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Identification of run-of-river hydropower investments in data scarce regions using global data

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ABSTRACT

The increase in economic activities, population and rural electrification has significantly increased the energy demand in most of the developing nations. This demand has to be supplied from various sources, preferably renewable, among which hydropower is expected to be one of the major contributors. Though developed nations have already harnessed most of their hydropower potential, developing nations are still struggling in project identification and capacity assessment, mainly due to lack of data and difficulties of access. We present and test an assessment framework, developed for data scarce regions, to identify optimal location and installed capacity of multiple run-of-river hydropower projects within a river basin. The developed framework consists of two components: the first component is a hydrological model for flow duration curves, the second component is a so-called hydropower model. Flow duration curves are obtained using an existing probabilistic hydrological model which derives the probability distribution of streamflow as a function of few topographic and climatic parameters. A novel optimization procedure is developed, where viable hydropower projects are identified minimizing their specific cost, which depends mainly on discharge, head and length of conduit system. We tested the assessment framework in the West Rapti basin (Nepal). The application showed that the total potential of this basin maybe achieved with 79 different projects with capacity ranging from 1 to 17 MW. The framework was developed using open languages and software and can therefore be freely used after request to the corresponding author.

Introduction

A recent study by the U.S. Energy Information Administration shows that the world's energy consumption will increase by 28% between 2015 and 2040; moreover this increase will not be uniformly distributed, but will be drastically higher in countries not belonging to the Organization for Economic Cooperation and Development (OECD), with an expected increase of 41% in comparison to a 9% in OECD countries (E. I. Administration (U.S.) & G. P. Office, 2016). The increase of economic activities, of access to energy and population growth is expected to be the main drivers of this process. The energy consumption rate will be even more in Asia, mainly due to the influence of China and India. It is expected that Asia will require almost 50% more energy to maintain its increasing economic growth in the next three decades (E. I. Administration (U.S.) & G. P. Office, 2016). Most probably conventional fossil fuels will still represent a major energy source, however, due to increasing global concerns towards the effects of climate change and depletion of available fossil resources, the exploitation of renewable energy sources will increase in the future. Hydropower is a key element in the renewable energy mix, thus an inevitable resource to be considered when equating the reduction of carbon emissions from electricity production and for the substantial increase of renewable energy demanded to meet the Sustainable Development Goal 7 (Marence & Franca, 2018).

With a global share of around 71%, hydropower stands as the biggest contributor to the total renewable electricity production (*World energy resources hydropower* 2016, 2016). Even with such impressive input, the present hydropower energy production can only fulfil around 3% of the global annual energy demand. This value is far below the theoretical potential, which has recently been estimated as capable of supplying one third of the total energy demand (Hoes et al., 2017). Almost 48% of the global energy potential is located in Asia and is still greatly untapped, therefore this continent is facing a significant growth in the number of projects both planned and in development (Zarfl et al., 2015). These facts remark the importance of a proper development of the hydropower sector, in order to increase the sustainability of the current energy mix. From this point of view, given their limited availability,

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water resources should be exploited in an optimal way and therefore hydropower development should start with a basin scale optimization of project locations and production capacities.

In general terms, the design and location of hydropower investments depend on a series of geophysical (topographic, geological, hydrological and morphological), ecological and environmental (local and global impacts) and societal (additional purposes, impacts and needs of local communities, transboundary implications, available financial means, etc. …) criteria. Moreover, most hydropower plants are designed as individual projects, whose development is based on knowledge acquired by previous experiences of the designer and developer. It is common to classify hydropower projects in two types: storage plants (when the reservoirs have carryover capacity) and run-of-river (RoR) plants. Due to their smaller size and less interference in the hydrological cycle, the latter type of projects usually have less socio-political, environmental and economic implications, compared to projects with carryover reservoirs. Furthermore, the development of RoR requires less expertise and investment, making them interesting for local private investors (Singh & Nachtnebel, 2016). This research focuses on RoR projects, with the primary objective of identifying locations and capacities within ranges that could be reasonably developed by local investors.

The first step in the development of a hydropower project is the quantification of the available flow. Depending upon the quality and quantity of available data, this can be done using various statistical or process-based methods (Müller & Thompson, 2016). Statistical methods use data available for one catchment to infer the flow duration curve (FDC) of a (hydrologically) similar catchment where there is no data, a procedure known as regionalization. Since they do not establish any type of causal relationship between rainfall and runoff, their accuracy might be affected by climate and geomorphological heterogeneity and nonstationarity. Finally their reliability is highly dependent on the spatial distribution of available discharge data (Müller & Thompson, 2016; Blöschl et al., 2013). Examples of statistical methods that have been applied for hydropower potential estimations comprise multi regression analysis (Coskun et al., 2010), methods based on the regionalization of quantiles of the streamflow distribution (Jha, 2010), methods based on the application of a single rainfall-runoff coefficient (Palomino Cuya et al., 2013) and methods based on the regionalization of the ratios of monthly dimensionless flows (Rojanamon et al., 2009).

On the other hand, process-based methods establish a relationship between rainfall and runoff, therefore allowing the inclusion of nonstationarity in climate and catchment properties. Two major types of process-based methods exist for FDCs estimation: continuous modelling methods and derived distribution methods. The former consist of long-term applications of a rainfall-runoff model, from which the distribution of discharges can be derived. The latter mechanistically links rainfall and soil water balance to streamflow and moreover, under a number of hypothesis on the rainfall process, they allow the analytical derivations of the probability density function (PDF) of streamflow.

Several continuous modelling models e.g. SWAT and HEC-HMS have been applied for hydropower potential assessment (Kusre et al., 2010; Pandey et al., 2015). These models allow a more detailed description of the different processes contributing to runoff formation at the expenses of an increase in model complexity and computation time. Moreover they usually require the estimation of a large number of parameters, some of which might have to be defined a priori and therefore their applicability to data scares regions and ungauged basins is still limited. This highlights the need for parsimonious hydrological models capable of quantifying FDCs in poorly gauged basins, possibly using remotely sensed data and not requiring expensive and time consuming data collection campaigns. In this regard analytical models could provide useful estimations, especially thanks to their limited data requirements and to their flexibility (Doulatyari et al., 2015)–(Müller et al., 2014).

Derived distribution methods have been mostly applied to analysis of hydropower plants optimization (Basso & Botter, 2012)–(Lazzaro & Botter, 2015) but, to our knowledge, only one study has been proposed using them for potential estimations (Crosara Selvatico, 2014). The basin-scale optimization of the location and sizing of hydropower investments implies the simultaneous definition of several interrelated design variables: discharge, head (and length and type of related conduit), turbine type and number, etc. making the problem very complex and less prone for expedite analysis. Available models define the optimal size of a plant, once its location is given, according to economic or ecologic criteria. Most hydropower potential studies focus on calculating the total theoretical potential of a river basin based on the river's topography and available discharge, but they do not consider different possible plant sizes i.e. once they identify the intake location, they do not analyse the optimal location of the powerhouse in terms of power production versus construction costs (Jha, 2010; Palomino Cuya et al., 2013; Kusre et al., 2010; Pandey et al., 2015).

There is hence the need for tools allowing the identification of combinations of plants locations and capacities that maximise the energy production at a river basin scale. Furthermore, in developing nations project assessment is hindered by the lack of data and difficulties of access to the sites. We provide an assessment framework suitable for poorly gauged basins relying mostly on globally available datasets. The framework, developed for RoR hydropower, is composed of two major components: a hydrological model and a hydropower model (see the flowchart in Fig. 1). The hydrological model requires the following inputs: precipitation, potential evapotranspiration data and a digital elevation model (DEM); moreover; discharge data, if available could be used for model validation. The model then produces a raster representing the design discharge for each pixel representing the river network. The hydropower model requires a (DEM) of the basin and a number of parameters related to the size and cost of hydropower projects commonly developed in the region, and provides the optimal combination of plants capacities and locations that maximises the hydropower energy production within a catchment. We show and discuss an example of application of the assessment framework in the West Rapti basin, Nepal.

