Derivation of Flow Duration Curves to Estimate Hydropower Generation Potential in Data-Scarce Regions

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Abstract: Small-scale hydropower is a robust and reliable form of sustainable energy supply in remote areas. On the one hand, the potential for hydropower generation depends on the specific climate in a given place, and precipitation above all. On the other hand, such potential also depends on the catchment's characteristics, e.g., topography, land use, and soils. In the absence of discharge measurements, the available river flow for hydropower production can be estimated in the form of a flow duration curve based on these variables. In this study, the lumped rainfall-runoff method by Crawford and Thurin (1981) was modified to calculate a flow duration curve with a daily time step for an ungauged catchment in Nicaragua. Satisfactory results could be obtained by calibrating the method with the aid of a few discharge measurements. Best results were obtained with a parameter set for groundwater flow and recharge to groundwater from excess soil moisture of 0.014 and 0.6, respectively. Considering the climate and catchment characteristics of the study site, this parameterization can be physically reasoned.

1. Introduction

Small hydropower is a mature technology that is economically feasible and has, if properly planned, minimal impact on the environment. It has significantly contributed to solving the problem of rural electrification through improving living standards and production conditions, promoting rural economic development, alleviating poverty, and reducing emissions. With its most ancient use, the water wheel, small hydropower can also foster local tourism and provide mechanical power, such as for crop grinding, for example [1]. Overall, approximately 36 percent of the total global small hydropower (<10 MW) potential has been developed as of 2016 [2].

The United Nations Sustainable Development Goals include affordable and clean energy, climate action, life on land, no poverty, industry, innovation, and infrastructure [3]. All of these topics are also part of rural electrification in developing countries via small hydropower. The use of clean energy sources and long-living material reduces environmental pollution and leads to reduced poverty by also empowering local communities with self-sustaining production cycles.

Compared to other sources of energy, hydropower has several advantages. It is a more concentrated source of energy than wind and solar energy, due to the density and kinetic energy of water; the available power is predictable; energy is normally available on-demand; no fuel is needed, and minimum maintenance (machinery and civil works usually have a lifespan of more than 50 years) is required [4]. Hence, the use of small hydropower as a reliable and renewable energy source remains a promising option for the electrification of remote areas, especially in developing countries

where national electric grids are too far away to become a feasible connection. According to common terminology, hydropower covering less than 100 kW is often referred to as "micro-hydropower" (MHP) [5].

However, in many cases, little data for describing the conditions of a site is available, and as a result, the planning process can be difficult. A principal means for the feasibility study of a hydropower plant is sufficient information on river discharge at a potential plant site. Whereas the plant site can be more or less easily determined through a topographic survey, (historical) discharge measurements over sufficient time spans are usually lacking, and have to be estimated. The usual basis for the hydropower plant design, defined by the working range of the turbine to be used, represents a flow duration curve (FDC) of measured or estimated discharge. The FDC provides a graphical representation of the frequency distribution of the complete flow regime of a catchment, and allows the estimation of the percentage of time that a specified stream flow is equaled or exceeded. In order to achieve a higher accuracy and better representation of characteristic discharge behavior, daily time steps are required for the construction of FDCs. A higher accuracy can also be used for feasibility studies for micro hydropower plants. By knowing the number of days during which specific stream flows are exceeded, a feasible micro hydropower plant design that accounts for both energy production and energy consumption can be elaborated.

Over the past century, many methods have been developed to derive FDCs for sites where discharge measurements are inadequate or completely absent [6–8]. Often, an approximation for a flow duration curve at an ungauged site is obtained either from the ratio of mean annual flows at ungauged and gauged sites, from the ratio of catchment areas, or from the correlation of flows [9]. Referring to the former method, it can be argued that two rivers having similar mean flows might nevertheless have completely different low-flow characteristics because of their respective geological or soil conditions, for example. None of the methods mentioned above explicitly takes into account characteristics of the upstream catchment, e.g., the topography, lithology, soil characteristics, or rainfall patterns. However, the consideration of such parameters is expected to provide a higher accuracy of low-flow estimation.

This study focuses on a hydrological approach to construct reliable flow duration curves to design micro hydropower plants based on given data and information scarcity in ungauged catchments. The lumped rainfall-runoff method, which was used for this study, is designed for the calculation of heights of monthly discharges in mm. The presented approach is to our knowledge the first documented study that implements a modification of the calculation steps to work on a daily time scale. Facing the situation of scarce discharge data, this allows for the calibration of the few and reasonable model parameters with a small set of discharge measurements. The calculation of daily discharges further provides better information for the feasibility analysis of a micro hydropower plant.

The method by Crawford and Thurin used in this study has been applied in different contexts and for different purposes elsewhere, mostly in Indonesia. Shrestha et al. [10] have used the method for water resources assessment in a poorly gauged mountainous catchment of Nepal with satisfactory results. In a study for ground water conservation, Hargono et al. [11] used the method in order to calculate the volume of the total flow, base flow, and direct flow in a catchment in Indonesia. Ginting et al. [12] applied it to calculate the inflow to a reservoir in Indonesia. As a simple lumped rainfall-runoff model, the method was applied by Hatmoko et al. [13] to calculate the runoff at a weir in Indonesia based on remote sensing data from satellites. The results were qualified as satisfactory. These examples show a broad application of the method, with generally satisfying results.

In several other studies, the method by Crawford and Thurin has been compared with other approaches for ungauged catchments. Limantara [14] used the method by Crawford and Thurin to calculate the water balance of a small dam for domestic water supply in Indonesia. In his study, he realized a comparative assessment between applying the method by Crawford and Thurin and using a method developed by Mock [15]. The method by Crawford and Thurin led to lower results in discharge, yet because of the lack of discharge measurements, no validation of results could be realized.

