularly in areas of low relief, e.g. large river floodplains. The radar signal is, at least partly, reflected from atop and within the vegetation cover and the returned signal is thus a complex mix of land surface elevation and vegetation height.
- Low-relief coastal areas, in part due to the barrier effect of mangroves.
- Large-scale roads or clearings in vegetation of low-relief areas. The lack of vegetation causes artificial depressions in the elevation surface.
- Rivers less than 90 m wide enclosed by riparian vegetation. The vegetation effect can cause the river channel to appear slightly elevated.
- Braided rivers and deltas. The use of the single flow direction algorithm does not allow for depiction of river bifurcations.
- Narrow gorges. If the gorges are less than 90 m wide, they can appear closed on the elevation surface at 3 arc-second resolutions.
- Inland sinks and depressions. These are often ambiguous or temporary in nature. Additionally, in karst areas flow paths are not necessarily terminated at sinks due to possible underground connectivity, and artificial depressions like large-scale mining may have flow bypasses.
- Elevated “barriers” in the elevation surface that in reality have no effect on flow continuity (e.g. bridges, high-density housing areas).

All these potential errors and uncertainties might lead to incorrect river paths, especially in flat areas. For this research the main purpose is not to come up with exact river paths on local scale but to make an assessment of the global hydropower potential. For this purpose the HydroSHEDS data is the best available global dataset. In general the results obtained by HydroSHEDS flow directions are very satisfying, leading to reliable and realistic river flow paths.

For both the accuracy of the Head (5.3 Input Variables) and the location of the flow path the uncertainties need to be kept in mind.

The hydropower calculation exists of several calculation steps and input data. A qualification and description of potential inaccuracies is presented in Figure 30 below.

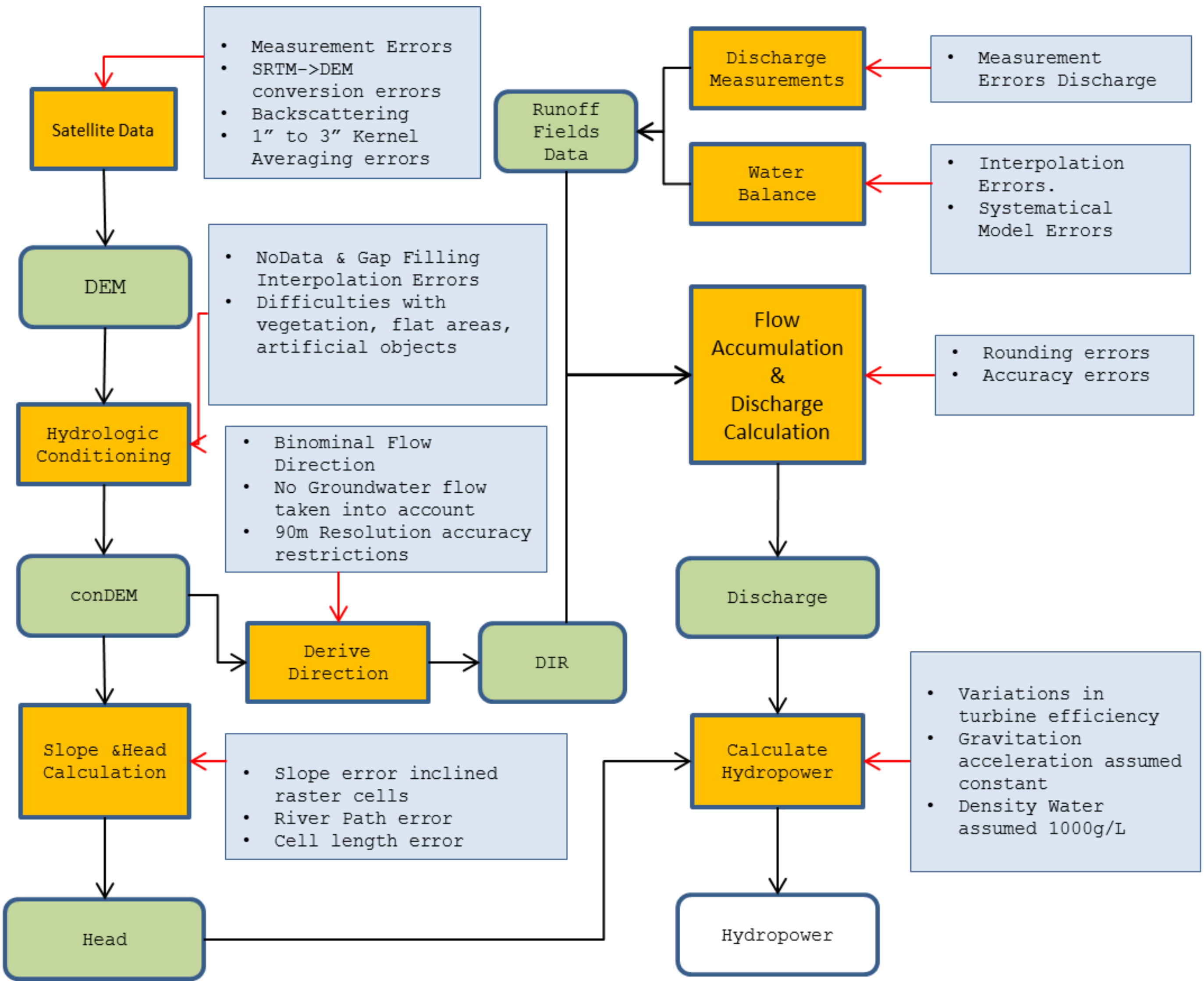


Figure 30: Error Qualification

The hydropower formula directly depends on the Head, Discharge and Turbine efficiency. The quantification of the errors in these factors is very hard, but it is important to be aware of the fact that errors will occur. An attempt to qualify these errors has been made.