Materials and methods

Hydrological model

The hydrological model implemented in this tool is the lumped, process based stochastic analytical model developed by Botter et al. (2007) and later improved by Doulatyari et al. (2017). The model is based on a basin scale water balance, forced by rainfall, which is modelled, at the daily timescale, as a marked Poisson process. In the first version of this method, the basin was modelled as a linear reservoir, in that the total runoff is assumed to be proportional to the volume of water storage. The model was then improved by Botter et al. (2009) introducing non-linear storage-discharge relationships for which the probability density function and the FDC were analytically derived. In the latest version of this method, proposed by Doulatyari et al. (2015), the model was further improved to take into account the dynamic growth and shrink of the river network as proposed by the Geomorphological Recession Flow Model (GRFM) introduced by Biswal and Marani (2010). Further extensions of this model were done by Schaefli et al. (2013) to incorporate the delaying effect of snowmelt with the introduction of an additional residence time parameter for snow-fed catchments and by Müller et al. (2014) to derive the annual FDC in seasonally dry climates. The tool presented here adopts the non-linear version of the model, which showed a better agreement with field data in comparison to the linear one in several climatic and geomorphological settings (Ceola et al., 2010; Santos et al., 2017). Since the aim of this paper is the application of the analytical model for FDCs for the estimation of optimal sizes and locations of RoR

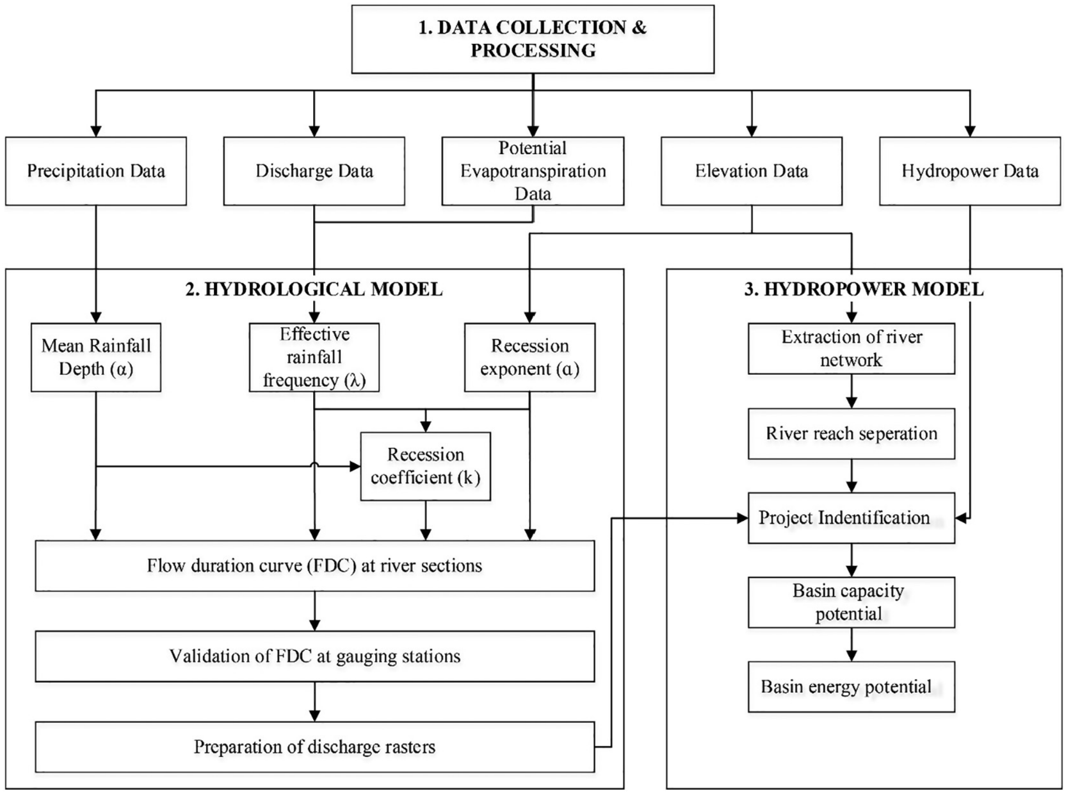


Fig. 1. Overview of the modelling framework; it consist of a hydrological and a hydropower model. Flow information obtained from the hydrological model are used by the hydropower model to identify hydropower projects.

hydropower plants, the hydrological model and the underlying assumptions will be briefly introduced, leaving the reader to the referenced papers for the details. The main assumptions of the hydrological model are:

1. The catchments are small enough to allow the assumption of homogeneous rainfall, soil and vegetation distribution.
2. The only external driver of discharge dynamics is rainfall, therefore snowmelt and/or glacier contributions are negligible.
3. Rainfall is modelled, at the daily time scale, as a marked Poisson process.
4. Discharge is assumed to be a non-linear steady function of water storage.

Under the above hypothesis, the temporal dynamics of specific streamflow Q (i.e. discharge per unit watershed area) can be modelled, at the daily timescale, according to the Langevin equation:

$$\frac{dQ(t)}{dt} = \xi_Q(t) - KQ(t)^a \quad (1)$$

where K and a are the coefficient and exponent of the power-law relationship reproducing the decay of streamflow during recessions, meaning between two consecutive streamflow producing rainfall events and $\xi_Q(t)$ is a stochastic noise reproducing jumps in discharge due to rainfall events capable of overcoming the soil moisture deficit in the root-zone. The PDF of discharges can be obtained as a derived distribution from the steady state PDF of soil moisture (Botter et al., 2009). The resulting PDF (Eq. (2)) is a Gamma distribution, whose complete shape depends on four parameters:

$$p_Q(Q) = CQ^{-a}\exp\left(\frac{Q^{2-a}}{\alpha k(2-a)} + \frac{\lambda Q^{1-a}}{k(1-a)}\right) \quad (2)$$

where: C is a normalizing constant, α is the mean rainfall depth [L], λ is the frequency of rainfall events producing stream flow [T^{-1}] and a and k [$L^{1-a}T^{a-2}$] are the exponent and the coefficient of discharge in the Langevin equation representing the dynamics of discharge values. Eq. (2) therefore allows the computation of the PDF of discharges at any point along a river network as a function of four parameters representing the physiographic, climatic and ecological characteristics of the basin. The methodology adopted in our model for their computation is explained in the following sections (Kusre et al., 2010; Pandey et al., 2015).

In order to compute the mean rainfall depth α [L], and the frequency of rainfall events producing stream flow λ [T^{-1}], the daily rainfall data available for specific locations must be interpolated on the catchment area using a suitable interpolation technique. In our applications, daily rainfall rasters were produced using the Inverse Distance Weighting (IDW) method with an exponent parameter equal to 2. The upstream contributing area was computed for each node of the river network (see Section 0 for its extraction); this allowed the computation of the average daily rainfall depth in the contributing area. In order to compute the frequency of rainfall events it is necessary to define whether a day has to be considered as rainy or not, for each pixel belonging to the river network. This is performed using a threshold on the average daily rainfall: for each day a Boolean raster is created, assigning a 1 to the pixel if the daily average rainfall exceeded the threshold or a 0 otherwise. The created rasters were added and the sum was divided by the length of the time series to calculate precipitation frequency (λ_p), which represents the relative number of rainy days exceeding interception threshold. The aforementioned series of spatially averaged precipitation raster are then averaged over time to compute the cumulative average precipitation $\langle P \rangle$. The mean rainfall depth (α) at every point along the river network is finally computed dividing $\langle P \rangle$ by λ_p. The frequency of rainfall events producing stream flow (λ) was calculated multiplying λ_p by the run-off coefficient (φ).