In a study by Rintis et al. [16], the method by Crawford and Thurin [17] was compared to the method by Mock [15] and the GR2M (Global Rainfall-Runoff Model—a two-parameter monthly water balance model) method [18]. The correlation of the calculated flow duration curves was very high, with a correlation coefficient of >0.955. Compared to the method proposed by Mock [15], the method by Crawford and Thurin requires less input data. However, input data requirements are lowest for the GR2M method [18]. The simplicity of the approach by Crawford and Thurin, while also achieving satisfying results, was seen as a comparative advantage in these studies.

2. Materials and Methods

2.1. Study Site

The study area (Lat $13°08'09''$ N, Long $85°44'11''$ W) is located in the mountainous region of the departments Jinotega and Matagalpa in the central north region of Nicaragua, Central America. The climate is sub-tropic and semi-humid. Annual precipitations vary between 2000 and 2500 mm, while mean temperature varies between 22 and 24 °C. Altitudes of the study area vary between 755 and 1386 m a.s.l.

Relevant water resources within the study area are the Porvenir and Cañas rivers. The Porvenir River yields very little water, and is only used for potable water consumption. The Cañas River provides water for coffee processing for the INA Oriental coffee farm, located in the study area, and is of further interest for this investigation. The Cañas River has a waterfall with an altitude of 29 m, and its lower part towards the coffee farm border is relatively close to the coffee farm installations (which include housing for administrative staff and coffee workers). Its mean annual flow was calculated as 115 L/s, using the later described model.

The closest distance between the river and electric power distribution (17 kV) is 310 m. Assessment of the collected data made clear that the waterfall would be a fundamental element for taking advantage of MHP on the site. From the top of the waterfall to the nearest distance between river and electric power distribution, the brutto (initial, not accounting for energy losses on the conveyance towards a turbine) head measures 83 m. Figure 1 shows the studied site, with the calculated stream network based on a digital elevation model, the catchment of the planned MHP intake (where the discharge measurements for calibration have also been taken, and which is the position of the waterfall), the GPS-measured locations of the stream course downstream of the waterfall, and the position of the precipitation gauging station.
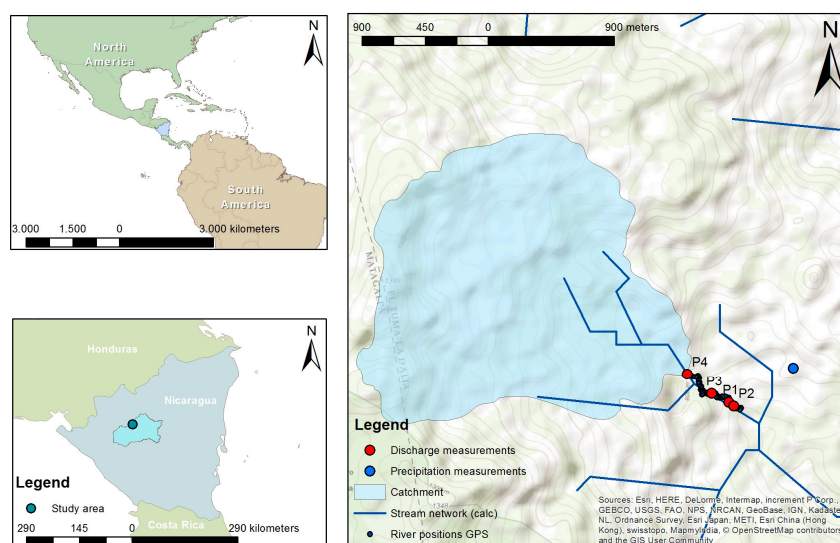

Figure 1. Study area location.

The total catchment area of the Cañas River at the waterfall is 2.89 km^2. The Cañas River belongs to the river network of the Tuma River, which is one of the principal rivers of Nicaragua, with a total catchment area of 2859 km^2 draining to the Caribbean Sea.

2.2. Data Assimilation

2.2.1. Precipitation Data

A precipitation gauging station exists close to the coffee farm office, where observations are collected every morning. A supportive archive exists containing monthly precipitation heights (mm) from the years 2007–2011, and daily precipitation heights (mm) from 2012 to present. An analysis of the data showed monthly heights fluctuating between 0 and 637 mm of precipitation, and daily heights fluctuating between 0 and 175 mm. Annual heights range between 2054 and 2491 mm, and have an average value of 2337 mm. Rainfall peaks are noticeable during the months of June and October, revealing the bimodal character of the raining season from May to November, although they vary from year to year. Figure 2 illustrates average monthly precipitation for the years 2007–2015.
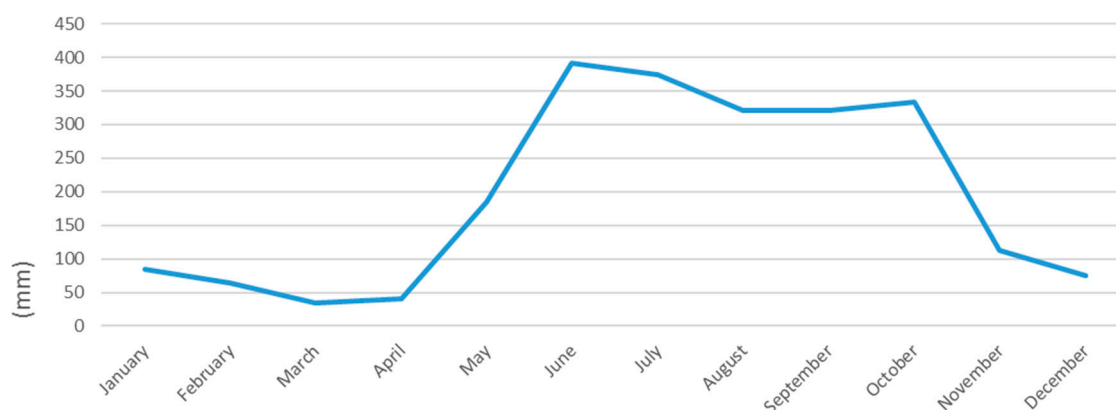

Figure 2. Average monthly precipitation in the study area 2007–2015.