Runoff

The runoff fields are based on disaggregated discharge measurements combined with water balance models. Errors in here are inevitable. However on a monthly average, and even more a yearly average month these errors will level out as well. Nevertheless a fluctuation of the actual runoff around the calculated monthly average can occur in the order of about 50%.

Discharge

The discharge depends on the fluctuations in the runoff, as well as the accuracy of the Flow Direction Matrix from HydroSHEDS. A lot of effort has been made to improve this dataset as much as possible, still some errors will occur and flow will be accumulated in another way than it is the case in reality. For this research some river discharges have been checked on river data bases and some field work measurements. For larger rivers the accuracy of the monthly average discharge was in the order of 20% and for smaller rivers in the order of 50%. On a global scale it is impossible to execute a more detailed analysis it is therefore assumed that the discharge accuracy is about 50%.

Head

The head is derived from the slope which is derived from the DEM. The DEM itself has quite a large error in absolute elevation but for slope calculations we are interested in the elevation of specific cell in reference to another cell and that accuracy is much higher.

Another aspect in favor of the accuracy for this purpose is that in steeper areas with more slope (>10%) the accuracy of the SRTM increases. Hydropower needs certain head and thus slope and thus are the elevation points that are relevant for this research more accurate than average [Y. Gorokhovich, A. Voustianiouk 2006].

- The accuracy of the vertical errors ranges between +/- 0,47m to +/- 7.58 m depending on the location and the slope. For this research it is assumed that the maximum error in vertical elevation will occur over a certain area and not between two adjacent cells.

Figure 31shows the SRTM data plotted against GPS measurements. The graph shows that there is no systematical error and the actual value might be higher or lower than the indicated vertical elevation by the DEM. This implies that on a global scale that there is a certain error but the effect might be damped.

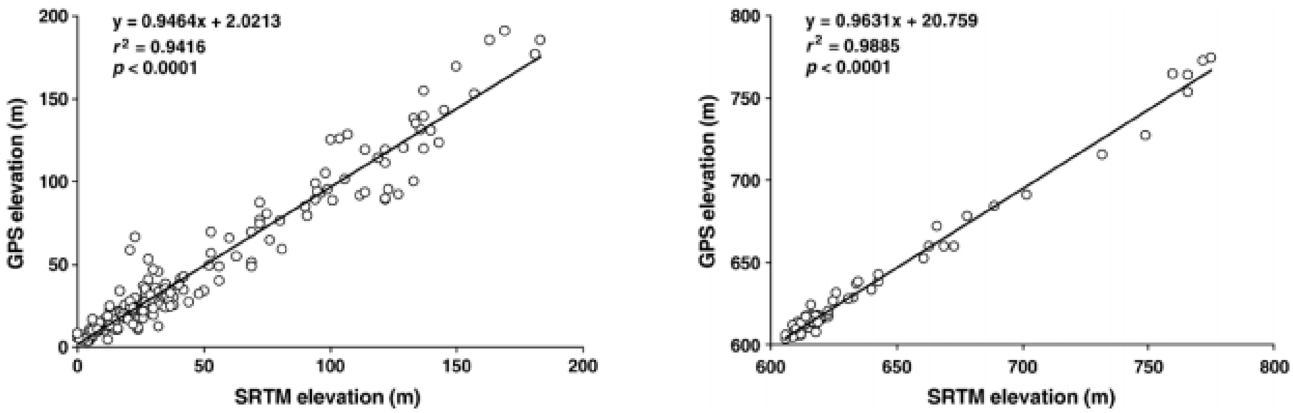


Figure 31: SRTM Elevation data accuracy [**Y. Gorokhovich, A. Voustianiouk 2006**].

The part 'Calculate Slope & Head' from chapter 5.2 already dealt with the cell size error and the configuration errors for the slope. Inclined cells are subject to a certain error of about 30% and the positioning of the river path in reference to the smallest or largest cell length (see chapter en decreasing cell length at certain latitude; " Cell Size (m2) and Cell Length (m)") includes another error.

It can be concluded that the head is subject to diverse errors, namely the SRTM data error, the cell configuration error, the cell size error and the 'actual river path' error. As a matter of fact these errors occur independent from each other. An integral error of 50% is assumed for this research.

Turbine efficiency

This research assumes a turbine efficiency of 70%. In reality this value fluctuates between 60% and 90%, depending on the optimal operation specifications, turbine type and many other factors. An error of 30% is accounted for in this research.

Approximated integrated error

The errors in head, discharge and turbine efficiency are regarded to be independent and thus non-correlated errors. Therefore the integrated error for the hydropower can be estimated by the hydropower formula (1) in terms of errors;

$$Error\ Hydropower\ P\ (\%) = Discharge(50\%) + \Delta H(50\%) + \eta(30\%) + g(0{,}25\%) \qquad (21)$$

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Appendices

Appendix I – Interface

The model is setup in a relative user friendly way. All input data and input variables can be inserted in the required fields. A help function is available for every field as well. The output location for micro, small and large hydropower needs to be determined as well.