Among various methods available, Budyko's empirical method was selected to calculate φ. Budyko's analytical function (Eq. (3)) defines the runoff coefficient as a nonlinear function of the Dryness Index (D_1). This index can be easily calculated using precipitation and potential evapotranspiration data. For this purpose daily average potential evapotranspiration rasters can be freely obtained from global datasets. The cumulative average potential evapotranspiration $\langle PET \rangle$ can be computed at every point along the river network from the spatial average PET in the upstream contributing area to each river pixel. Finally D_1 can simply be obtained as $\langle PET \rangle / \langle P \rangle$ pixel wise. This allows the use of Eq. (3) to compute the run-off coefficients at every pixel along the river network.

$$\phi = 1 - \left[D_1 \left(1 - e^{D_1}\right) \tanh\left(\frac{1}{D_1}\right) \right]^{0.5} \tag{3}$$

The recession exponent a and coefficient k are estimated under the hypothesis underlying the GRFM model (Biswal and Marani, 2010), which will be here briefly described. The basic assumption is that the decrease of discharge during recessions is dominated by the geomorphological properties of the river basin. The model assumes that the specific discharge can be expressed as $Q = q\,G/A$, where q represents the discharge generation per unit river length, G is the length of the Active Drainage Network (ADN) and A is the catchment area. Under a series of hypothesis on the drainage density, q and G, the authors derive a relationship between the number of reaches at distance l from the channel heads, $N(l)$, and the total number of reaches located at a distance equal or bigger than l, $G(l)$:

$$\frac{N(l)}{A} = \acute{\rho} \left(\frac{G(l)}{A}\right)^{a} \tag{4}$$

where $\acute{\rho} = Kq^{a-1}/c$ and c is the constant speed at which the ADN shrinks during recessions. The values of $N(l)$ and $G(l)$ can be derived from a Digital Elevation Model (DEM) of the area. The recession exponent can therefore be computed performing a least square regression of $N(l)$ versus $G(l)$. Finally, the recession exponent k, can be calculated as a function of three parameters previously introduced:

$$k = \theta\,(\alpha\lambda)^{1-a} \tag{5}$$

where, θ is assumed to be a constant equal to 0.23 d^{-1} (coherently with (Doulatyari et al., 2015)), independently of the location of the basin or of the season. Readers are directed to the GRFM related literature (Biswal & Marani, 2010, 2014; Biswal and Nagesh Kumar, 2013) for a detailed description of the model.

The previously described procedure allows the derivation of the PDF of discharges $p_Q(Q)$ for each pixel belonging to the river network. The Cumulative Distribution Function (CDF) represents the FDC and can be computed according to Eq. (6). The design discharge of RoR hydropower projects (Q_D) is often assumed as the discharge corresponding to a certain exceedance probability. In case of Nepal, this corresponds to the discharge with 40% exceedance probability, as will be described in Section 0 and used from now on. Based on this assumption the model produces a new raster containing, for each pixel belonging to the river network, the value of Q_D that a hypothetical intake place on that pixel would have.

$$D(Q) = \int_{Q}^{+\infty} p_Q(x)\,dx \tag{6}$$

Hydropower model

A new hydropower model was developed to calculate the theoretical potential of the basin and to identify the optimal combination of location and capacity of the projects. The model aims at the identification of projects that could be realistically developed by private investors and was developed in particular for the Nepalese hydropower market. The basic assumption is that the construction cost of the plant can be estimated summing the costs of its basic components: the intake works, the conveyance system and the powerhouse (Singal et al., 2010)–(Belbo, 2016). A further assumption is that these costs can be parameterized based on a linear regression of available data on costs of RoR plants developed in the region. Under these assumptions the construction cost of a project C_C [\$] can be estimated as:

$$C_C = \alpha_I\, Q_D + \alpha_L L\, Q_D + \alpha_P P \tag{7}$$

where:

α_I: Cost of the diversion and intake works per cubic meter of discharge [\$m^{-3}s]

α_L: Cost of the conveyance system per unit discharge per unit length [\$m^{-4}s]

α_P: Cost of the power house per MW of installed capacity [\$W^{-1}]

L: Length of the conveyance system from intake to power house [m]

Q_D: Design discharge for the plant [m^{3}s^{-1}]

P: installed capacity [W]

The parameters α_I, α_L and α_P are considered constant within the given catchment since they are related to the local costs of the plant's components. α_I includes the cost of all civil and hydro-mechanical components related to the diversion and intake structures e.g. weir, sluices, sediment trap, approach canal and settling basin. The cost of the conveyance system per unit discharge per unit length varies widely based on the type of conveyance system used, which generally may include a pipeline, a tunnel, a canal or a combination of these. The power house cost per unit capacity includes the costs of all civil, electro-mechanical and hydro-mechanical components installed inside the power house including the tail race. In order to identify the projects that could be attractive for developers in the private sector, additional thresholds were introduced on the maximum capacity of the projects (P_{max}) and on the minimum and maximum length of the conveyance systems (L_{min} and L_{max}). The conveyance system type can vary widely due to local topography, geology, geotechnics and common practices. The associated costs can therefore have a widespread. Since the normalized conveyance cost of the pipeline system was reasonably similar to consider a single average value, our model assumes for simplicity the use of a pipeline system running parallel to the river (therefore neglecting solutions involving tunnels). The length of the conveyance system is therefore computed as the distance along the network from the intake to the downstream powerhouse.

The full algorithm employed is shown in Fig. 2 while here we will describe the basic idea. The first step involves the extraction of the river network which is performed using a drainage area threshold method. The hydrological model previously described associates to each pixel of the network, the design discharge Q_D of a hypothetic RoR hydropower intake placed there. The next step involves the separation of different river reaches from the overall network. This operation is performed starting from the basin outlet and proceeding upstream. Every time a junction is found the model continues upstream selecting the reach with the maximum discharge until it reaches the source and therefore defines the first reach. The algorithm then returns to all previously identified junctions and repeats the process until all reaches have been separated (n).

The estimation of the optimal potential for each reach is performed analysing each reach individually. The model starts at the source of the reach (pixel i) and iteratively considers the closest downstream river pixel (pixel j) placed at a distance greater than L_{min}. For this location all hydraulic and topographic properties are known therefore, neglecting head losses, it is possible to