2.2.2. Discharge Data

River discharge was measured during a field trip at various points along the stream course, and with different methods. Those include velocity-area measurement, weir discharge measurement, and barrel discharge measurement. Four points of the river with a suitable cross-section were identified, and measurements were conducted there. Figure 1 contains the locations of those measurements (P1–P4). The highest point was located directly upstream of the waterfall. The selection of different methods served for comparability and validation, as well as testing for reasonable groundwater sources that would result in a difference of the discharge between different measurement points.

1. *Sections 1 and 3: Barrel Method*

Similar to the widely known and very simple bucket method, a barrel of 220 L volume was used to measure the time until it was filled by the discharging water. The corresponding discharge was then calculated. For deviation of the water at the measurement location, a tube of eight inches width and 3 m length was used. A provisional barrage of stones and grass was set up across the cross-section, and leakage was reduced by using plastic canvas. The amount of leakage was later estimated.

2. *Section 2: Weir Method*

The lowest cross-section was measured with a weir of a triangular-shaped notch, the following two sections with a barrel, and the highest point with the velocity-area method using floaters. The discharge passing the triangular weir can be calculated using the formula:

$$Q = 4.28 \times C_e \times \tan\left(\frac{\theta}{2}\right) \times (h + k)^{\frac{5}{2}},$$ (1)

with

C_e Effective discharge coefficient
θ Angle of the v-shaped notch
Q Discharge
h Water depth at the notch of the weir
k Head correction factor

In the studied case, the simpler form is used, as given in [7]:

$$Q = 1.4h^{5/2},$$ (2)

where Q and h are as previously defined.

3. Section 4: Velocity-Area Method

A riverbed section of great use for discharge measurements was discovered just upstream of the waterfall, with a rocky streambed and an area that was easy to measure. Velocity measurements were realized over a distance of 1 m, and over three parts of the section (left, middle, right). After measuring the dimensions of the two cross-sections of entrance and exit, an average value of the area was taken and multiplied by the time needed to travel the distance of one meter. A correctional factor of 0.8 was considered for the conditions of the streambed after cleaning it from bigger stones and rubble.

4. Results

At two cross-sections, considerable losses could not be avoided, since water was leaking through the sandy streambed below the weir or through the sides of the barrages. Accordingly, for the two lower cross-sections, losses of 20% were estimated. The third cross-section was more suitable for measurement, and water leakage could be identified to be approximately 2 L/s, which corresponds to 11%. The last and highest located cross-section of the river was suitable for easy measurement and calculation. Since no barrage was required, it did not present any water losses.

Assessment of the resulting data clearly showed that discharge varied only to a small extent, and therefore, other considerable water sources seem to be absent. This led to the conclusion that a representative and well-fitting cross-section for future discharge measurement of the studied river would be the location above the waterfall.

In 2015, additional measurements have been conducted by two students of TU Darmstadt, L. Matthies and F. Glöckner, as well as by an instructed team of the plantation workers. All of those measurements were conducted on the profile on top of the waterfall, since it provided the most reliable results. Starting on 30 July 2015, the method for measurement and calculation was expanded to include the averaging of five cross-sections, reduced to velocity measurements at two sides of the stream (left and right), and later averaged. Also, the correctional factor was changed towards 0.725 as a correction factor between 0.6 and 0.85 for a streambed condition between pebbly and smooth, respectively [8]. The results of those valuable measurements are shown in Table 1 and Figure 3, which also compare measured discharges with the measured precipitation in 2015 and show the estimated base flow, which emerged through the analysis of the precipitation data from 2012 to 2015 and the modelled discharge results.

Table 1. Discharge measurements 2015.

Date	Discharge (L/s)
30 April 2015	20
25 June 2015	92
30 July 2015	71
12 August 2015	71
31 August 2015	130
1 September 2015	98
8 September 2015	59
9 September 2015	50
16 September 2015	55
24 September 2015	64
30 September 2015	93
5 October 2015	57
22 October 2015	88
29 October 2015	69
18 November 2015	90
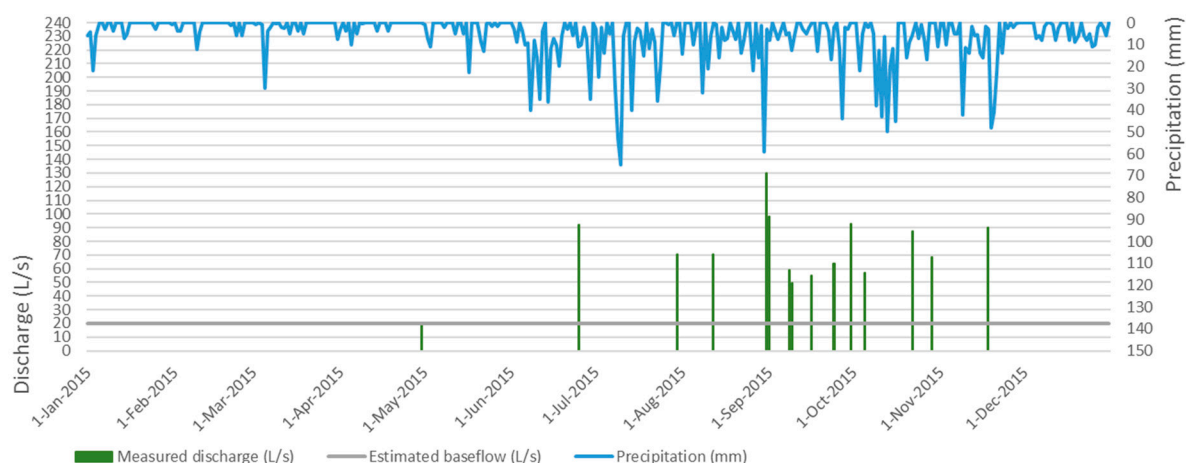
Figure 3. Discharge and precipitation measurements in 2015.

