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Bridging the information gap: A webGIS tool for rural electrification in data-scarce regions

Marc F. Müller [a,*], Sally E. Thompson [a], Maggi N. Kelly [b]

[a] Department of Civil and Environmental Engineering, Davis Hall, University of California, Berkeley, CA, USA
[b] Department of Environmental Sciences, Policy and Management, Mulford Hall, University of California, Berkeley, CA, USA

HIGHLIGHTS

- Information gaps restrict the dissemination of sustainable rural electrification technologies.
- Open source, interactive, webGIS tool addressing these gaps for micro-hydropower.
- Optimizes the placement and size of local designs using remote sensing inputs.
- Collects local economic constraints and generates regional feasibility maps.
- Successfully predicts the location of existing micro-hydropower plants in Nepal.

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ABSTRACT

Rural electrification in developing countries is often hampered by major information gaps between local communities and urban centers, where technical expertise and funding are concentrated. The tool presented in this paper addresses these gaps to support the implementation of off-grid micro hydropower infrastructure. Specifically, we present a method to site, size and evaluate the potential for micro hydropower based on remote sensing data. The method improves on previous approaches by (i) incorporating the effect of hillslope topography on the optimal layout of the infrastructure, and (ii) accounting for the constraints imposed by streamflow variability and local electricity demand on the optimal size of the plants.

An assessment of the method's performance against 148 existing schemes indicates that it correctly identifies the most promising locations for hydropower in Nepal, but does not generally reproduce the specific design features of constructed plants, which are affected by site-specific constraints. We develop a proof-of-concept computer tool to explore the potential of webGIS technology to account for these constraints by collecting site-specific information from local users.

1. Introduction

Access to electricity remains an impediment to development in many parts of the world, particularly in rural areas that will stay out of reach of centralized power grids due to low population densities and prohibitive grid extension costs [1]. In this context, decentralized distributed generation, whereby electricity is generated at the point of consumption, offers a promising and affordable strategy for rural electrification [2]. Community-scale run-of-river hydropower – *micro hydropower* – is a particularly attractive technology in mountainous regions, where appropriate slope and runoff conditions are encountered, and where grid extension is expensive because of the complex topography. Thanks to the low level of technology of its components, micro hydropower often emerges as the most cost effective distributed generation option for mountain communities [3]. Unlike conventional hydropower, micro hydropower has a limited impact on the landscape and on the flow regime of the stream because it does not store nor divert significant volumes of water.

Despite their promise, micro hydropower programs have had mixed success globally. In Nepal, despite a huge hydropower

Abbreviations: AEPC, Alternative Energy Promotion Center of the Government of Nepal; CSR, complete spatial randomness; DEM, digital elevation model; GIS, geographic information system; NGO, Non Governmental Organization; VDC, village development committee.

* Corresponding author.
E-mail addresses: marc.muller@berkeley.edu (M.F. Müller), sally.thompson@berkeley.edu (S.E. Thompson), maggi@berkeley.edu (M.N. Kelly).

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Nomenclature

ρ	density of water, kg m^{-3}
g	gravitational acceleration, m s^{-2}
η	plant efficiency, –
k	linear friction losses, –
Δz	elevation difference (along penstock), m
H	net hydraulic head, m
A	catchment area, km^2
L	penstock length, m
α_0	average cost of a unit (1 kW) micro hydropower scheme, Nep. Rupees (NRp)
α_C	scale elasticity of micro hydropower costs, –
γ_0	household electricity demand at unit price, kW
γ_p	price-elasticity of household electricity demand, –
Q_d	capacity flow, m^3 s^{-1}
$P\{Q \geqslant Q_d\}$	exceedance probability of Q_d, –
C	electrical capacity, kW
pop	community size, Number of households
p	unit price of electrical capacity, NRp per kW
TSI	topographic suitability index, –
CVI	community value index, –

potential [4], favorable policies and substantial local hydropower expertise [5], micro hydropower currently supplies about 200,000 households [6] (about 7 million people remain unconnected [1]), and up to 30% of existing micro hydropower plants are not in operation [7]. These poor outcomes point towards major information gaps between key actors in the micro hydropower sector. These gaps arise at the earliest stage of project development and prior to in situ feasibility assessments. Policy makers at the regional level lack appropriate local information to identify promising locations for micro hydropower development, while would-be project enablers at the local level lack awareness and technical expertise for local resource assessment [8,9]. These gaps are particularly evident in Nepal where, paradoxically, the extreme topography of the region is at once responsible for its enormous hydropower potential, and for the low physical accessibility of most communities. It ensues an ineffective transfer of information between urban centers, where funding agencies and technical expertise are concentrated, and rural communities, where micro hydropower facilities are installed, used and maintained.