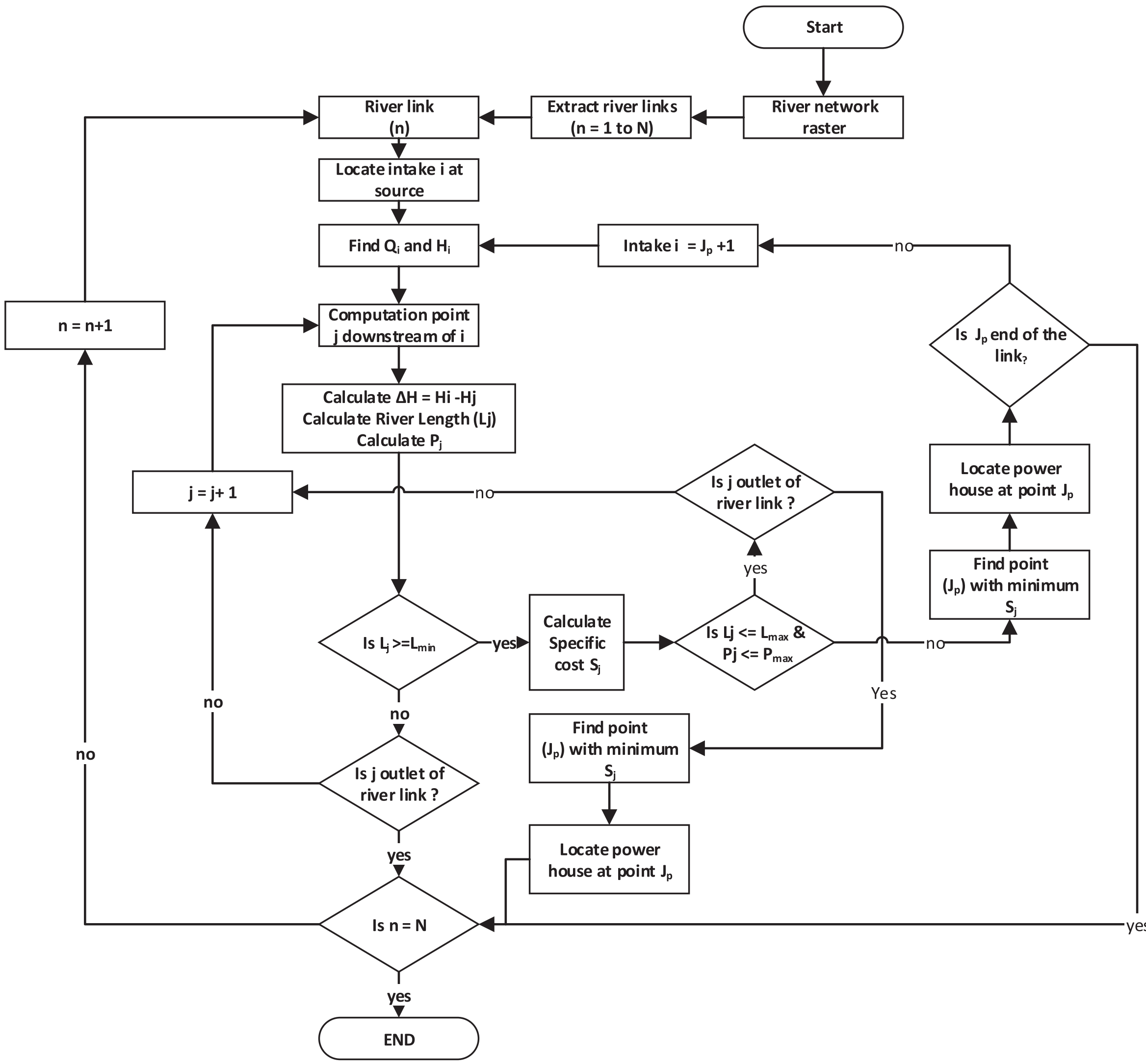


Fig. 2. Flow chart of the hydropower model.

estimate the plant's capacity P [W] as $P = \eta\gamma Q_D \Delta H$, where η is the overall efficiency of the plant (including conveyance, turbine and generator), γ is the specific weight of water [N/m^3] and ΔH is the gross head available for the plant [m], computed as the difference between the elevation of the intake pixel H_i and that of the powerhouse pixel H_j. These values are assumed for simplicity as constant for a specific project and independent of discharge.

The model therefore computes the specific cost $c = C_c/P$ [\$/W] associated with this location of the powerhouse. This process continues until the either $L > L_{max}$, $P > P_{max}$ or the end of the reach is reached. The selection of the optimal location for placing the powerhouse is based on the minimum of the specific cost function, which is therefore the objective function for the optimization. The pixel placed immediately downstream of the powerhouse is then selected for the next intake (i). This process continues until the end of the reach and then repeated for all remaining reaches. The output of the hydropower model are the capacities of the plants, the locations of their intakes and power houses, the related design discharges and heads and the total annual energy generated.

Environmental flow consideration and energy production estimation

The approach commonly adopted by most RoR hydropower projects to enhance their environmental sustainability is based on the concept of environmental flow (e-flow), defined as the minimum flow required in the dewatered section of the river to maintain its ecological condition (McClain et al., 2013). Usually, this quantity is defined either in the environmental impact assessment (EIA) or in national or regional policies. In some areas, the e-flow is defined as a percentage of a reference flow, determined according to a certain exceedance probability of the FDC (Boodoo et al., 2014; McClain et al., 2014; Cavazzini et al., 2016).

The model presented in this paper can potentially integrate e-flows computed according to topographic or hydrologic criteria based on FDCs (sub-basin surface, percentage of the design discharge or similar). In the application that we present, the model was adapted to the Nepalese regulation. The Hydropower Development Policy-2001 of Nepal states in Section 6.1.1 that each project must release a discharge equal or higher than either 10% of the minimum monthly flow or the minimum release as identified by the EIA study. Since the framework developed in this work aims to be applied in data scares regions, this model does not allow for a direct estimation of EIA recommendations nor the estimation of monthly average discharges. Therefore the reference flow for the calculation of the e-flow has been determined based on the 92% exceedance probability, which was found to be close to the minimum monthly flow for the available gauging stations. Once this reference flow was determined, the e-flow was calculated considering the proportion

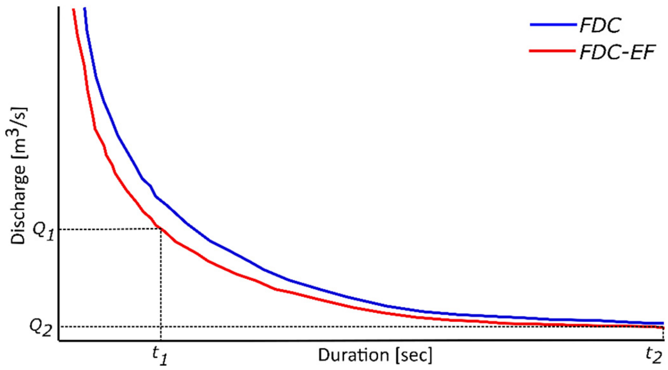


Fig. 3. Example of flow duration curves, with (red) and without (blue) environmental flow consideration. The upper curve was used for capacity estimates, whereas the lower curve was used for energy estimates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stated in aforementioned policy. Finally, according to the Nepalese practice, the design discharge Q_D has been defined according to the 40% exceedance probability of the natural FDC, while the estimation of the energy production is based on disposable flows, meaning on the FDC deducted by the e-flow (Eq. (8)).

Excluding leap years, it is possible to convert exceedance probability to durations [s] simply multiplying by the number of seconds in a 365 days year. In Fig. 3, t_1 represents the duration [s] of the discharge value Q_{40} for the FDC of disposable flows, while t_2 [s] represents the duration of the minimum disposable discharge. Based on the simplifying assumption of constant efficiency, density and head, the annual energy production can be expressed as:

$$E = \eta\gamma\Delta H\left(Q_{40} \times t_1 + \int_{t_1}^{t_2}(Q(x) - EF)dx\right) \quad (8)$$

where:

E: annual energy production [J]

Q_{40}: discharge corresponding to 40% exceedance probability on the FDC [m^3/s]

t_1: duration of Q_{40} on the duration curve of disposable flows

t_2: duration of the minimum disposable discharge

The energy generated by every individual project is summed up to estimate the total annual energy production for the catchment.

Application

Case study

The developed framework was tested on the West Rapti River basin, Nepal. The West Rapti is a transboundary river that originates in the mid-western region of Nepal and flows into the Ghaghara River, one of the major tributaries of the Ganges River. The total area of the basin, closed at the Nepal–India border is around 6417 km^2, 60% of which lies in the northern mountain region while the remaining 40%