Analysis of the daily precipitation data 2015 shows that the discharge measured on 30 April 2015 is acceptable as a representative value for low flow of the river, since no precipitation happened for a period of 11 days before that date, which was in fact the longest period without any measured precipitation during 2015. The discharge measured on 31 August 2015 happened after the second-strongest precipitation of 2015, which was measured on 30 August 2015 with a height of 59 mm. This was only surpassed by rainfall on 10 July 2015, which produced a height of 65 mm. A first possible range of discharges could therefore be roughly estimated relying on these data, resulting in a span between 20 and 150 L/s. An estimation of the upper limit is difficult to make, since moisture and groundwater storage conditions, as well as retention behavior, are at first unknown. The dominant responsible runoff-generating mechanism is believed to be an infiltration excess overland flow, since the studied area is mainly characterized by hillslopes.

2.2.3. Climate Data

Historic climate data for the region of INA Oriental has been obtained through the International Water Management Institute (IWMI), Sri Lanka, which in its "Water and Climate Atlas" provides data from worldwide weather stations, dating 1961–1990 [19]. The "Water and Climate Atlas" daily climate data provide reference evapotranspiration calculated using the Penman-Monteith equation. It is used by the model as (potential) evapotranspiration under optimal conditions.

2.3. Methodology

In order to develop a flow duration curve for the studied site, and to estimate the available discharges, a lumped rainfall-runoff model is used. Accounting for the scarce knowledge about the hydrologic behavior and characteristics of the catchment, a simulation method as described by Crawford and Thurin (1981) [17] is used and slightly adapted in order to improve the calibration of the predicted flow behavior. Input data for the described model are: precipitation, potential evapotranspiration and the adjustable parameters for soil-moisture storage, the sub-surface runoff fraction of the total runoff, and a time index for this flow to reach the stream. For the separation of the base flow, two storages are used: moisture storage and groundwater storage. Excess moisture leaves the moisture storage as either direct flow or recharge to the groundwater storage. For each time step of the simulation, a constant fraction of groundwater storage, which joins the total discharge, is defined as groundwater flow. Figure 4 gives a basic overview of the model structure.
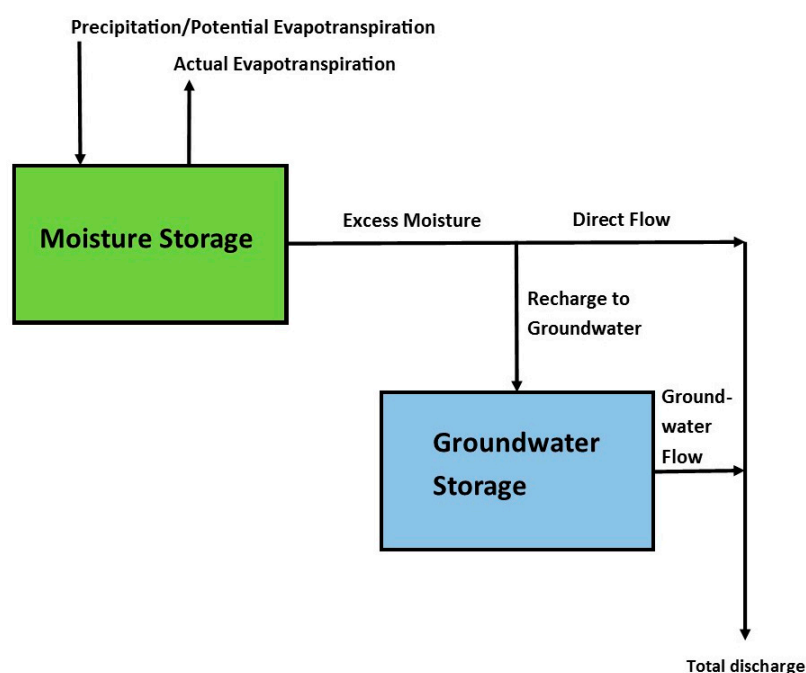

Figure 4. Model structure of the empirical rainfall runoff model, including water flows and storage system (based on Crawford and Thurin [17]).

Input values for the simulation are daily precipitation heights (mm), which were taken from measurements on site, and evapotranspiration estimates via the Penman-Monteith formula, obtained from IWMI (2016), as described above [19]. This approach differs from the original approach proposed by Crawford and Thurin [17], which only calculated monthly discharge heights. The reason for a calculation on daily time steps is the available daily resolution of precipitation measurements, and the intent to calibrate parameters of the model with discharge measurements. The function of the original model is covered in the following descriptions for parameter values and calculation steps. Two correlations (see Figures 5 and 6) are originally only represented by analog graphical data, and have been implemented in a worksheet routine for the easier calculation on a higher temporal resolution.