This study investigates the combination of two promising recent information technologies, remote sensing and open source webGIS, as a means to address information barriers at early project stages. We devise the tools and analysis framework necessary to assess these technologies in the specific case of Nepal, with the expectation that the methods provide a prototype for other regions where similar opportunities and challenges relating to micro hydropower arise. Specifically, the contributions of this paper are twofold. First, we formulate and assess a novel algorithm using remotely sensed digital elevation models (DEM) and state-of-the-art hydrological models to identify optimal micro hydropower locations. Second, we develop an operational web tool to support micro hydropower development in Nepal. Web-based geographic information systems (webGIS) are increasingly used[1] to collect, merge and disseminate heterogeneous data from a wide variety of stakeholders. Yet to our knowledge, this is the first attempt to leverage its interactive, open-source and cloud-based nature to support rural electrification.

The location of micro hydropower infrastructure components on the landscape is a key design decision: it determines capital costs, hydraulic head and mean flow, which are the features determining the scheme's ultimate economic performance. The effects of location on these features should therefore be incorporated into attempts to map hydropower potential. Infrastructure siting is driven by topography, which affects both the potentially harvested power, through the hydraulic head and the area of the contributing catchment; and the cost of the infrastructure, by affecting the lengths of the penstock and headrace canal. This dependence on topography allows layout optimization to be automated – albeit in a simplified fashion – for the purpose of mapping hydropower potential, thanks to the global availability of free, high resolution DEMs from remote sensing platforms[2]. An extensive review of recent DEM-based potential assessment techniques can be found in Punys et al. [15]. In their most basic form, existing algorithms estimate gross hydropower potential by computing watershed boundaries and river reaches from a digital elevation model e.g., [16]. The elevation difference obtained within each reach (or arbitrary river segment as in Kusre et al. [17]) is then multiplied by the area of its contributing catchment and a regional runoff parameter. In a more sophisticated approach, Yi et al. [18] implemented a cell-by-cell search algorithm along the drainage network. Unlike previous approaches, the method allows for water diversions from lower to higher order streams and identifies potential (straight line) waterways from each stream pixel within a series of predefined search radii. The hydropower potential of each waterway is then evaluated based on its average (straight distance) slope. A similar search algorithm was further developed by Larentis et al. [19], allowing for water storage reservoirs, and accounting for the effect of preexisting schemes on the exploitable potential.

A common aspect of all these methods is their sole reliance on the elevation profile of the stream channel itself to evaluate the hydraulic head. Yet hillslopes are typically steeper than channels in mountainous regions, and the optimal penstock position may be located on a favorable slope at a significant distance from the stream, as illustrated in Fig. 1. As a result, headrace canals exceeding 500 m are commonly found in Nepal e.g., [20]. Secondly, hydropower potential is constrained by streamflow variability, as described by the flow duration curve of the stream. The effects of flow constraints on the optimal size of hydropower plants are well understood and have been the focus of substantial recent research. An extensive review of recent optimization approaches to size run-of-river hydropower plants is available in Bozorg Haddad et al. [21]. However, existing methods were typically developed to design grid-connected schemes in developed countries, where electricity prices are exogenously determined (e.g., through feed-in tariffs). They are not applicable off the grid, where micro hydropower revenue is affected by local electricity demand. Further, flow duration curves are notoriously difficult to predict *a priori* in ungauged catchments, particularly in hydrologically complex and poorly gauged mountainous regions like Nepal [22]. Consequently, despite being essential to optimize the capacity of micro hydropower plants, streamflow variability has been largely omitted from

[1] For instance, webGIS has been used to predict environmental [10] and health-related [11] risk, manage environmental resources [12] and support ecological modeling [13].

[2] For instance, ASTER GDEM v2 used in this paper provides quasi global land surface elevation (i.e. between 83°N and 83°S) with 30 m grid postings [14].