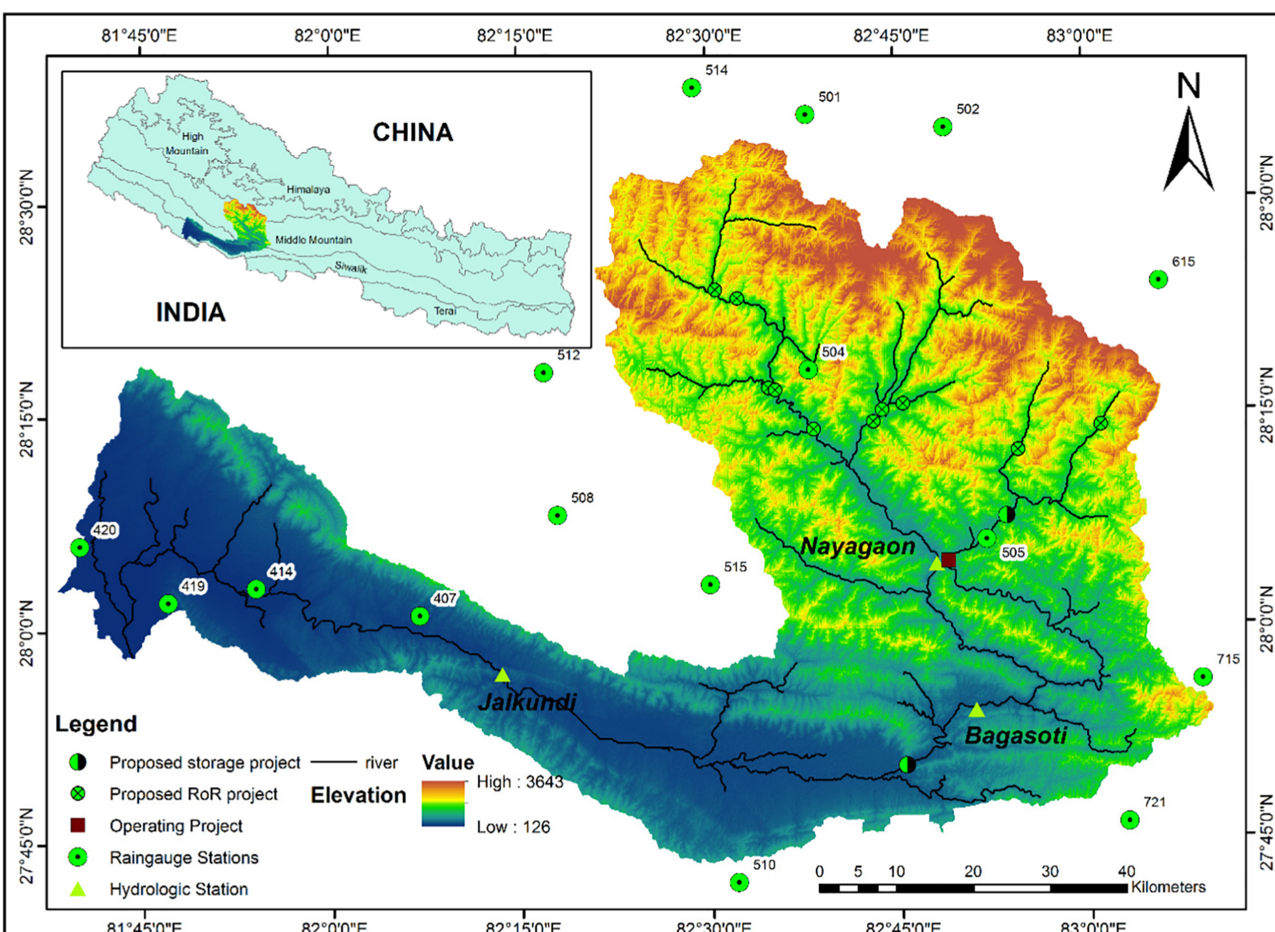


Fig. 4. Map of the West Rapti River basin. Operating and Proposed RoR and storage project are also indicated, together with the locations of existing rain gauges and stream gauging stations.

Table 1
Overview of the 15 rain gauge stations considered in this study.

Stat. ID	Station ID	From	To	Annual [mm]	Latitude	Longitude	Elevation [m.a.s.l.]	District
1	407	2001	2009	1447	28°01′	82°07′	235	Banke
2	414	2001	2009	1123	28°03′	81°54′	226	Banke
3	419	2001	2009	1490	28°02′	81°47′	195	Banke
4	420	2001	2009	1548	28°06′	81°40′	165	Banke
5	501	2001	2009	1920	28°36′	82°38′	1560	Rukum
6	504	2001	2009	1778	28°18′	82°38′	1270	Rolpa
7	505	2001	2009	1189	28°06′	82°52′	823	Pyuthan
8	508	2001	2009	1678	28°08′	82°18′	725	Dang
9	510	2001	2009	1719	27°42′	82°32′	320	Dang
10	512	2001	2009	807	28°18′	82°17′	885	Salyan
11	514	2001	2009	2246	28°38′	82°29′	2100	Rukum
12	515	2001	2009	1606	28°03′	82°30′	634	Dang
13	615	2001	2010	2494	28°24′	83°06′	2273	Baglung
14	715	2001	2009	1707	27°56′	83°09′	1760	Arghakhanchi
15	721	2001	2010	2175	27°46′	83°03′	200	Kapilbastu

Table 2
Overview of the three discharge stations whose data have been used for validation.

Station ID	From	To	Q Avg. [m^3/s]	Catchment area [km^2]	Latitude	Longitude	Location
330	2001	2009	63	1957	28°04′20″	82°48′00″	Nayagaun
350	2001	2009	109	3587	27°51′12″	82°47′34″	Bagasoti Gaun
360	2001	2006	141	5137	27°56′50″	82°13′30″	Jalkundi

lies in the southern flatter regions known as Siwalik and Terai. The geology of the southern part is characterised by sedimentary rocks such as mudstone, sandstone and conglomerate whereas the northern part is dominated by low grade metamorphic rocks consisting of slate, schists, quartzite, phyllite, metasandstone and garnet-schists (Belbo, 2016).

There exists a significant variation of climate within the basin. The northern part of the basin has a temperate climate, whereas the southern Terai region is characterised by a tropical to sub-tropical climate. Temperatures along this basin vary from 46 °C in the southern region during summer to 2° in the northern mountains during winter. The average annual precipitation in the basin is around 1500 mm out of which 80% is received during the monsoon period, which spans between June and September. Since only a small part of the catchment lies above 3000 m.a.s.l., the contribution from snow melt can be neglected (McClain et al., 2013).

The only hydropower project developed in the basin to date, the Jhimruk Hydropower Plant has an installed capacity of 12 MW. However ten additional RoR projects, with a total installed capacity of 52 MW, have been identified by private developers. Along with these, two other storage projects with a total installed capacity of 400 MW are under consideration. Fig. 4 provides an overview of the West Rapti River basin including all the identified and operating hydropower projects and the locations of rain gauge and discharge measuring stations.

The data required for the study include elevation, potential evapotranspiration and precipitation. Discharge data are needed for validation purpose. Data on existing and in-development hydropower plants including their cost are needed for the estimation of the technical and economical parameters of the hydropower model. Observed rainfall data, measured at daily time scale from 15 rain gauge stations were used to create a series of daily input precipitation raster. Point rainfall data have been interpolated using the IDW method as explained in Section 2.11 using the 12 nearest rainfall stations. Daily discharge data at three gauging stations were used for validation. These data were obtained from a previous study conducted within the same basin (Thapa, 2017). A summary of these data is presented in following tables (Tables 1 & 2).

Potential evapotranspiration and topographic data were also collected: a 90 m resolution freely available DEM was obtained from the CGIAR-CSI website (http://www.cgiar-csi.org/data). Two river networks were extracted, using a catchment area threshold of 0.1 and 40 km^2 respectively. The first network was used in the hydrological model since an accurate description of the river network allows a better estimation of the recession exponent within the GRFM. The hydropower model instead focuses on the reaches having a discharge high enough to justify the construction of a RoR hydropower plant; therefore the second network was used in order to omit lower order streams. PET data were also downloaded from CGIAR dataset at 1 km^2 resolution. The current version of this model requires all raster datasets to have the same resolution and extent, therefore the PET dataset were resampled and cropped to match the DEM's extent and resolution. The resampling was done using the nearest neighbour method.

Table 3
Values of three cost parameters used in the hydropower model.