The model uses three parameters, which need to be estimated. These are called NOMINAL, PSUB and GWF. NOMINAL is an index of the total soil moisture storage capacity in the studied catchment. PSUB represents the fraction of runoff that leaves the catchment as groundwater flow, and relates to "recharge to groundwater" in the model structure (Figure 4). GWF is the time index for the groundwater flow to reach the stream, as mentioned above, and is therefore the "groundwater flow" in the model structure.
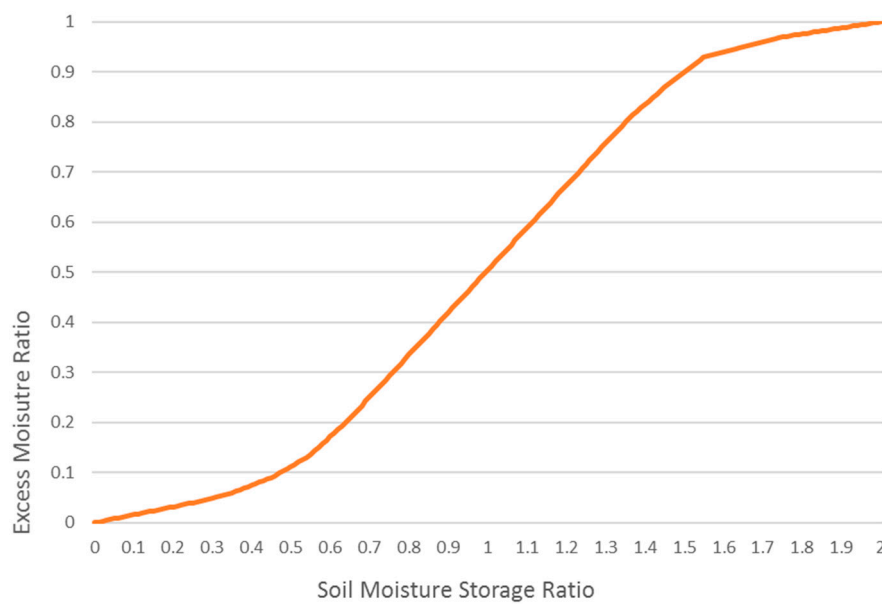
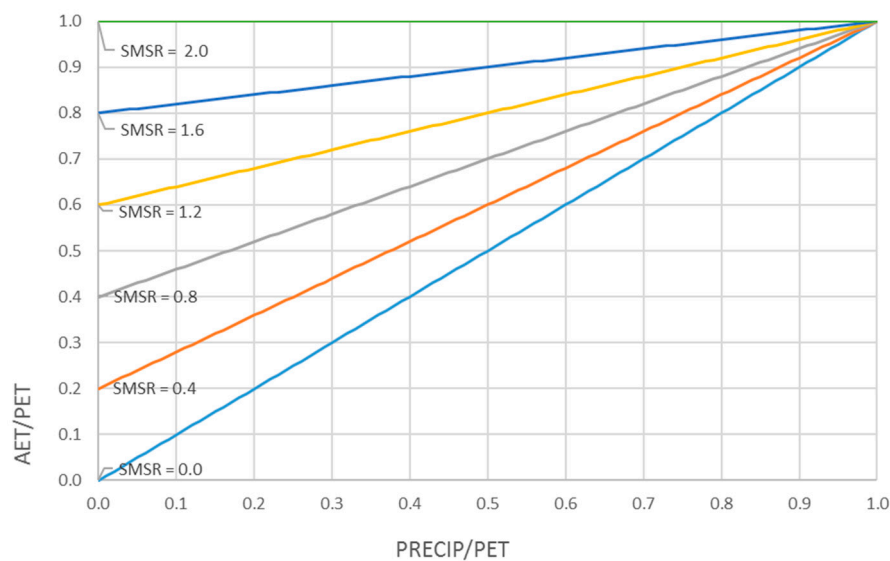**Figure 5.** Soil moisture storage ratio/Excess moisture ratio.

Figure 6. Actual evapotranspiration (AET)/potential evapotranspiration (PET) ratio as function of precipitation (P)/PET and soil moisture storage ratio (SMSR).

NOMINAL means the amount of storage in soil moisture that leads to half of the positive monthly water balance leaving the catchment as excess moisture, which can be direct runoff or groundwater flow. The soil moisture storage itself may be greater than or less than NOMINAL. In the case of soil moisture storage being less than NOMINAL, most of the positive monthly water balance will be retained in the moisture. If it is bigger than NOMINAL, then accordingly, most of the positive monthly water balance will result in direct runoff or add up to the groundwater storage. NOMINAL is valued in millimeters. PSUB accounts for the permeability of the soil and drives the simulation of flows in dry periods. The more permeable a soil is, the more flow will be sustained and reach the groundwater, which leads to higher flows in dry periods. Since PSUB and GWF are describing fractions, they are dimensionless.

Estimates, without any prior knowledge of a watershed, can be set as in Crawford and Thurin [17]:

$$\text{NOMINAL} = 100 + \text{C} \times \text{mean annual precipitation,} \tag{3}$$

where C varies between 0.2 for catchments with rainfall throughout the year and 0.25 for catchments with seasonal rainfall. In areas with thin vegetation, it could be reduced by 25 percent, which is not the case for the studied region.

A standard value for PSUB can be set as 0.6. The upper limit is 0.8 for a catchment with high permeable soils, and the lower limit is 0.2 for catchments with low permeability or thin soils.

For GWF, the standard value is 0.5, where it may increase to 0.9 for catchments with little sustained flows and decrease to 0.2 for catchments with high sustained flows. All of these values apply for the original approach as suggested by Crawford and Thurin, which is meant for monthly time steps. As a logical consequence, for the calculation of daily average discharges, the value for GWF must be significantly smaller. This is due to its meaning for the calculation process: since GWF describes a fraction of the total groundwater storage leaving that storage during each time step, the fraction must be smaller when the time step is shorter.