Symbol	Description	Cost
α_I	Intake cost per unit discharge [€ m^{-3} s]	307,581
α_C	Conveyance cost per unit length per unit discharge [€ m^{-4} s]	36
α_P	Power house cost per unit installed power [€ MW^{-1}]	307,762

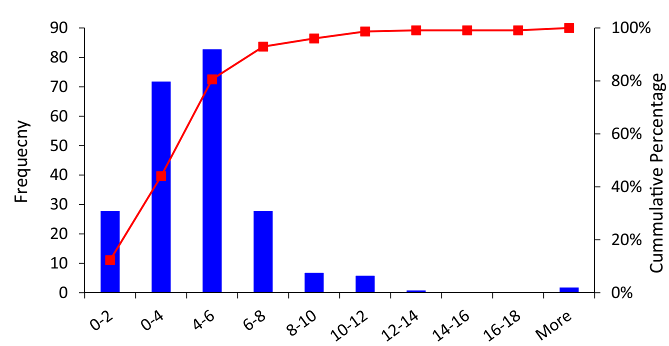


Fig. 5. Distribution of lengths of conveyance systems estimated from the projects identified by private developers and included in the list of the Department of Electricity Development. Blue bars represent the number of projects in each length class while the solid line represents their cumulative distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

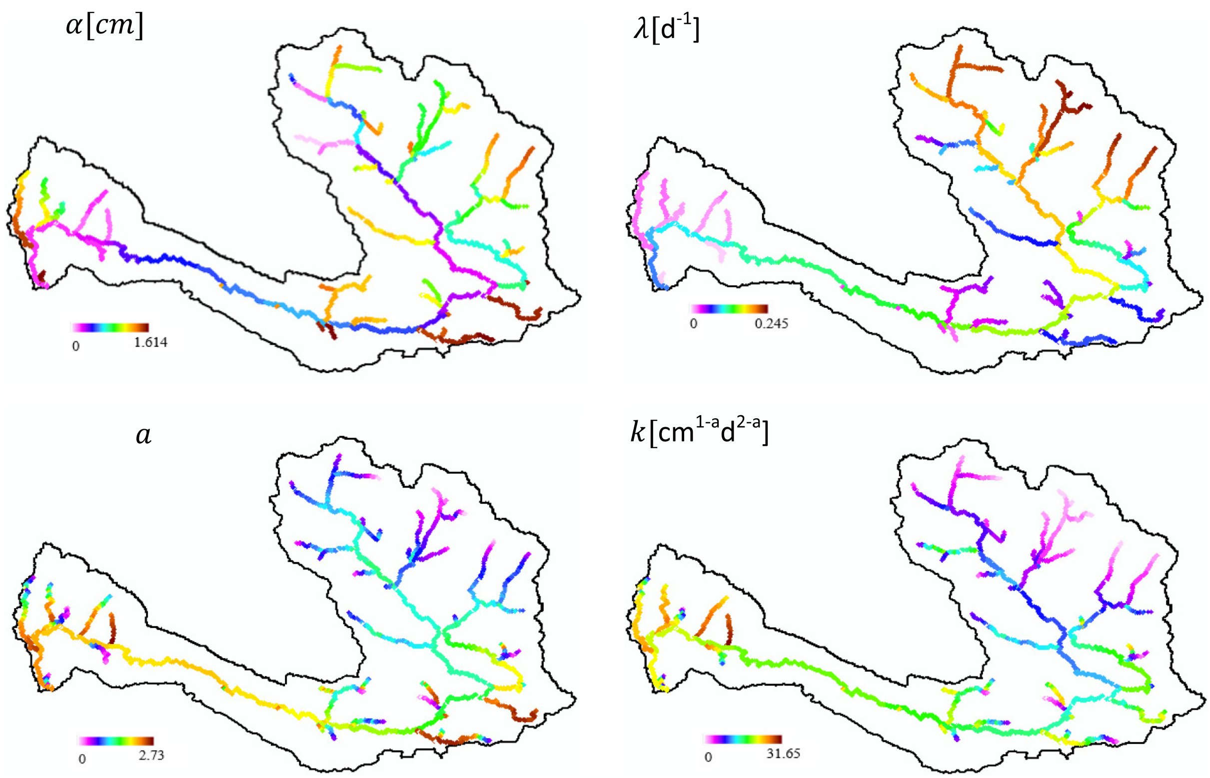


Fig. 6. Distribution of the parameter governing the PDF of natural discharges along the West Rapti River basin: α [cm], λ [d^{-1}], a, k [$cm^{1\text{-}a}d^{2\text{-}a}$].

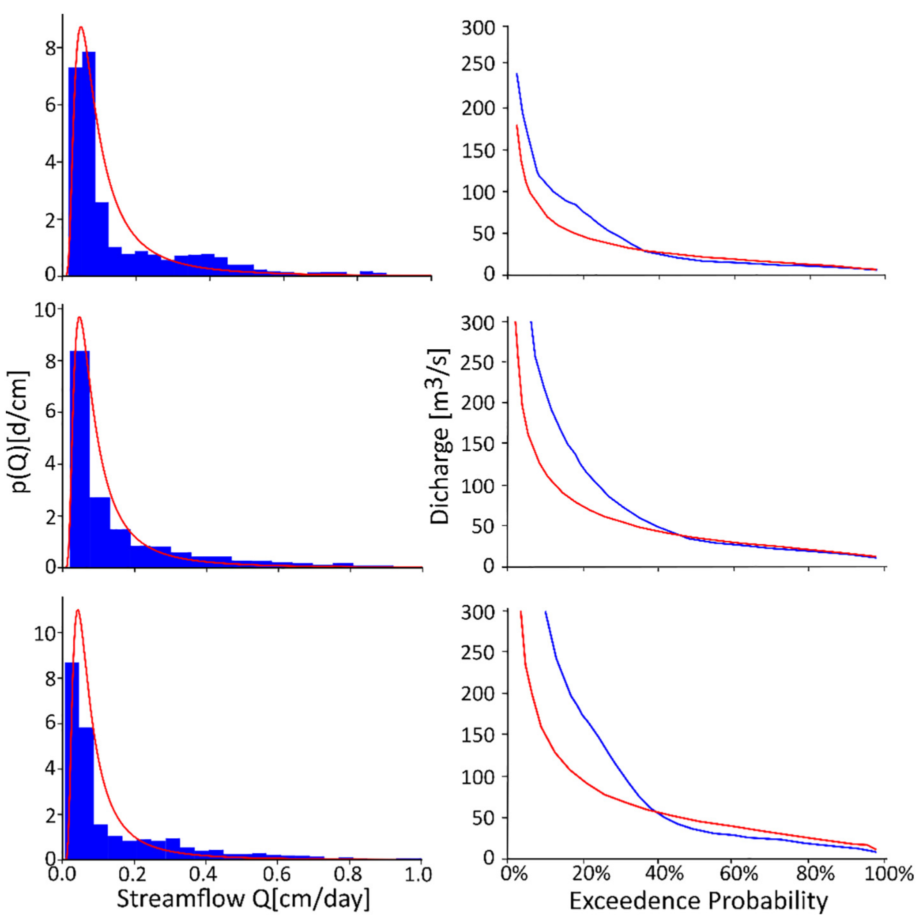


Fig. 7. Probability distribution function (left) and flow duration curve (right) at three gauging stations: Nayaguan (top), Bagasoti (middle), Jalkundi (bottom). Observed values are in blue, while model results are in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The cost parameters required for the hydropower model were calculated from a list of recently constructed and planned projects in Nepal. Individual parameter values were calculated for each project and were then averaged to get the single value for each parameter. The conveyance cost parameter was calculated considering a pipe system supported by saddles and anchor blocks. The selection was done based on its flexibility, being suitable for a wide range of topographies. The final values adopted for these parameters are given in the Table 3. The overall efficiency of the identified projects, based on the authors experience in feasibility study of hydropower projects in Nepal and also as recommendation of Mosonyi, 1987 (Mosonyi, 1987), was assumed to be 86% (Turbine efficiency 91%, Generator efficiency 95% and Transformer efficiency 99%).

In order to determine the maximum and minimum length threshold for the conveyance system (L_{max}, L_{min}), data on RoR projects developed in Nepal were gathered from the Department of Electricity Development (DoED) (http://doed.gov.np). The length of the conveyance system of all RoR projects smaller than 100 MW was estimated based on their license area, which is defined as a rectangular area which identifies the extent of each project. This area is provided by DoED in the form of two pairs of coordinates defining two opposite vertices of the rectangle. Assuming that the pipeline of each project runs almost parallel to the river, its length was estimated as the river length within each license area. The histogram and cumulative distribution function of these lengths is shown in Fig. 5.

In this analysis, L_{min} and L_{max} have been defined as the 10% and 90% percentiles of the distribution of conveyance systems' lengths respectively. These thresholds have been approximated to 2 and 7 km respectively. The last parameter required by the hydropower model is the maximum installed capacity (P_{max}) of the project; this has been determined based on the study of suitable capacity of the project, recommending 100 MW as a maximum threshold (Singh & Nachtnebel, 2016).

Results and discussion

Hydrological model

The application of the above described hydrological model provided the values of the four governing parameters for the whole network of the West Rapti River basin as shown in Fig. 6.

Discharge data were available from three gauging stations (Thapa, 2017): Nayagaon, Bagasoti and Jalkundiand; the PDFs of discharges in these cross-sections are plotted and compared with modelled values in Fig. 7.

The comparison of measured and modelled data suggests that the hydrological model is capable of reproducing discharge values for low flows, specifically around Q_{40}, therefore for exceedance probability above 40%, while it highly underestimates available streamflow in case of higher discharge values. The underestimation of higher streamflow values was witnessed in previous applications of this model (Botter et al., 2008). Possible explanations of this are the following: the model has been applied at yearly timescale without a distinction of the governing parameters for the different seasons that characterise the climate of the West Rapti River basin. For completeness we must report that a series of simulations were also performed dividing the hydrological year in two seasons: a "rainy season", corresponding to the monsoon approximately between June and September, and a "dry season" from October to May. The results were then combined to obtain the complete FDCs. These simulations, however, produced worst agreement with measured FDCs. The reasons for this behaviour we argue could be related to the slow groundwater contribution that continues long after the end of the monsoon season and could be responsible for maintaining high discharge values even in absence of any rainfall event. In these cases the applied hydrologic model could not be suitable for the hydropower potential assessment and we suggest possible alternatives that could be included in this framework like the model developed by Müller et al. (2014).

In this scenario, the suitability of this hydrologic model for identifying RoR hydropower projects was assessed comparing the observed and simulated discharges at various exceedance level (Fig. 8). The comparison of these two datasets proves the capability of this framework in predicting discharges with an exceedance probability higher than 40% with root mean square error below 10%. Since this value corresponds to the commonly adopted value for Q_D in Nepal, the application of our hydropower model for potential assessment is, in this case, justified. In different conditions, particularly in case of high seasonality and in absence of discharge data for actual control of the estimated FDCs, its application for hydropower potential assessment should be considered with due care.

Hydropower model

45 river links with minimum catchment area of 40 km^2 were identified within the basin, out of which only 16 were suitable for hydropower development (Fig. 9). It is possible to observe that, due to the topography of the basin, most of the river reaches suitable for hydropower development are concentrated in the high and middle mountain regions, since the low slopes in the Siwaliks and Terai regions make uneconomical the development of RoR plants considered by our model.

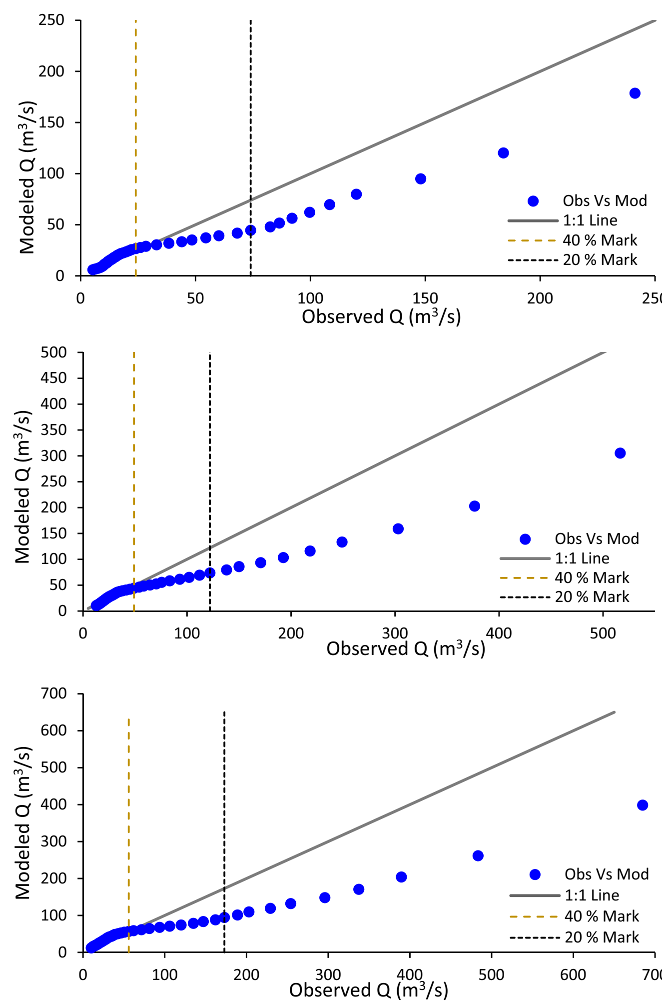


Fig. 8. Comparison between observed and simulated discharge corresponding to various exceedance probability; Nayaguan (top), Bagasoti (middle), Jalkundi (bottom).

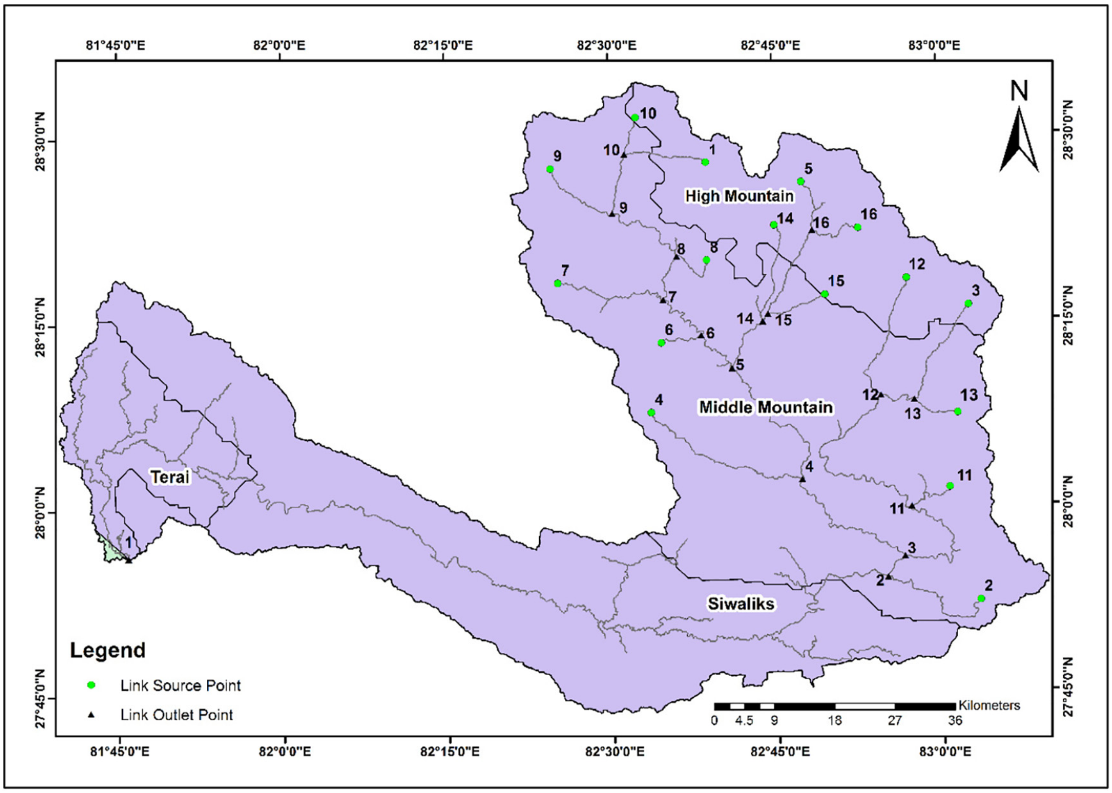


Fig. 9. River links suitable for hydropower development. 16 river reaches were found suitable for power production.