Total runoff (Q_t) to the stream per simulated time step is calculated as follows:

$$Q_t = Q_s + Q_{gw}, \tag{4}$$

$$Q_s = M_e - GW_R, \tag{5}$$

$$Q_{gw} = GFW \times GW_{s,end}, \tag{6}$$

$$GW_{s,end} = GW_{s,start} + GW_R, \tag{7}$$

$$GW_{s,start} = GW_{s,end} - Q_{gw}, \tag{8}$$

$$GW_R = M_e \times PSUB, \tag{9}$$

$$M_e = MS_{er} \times W, \tag{10}$$

$$W = P - [[AET/PET] \times PET], \tag{11}$$

$$\Delta M_s = W - M_e, \tag{12}$$

$$MS_{r,i} = M_{s,i-1,end}/NOMINAL, \tag{13}$$

$$M_{s,end} = M_{s,start} + \Delta M_s, \tag{14}$$

with

Q_t	Total runoff that leaves the catchment (mm)
Q_s	Surface runoff that leaves the catchment (mm)
Q_{gw}	Groundwater runoff that leaves the catchment (mm)
M_e	Excess moisture that cannot be stored in the moisture storage (mm)
GW_R	Groundwater recharge to the groundwater storage (mm)
$GW_{s,start}$	Groundwater storage at the beginning of the time step (mm)
$GW_{s,end}$	Groundwater storage at the end of the time step (mm)
MS_{er}	Moisture storage excess ratio (-)
W	Water balance (mm)
P	Precipitation (mm)
AET	Actual evapotranspiration (mm)
PET	Potential evapotranspiration (mm)
MS_r	Moisture storage ratio (-)
M_s	Moisture storage (mm)
ΔM_s	Moisture storage change (mm)
$M_{s,start}$	Moisture storage at the beginning of the time step (mm)
$M_{s,end}$	Moisture storage at the end of the time step (mm)

If the water balance W is >0, then the excess moisture ratio (MS_{er}) is derived from its dependency on the soil moisture storage ratio (MS_r). This dependency is displayed in Figure 5.

If the water balance W is < or equal to 0, then MS_{er} is 0. AET/PET is derived from its dependency on P/PET and the soil moisture storage ratio, as shown in Figure 6.

Groundwater storage and moisture storage start with initial values for the first time step, before they are calculated for the following time steps via storage changes. Values for NOMINAL, GWF and PSUB are set initially, and can be adjusted by trial and error as soon as the correlation between measured and calculated discharge values is considered. Starting conditions for soil moisture storage and groundwater storage need to be estimated first. Since storages vary with rainfall seasons and dry seasons, soil storages can be estimated as 10 per cent of NOMINAL in dry seasons, 125 per cent of NOMINAL in wet seasons, and equal to NOMINAL in catchments with rainfall throughout the year. Groundwater storage may be set to 5 percent in dry seasons, 40 percent in wet seasons, and 20 percent in catchments with rainfall throughout the year. Initial values for the soil storage can be found by either running a calculation for various years or not taking into account the first year, or by approximating the initial value iteratively for one year. For further details on the determination of the parameters from this paragraph, see Crawford and Thurin [17].

In order to calibrate the input parameters of the simulation, a calculation based on daily time steps was needed. This was because the measurements that had been taken at individual days did not allow the calculation of monthly discharge heights and their comparison with modeled values. Pearson's correlation coefficient was used for the measurement of the linear correlation between the measured and the calculated discharge values. It is a good estimate for the goodness of fit between the two datasets, and can be used in combination with hydrologic reasoning for the estimation of best-fitting parameters. During the calculation of the correlation coefficient, 14 of the 15 existing discharge measurements were taken into account. One measurement (9 September 2015) did not correlate at all with predicted flows and is highly likely to have been taken at an unfortunate moment when compared to the time of measuring the precipitation that day, which would lead to a wrong retention behavior. Precipitation was always measured in the morning hours between 8 am and 11 am. Where other modeled and measured discharge values—covering a wide discharge spectrum—reacted positively to calibration of the model parameters, this measured value did not. A possible situation would be that most of the discharge had already left the watershed when the discharge was measured; for example, if the discharge had been measured in the early evening. Therefore, explainable as either a timing or a reading error, this measurement was treated as an outlier and not used in the correlation analysis.

Using an excel sheet for automatic calculation and easy iteration via trial and error for the input parameters PSUB and GWF, calculated discharge values were averaged for a representative flow duration curve of one year.

3. Results

3.1. Lumped Rainfall-Runoff Method

After various iterations over the data from 2012 to 2015, and based on the model setup instructions, NOMINAL was estimated to be 684 mm, initial groundwater storage (1 January) to be 154 mm, and initial soil moisture storage to be 904 mm. For the year 2015, a minimal flow of 16 L/s and a peak discharge of 599 L/s were calculated, which lead to a Pearson's correlation coefficient between measured and calculated discharge values of 0.64. PSUB was estimated as 0.6, and GWF as 0.014. The value for PSUB is representative for an average-to-high soil permeability, whereas the value for GWF means a higher than average sustained flow. This makes sense for a humid and sub-tropic environment, and is comparable to the experienced catchment characteristics on site. Since the base flow index shows the ratio between groundwater flows and total streamflow, it is comparable to the parameter PSUB. The value of 0.6 for PSUB matches the calculated base flow index for the studied

region as part of the Global Streamflow Characteristics Dataset (GSCD) [20], which was 0.597, quite well. The calculated FDC is shown in Figure 7.
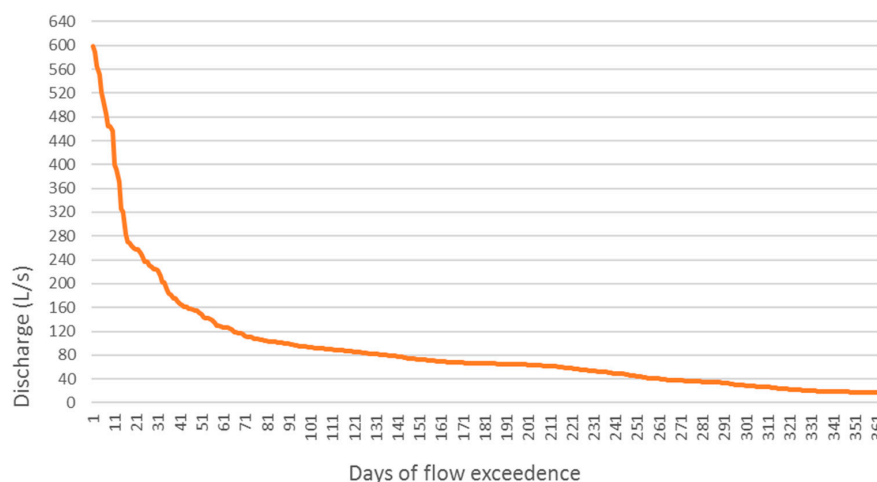

Figure 7. Calculated flow duration curve for the year 2015.