79 different projects with a capacity exceeding 1 MW were identified in these 16 reaches. Since their capacity ranges from 17 to 1.01 MW, they lay in the category of small hydropower projects that are commonly developed by private investors. The estimated total installed capacity and annual energy generated are around 320 MW and 2014 GWh respectively. The West Rapti (link number 1 in Fig. 9), the longest river of the basin, consists of 41 projects with a total installed capacity of 203 MW. The other two major tributaries of the West Rapti: the Jhimruk River (link 3) and the Lungri River (link number 5) have an installed capacity of 41 and 33 MW respectively. These three major rivers constitute about 86% of the total potential whereas the remaining 14 reaches contribute to the remaining 14%. The topographic characteristic of each river link and their potential is given in Table 4.

Table 4
Summary of reaches suitable for hydropower development.

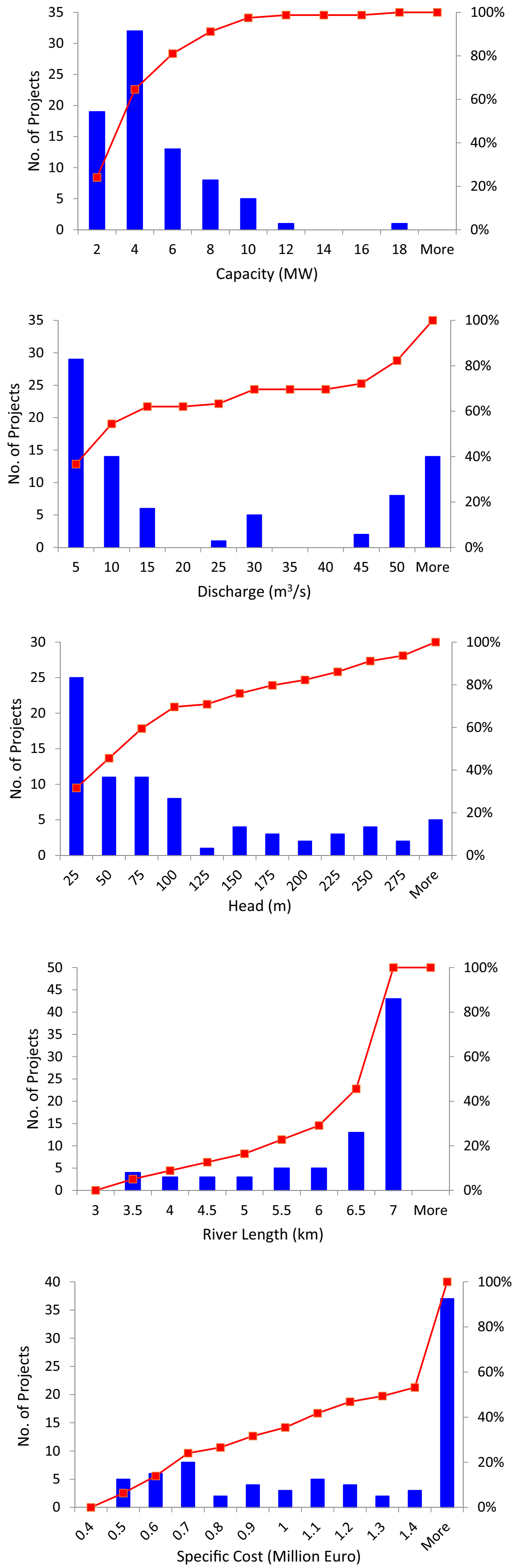
ID	River length [km]	Maximum elevation	Minimum elevation	Average slope [%]	No of projects	Power [MW]	Energy [GWh]
1	359.5	1898	130	0.5	41	203.1	1282.4
2	24.1	949	368	2.4	2	2.5	16.4
3	92.0	1387	408	1.1	13	41.5	261.8
4	30.8	986	550	1.4	2	2.9	18.3
5	37.1	1745	662	2.9	5	33.2	206.6
6	7.4	997	740	3.5	1	1.2	7.1
7	21.8	1273	875	1.8	2	4.0	24.6
8	8.6	1434	981	5.3	1	3.3	20.3
9	14.4	1651	1205	3.1	2	5.4	33.4
10	6.7	1568	1391	2.7	1	1.2	7.6
11	9.6	793	598	2.0	1	1.1	6.3
12	23.1	1603	867	3.2	3	10.1	61.4
13	7.8	1128	936	2.5	1	1.0	6.4
14	16.7	1523	797	4.3	2	4.5	27.8
15	10.3	1161	843	3.1	1	1.5	9.2
16	9.9	1660	1233	4.3	1	4.2	25.2
Total					79	320.7	2014.6

The distribution of the properties (design discharge, head, length of the conveyance system and specific cost) of all identified projects were analysed and plotted in Fig. 10. Almost 70% of the identified projects are smaller than 6 MW. Almost half of them have a design discharge smaller than 10 m^3/s and less than 75 m of head. This remarks the characteristics of the West Rapti basin, consisting of smaller and flatter sub-basins. This observation is moreover confirmed by the distribution of lengths of the conveyance systems, between the intake and the power house, with the majority of identified projects falling near the upper threshold of L_{max}. For these reasons, among others, the West Rapti has received, until this moment, less interest from private developers. As mentioned above, our model only considers one type of project layout, with a conveyance system composed of a pipeline running parallel to the river. The use of different systems, like tunnels, or a combination of open channels and penstocks, could provide different results. In these cases, different values of the specific cost for different conveyance technologies should be considered.

Conclusions

An assessment framework has been developed to identify RoR hydropower projects within a river basin by relying only on globally and freely available climatic and topographic data. River discharge statistics were estimated using an existing analytical model which provides flow duration curves based on four climatic and topographic parameters. A new hydropower model was also developed to identify RoR projects which, in turn, provides the total potential of the considered basin. The developed framework allows the selection of projects within pre-defined limits of the lengths of the conveyance system and of maximum plant capacity. Depending upon the investment capacity of the developers, these thresholds could be changed to better suit investors' objectives.

The framework was tested on the West Rapti basin, Nepal using global data and local data for validation. The simulated FDCs were



validated using three gauging stations. Although the hydrological model showed a tendency to underestimate stream flows for low exceedance probability (higher discharge values), it produced relatively accurate results for exceedance probabilities below 40%. Since the design discharge of RoR hydropower plants is usually close to this value, results from this hydrological model can be used for identification of projects at pre-feasibility stage in catchments characterised by hydrological conditions similar to the one we tested it in.

On top of identifying the locations of RoR projects, the hydropower model developed in this framework can provide valuable information on different characteristics for each plant. Data such as design discharge, head, project length, annual energy, tentative cost and location of the intake and power house are all required at pre-feasibility stage. This model could also be used by institutions responsible for the management of the development of river basins. The identified projects could be distributed to private developers based on bidding mechanisms in order to stimulate competition within the sector.

The use of this framework in different topographical and climatic setup is constrained by the underlying assumption of both the hydrological and hydropower model. The hydropower model assumes one single plant layout, therefore the results are limited by this assumption. Moreover the same thresholds for the length of the conveyance system and the plant capacity are adopted for all river reaches within the river basin. This however may be easily generalized allowing the consideration of different thresholds in different links depending upon their average discharge. This would provide a wider variability in the set of identified projects which might allow the entrance of all levels of investors. Further developments of this framework will include the assessment of plants optimality based on other economic and financial indicators e.g. Net Present Value (NPV), Benefit/Cost ratio etc.

The assessment framework herein presented, is based on a hydrological model which can be used for data scarce regions, providing an adequate tool to support the optimization of investments in developing regions of the World. This can be adapted (in terms of boundary conditions and internal links) to accommodate the analysis of other water usage fluxes making it an ideal tool to evaluate and predict Water-Food-Energy linkages at a river basin scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 10. Distribution of various project characteristics. The blue histograms count the number of projects in each class, whereas the black lines represent cumulative distributions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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