Considering that the highest measured flow was 130 L/s, it has to be well reasoned how flows exceeding this value are calculated. The high flows, as calculated here, make sense, taking into account descriptions and experiences from locals. Low flows are comparable to observations on site and measurements taken after times of drought. Here, a very representative discharge measurement (20 L) had been recorded on 30 April 2015, when it had not been raining for 11 days, and the total precipitation height of the month was 31 mm, which was also the year's driest period. Dry periods during other years of the existing precipitation data show similar values. It is therefore justifiable to define the low flow of the year 2015 to be around 20 L/s for the studied catchment. This corresponds to the FDC for 2015 (Figure 7).

In order to make a valuable statement about an average flow duration curve, which in the study case was the groundwork for the design of a micro-hydropower plant, the values of each year's FDC were averaged. The averaged flow regime ranges from a minimum annual flow of 21 L/s, via a mean annual flow of 115 L/s, to a peak annual flow of 866 L/s (Figure 8).
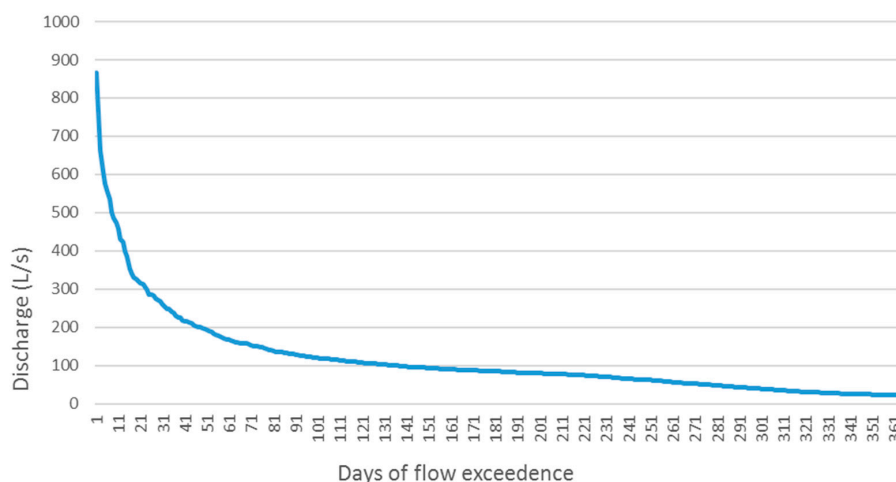

Figure 8. Calculated average flow duration curve, 2012–2015.

Due to high variations in the rainfall pattern, with intense rainfalls occurring in the wet period and dry periods lasting up to four weeks without rainfall events, high discharge peaks are likely to occur, while high soil permeability allows considerable groundwater flows that provide sufficient minimum flow in low flow periods.

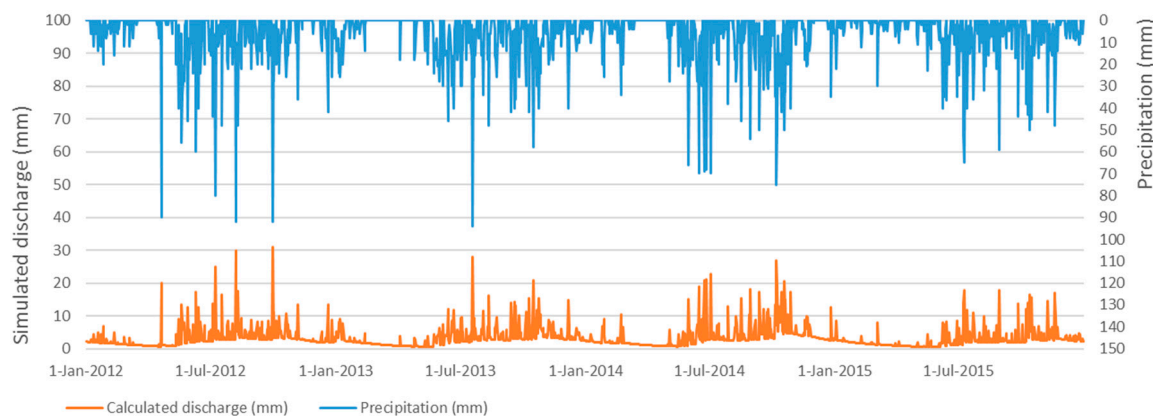The measured precipitation and modelled discharge are displayed in Figure 9.

Figure 9. Precipitation (**top**) and discharge (**bottom**), 2012–2015.

3.2. Design Characteristics of the Studied MHP Plant

Although it is not the scientific focus of this paper, the feasibility of a potential MHP plant design was studied as well, and results might be interesting for readers who are interested in the practical application of FDCs for MHP planning. Based on the site conditions, the calculated discharges, the daily energy consumption on site, and the estimated installation and operational costs, a break-even time for the investment could be calculated for both the case of solely self-consumption of the produced energy and the case of selling excess energy to the national grid.

With the goal in mind of obtaining a break-even period of the investment that is shorter than eight years, a feasible plant design could be chosen. With a gross head of 61.86 m, a design flow of 43 L/s, and a residual flow of 20 L/s, a single-jet Pelton turbine and a 20 kW eight-pole asynchronous generator running at 900 rpm (possible direct coupling) were chosen. The penstock (uPVC material) length would be 429 m, with a pipe diameter of 5.5 inches. These conditions result in an average net head of 44.92 m, a plant load factor of 0.76 and an annual energy output of 85.65 MWh at 7656 annual hours of operation. Estimating the investment costs to be between 2000 US$/kW and 5000 US$/kW, the break-even time was calculated as, accordingly, 2.15–5.74 years. These numbers would decrease to 1.77–4.69 years, if the excess energy was sold to the national electricity grid. Generally, the higher investment costs for hydropower in developmental countries are due to a number of reasons, which include likely missing subsidy concepts for the supply of excess energy to the national grid. Yet realistic estimations on the feasibility of a plant design are possible, and in the studied case, led to a positive statement on the feasibility of a potential investment.

4. Discussion

Although in the case of the presented study only 15 discharge measures were available, a Pearson's correlation coefficient of 0.64 was obtained. Where the possibility exists, representative discharge measurements can be taken (for dry period, average and high flows) and calibration will likely show satisfactory results. Even without discharge measurements, parameters can be set according to knowledge of the catchment (mainly soil properties). The model is likely to work in different climatic regions, but calibration will require a larger set of precipitation measurements. Regardless of its simple structure, the presented method calculates the total runoff produced in a catchment, including

surface runoff and base flow, to a satisfying level of precision, while using two different storages (soil and groundwater).

Sensitivity analyses done by Crawford and Thurin showed that calculated FDCs are most sensitive to uncertainty in monthly precipitation and potential evapotranspiration amounts. In humid climates, stream flow is even more sensitive to potential evapotranspiration [17]. This is important to note, since the potential evapotranspiration input used in this approach was derived from average monthly data during 1961–1990, which most probably had been interpolated to match the coordinates of the studied catchment and could differ slightly from real evapotranspiration data. An example for another source of PET data is the "Global Potential Evapo-Transpiration (Global-PET) geospatial dataset" [21,22]. While the FAO-PM (UN Food and Agriculture Organization—Penman Monteith) PET values ought to be more precise than the Hargreaves method used in the cited dataset, a comparative approach might still be interesting for the analysis of goodness of fit for the model of this study.

The method used in this study is especially useful for the prediction of runoff behavior (flow duration curves) on ungauged sites. This can be the case where a feasibility study for a remote hydropower site is carried out, as has been the case in this study. Applying the method by Crawford and Thurin to a simulation of daily discharges requires an adjustment of the parameter GWF to a daily time step as well. If the GWF is parameterized for a monthly calculation, as proposed by Crawford and Thurin, two major concerns arise: the problem of very low flows, while at the same time enormous peak flows seem to occur during a considerable number of days. This leads to the assumption that retention is not considered well enough, and, in fact, the value of GWF must be corrected. An essential point of improving the calculation's resolution is hence to correctly change the fraction of groundwater flow of total groundwater discharge leaving the catchment. If GWF is set to be very small (values between 0.01 and 0.03), those may represent a more realistic fraction of the groundwater flow leaving the catchment on a daily basis, which also implies a more realistic retention. Accordingly, two effects take charge: low flows reach higher values, and peak flows are dampened a little. This correction led to satisfactory results in the presented study.

Lower flows until an exceedance of >1.5 months (45 days) seem to be equally represented in both FDC resolutions. However, high flows and very low flows are captured in much more detail on a daily basis, and more realistic non-linear runoff behavior can be modeled. Since an FDC should consider average possible discharges from longer episodes of input rainfall data, the flow volumes can be calculated for all the years of available rainfall data, which represent the years 2012–2015 for the case study. Calculation of an FDC for 2015 based on daily data from 2012 to 2015 provided very similar results as the calculation using data from 2015 alone.

The studies conducted by other authors mentioned in the introduction applied the method by Crawford and Thurin in its original form using monthly time steps. The presented study here is the first one documented to apply the method for a daily time step. Therefore, the calibration results for the method of the other studies are not directly comparable. Hatmoko et al. [13], for instance, calibrated the method with a base flow fraction parameter PSUB of 0.90, and a groundwater discharge rate parameter GWF of 0.46. Hargono et al. [11] had best results, with a PSUB of 0.85 and a much lower GWF of 0.2. The calibrated value for PSUB in this study was 0.6, thus, lower than in the other studies. This can be explained with a lower permeability of soils in this study area. The GWF was calibrated with 0.014 in this study. This is a very low value compared to the other studies, but it is based on a daily time step. Extrapolation to a monthly value results in a GWF of roughly 0.43. This is very close to the value from the study of Hatmoko et al. [13].

Where more data on discharge, soil properties and land use are available, one might consider the application of the SCS-CN (U.S. Soil Conservation Service—Curve Number) model variant developed by Geetha et al. [23] and the assessment of the resulting correlations between measured and simulated discharges. This model approach considers temporal variations of the curve number, and simulates the total streamflow with its components such as surface runoff, through-flow and base flow. It is a

more complex model, which uses a set of 13 parameters, but also gives more insight into different runoff components. The model parameters need to be optimized by an algorithm.

Research could also focus on the applicability of data, which is available from remote sensing and would provide broader usability for different kinds of catchment characteristics. Those measurements enable the estimation of root zone storage capacity [24], landscape heterogeneity, dominant runoff generating mechanisms [25,26], sub-surface storage fluctuation, and groundwater recession [27].

5. Conclusions

The method by Crawford and Thurin operates with limited field data and produces results of moderate accuracy. Its calculation techniques are based on sound hydrologic principles and represent the key processes of continuous monthly streamflow. The method should not be applied for regions where discharge from snowmelt represents a significant process, as the snow accumulation is not reflected in the method. The method is also not suitable for catchments with large lakes, reservoirs or long transport sections, because hydraulic routing is not captured by it. Hence, the method should be applied to small catchments. For the same reason, when applying the method with a daily time step, the application should be limited to even smaller catchments.

Compared to other approaches to develop FDCs for ungauged catchments (e.g., FDC selection from standardized FDCs), the modified method presented here yields better site-specific results, as it takes climate and catchment characteristics into account, and can be calibrated with measured discharge. This can result in higher reliability of the planning base for small-scale hydropower development and improved economic viability.

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