European Journal of Operational Research 000 (2016) 1–12

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Eco-friendly location of small hydropower

Christina Ioannidou, Jesse R. O'Hanley*

Kent Business School, University of Kent, Canterbury CT2 7PE, United Kingdom

ARTICLE INFO

Article history:
Received 22 December 2015
Accepted 28 June 2016
Available online xxx

Keywords:
Small hydropower
Optimization
River connectivity
Backwater effects
Probability chains

ABSTRACT

We address the problem of locating small hydropower dams in an environmentally friendly manner. We propose the use of a multi-objective optimization model to maximize total hydropower production, while limiting negative impacts on river connectivity. Critically, we consider the so called "backwater effects" that dams have on power generation at nearby upstream sites via changes in water surface profiles. We further account for the likelihood that migratory fish and other aquatic species can successfully pass hydropower dams and other artificial/natural barriers and how this is influenced by backwater effects. Although naturally represented in nonlinear form, we manage through a series of linearization steps to formulate a mixed integer linear programing model. We illustrate the utility of our proposed framework using a case study from England and Wales. Interestingly, we show that for England and Wales, a region heavily impacted by a large number of existing river barriers, that installation of small hydropower dams fitted with even moderately effective fish passes can, in fact, create a win-win situation that results in increased hydropower and improved river connectivity.

1. Introduction

Efforts to reduce carbon emissions in both industrialized and developing countries has resulted in an increased interest in renewable energy production. Hydropower, in particular, has gained special attention. Although installation costs can be appreciable, operating costs are generally low, the technology is already well developed, and of the many other sources of renewable energy (e.g., wind and solar) it is far more reliable in terms of providing base load power generation. Among the various types, small hydropower plants (SHP) with an installed capacity of up to 10 megawatts are by far the most common and logistically feasible option in many places, particularly across Europe. According to the European Small Hydropower Association, SHP currently supplies enough electricity for 13 million households and plays a key role in greenhouse gas (GHG) emissions reduction through green energy production (ESHA, 2012). It also supports water management policies, aids in climate change adaptation through flood control, and contributes to the prevention of water scarcity and drought.

In the UK, the government has set a goal of reducing emissions by 18 percent by 2020 (HM Government, 2009a). Renewable energy is considered a key part of the overall plan with respect to electricity generation. In particular, the UK Renewable Energy Strategy has set a legally-binding target that 15 percent of energy production comes from renewable sources by 2020 (HM Government, 2009b). Even if small-scale hydropower is not expected to play a major role in this, the ambition is such that all sources of renewable energy are expected to deliver their maximum sustainable potential (EA, 2010). In particular, according to the UK's National Renewable Energy Action Plan (DECC, 2010), new SHP schemes of between 40 and 50 megawatts need to be installed annually until 2020.

Although clean in terms of GHG emissions, the installation of hydropower schemes can nonetheless have adverse impact on the environment, especially on fish populations and other aspects of river ecosystems (Bednarek, 2001; O'Hanley & Tomberlin, 2005; Roni et al., 2002; Stanford et al., 1996). Hydropower dams form physical barriers that often disrupt the natural connectivity of rivers by reducing water and sediment transfer, which can impact geomorphology processes and fragment river habitats. In particular, dams can impede fish access to essential breeding and rearing areas, resulting in reduced fish productivity and other changes in aquatic community composition (Lucas & Baras, 2001). Hence, any decision about installing hydropower dams normally involves a trade-off between renewable energy production on the one hand and healthy rivers on the other. This highlights the need for decision support tools in SHP location planning, which are capable of balancing these two basic but competing goals. Such tools would prove extremely useful to river management organizations in devising more sound and effective hydropower development strategies.

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* Corresponding author. Tel.: +44 1227 824286.
E-mail address: j.ohanley@kent.ac.uk (J.R. O'Hanley).

http://dx.doi.org/10.1016/j.ejor.2016.06.067
0377-2217/

Please cite this article as: C. Ioannidou, J.R. O'Hanley, Eco-friendly location of small hydropower, European Journal of Operational Research (2016), http://dx.doi.org/10.1016/j.ejor.2016.06.067

In this paper, the problem of optimally locating SHPs is addressed. We propose a series of integer programing models for siting SHPs in order to maximize overall hydropower generation capacity while limiting negative impacts on river connectivity. Studies thus far have dealt almost exclusively on searching for a set of feasible locations for installing SHP rather than optimizing site selection.

1.1. Hydropower location

Much of the literature on hydropower location focuses on the use of geographic information systems (GIS) to screen for potential dam locations, driven in large part by the increasing availability of satellite imagery and other remotely sensed data. Site feasibility and power generation potential are usually the two main concerns (Coskun et al., 2010; Cyr, Landry, & Gagnon, 2011; Dudhani, Sinha, & Inamdar, 2006; Kusre, Baruah, Bordoloi, & Patra, 2010; Ramachandra, Kumar, Jha, Vamsee, & Shruthi, 2004), with only occasional treatment of environmental aspects (Lee, Brizzee, Cherry, & Hall, 2008; Rojanamon, Chaisomphob, & Bureekul, 2009; Yi, Lee, & Shim, 2010). A good example is the study by Yi et al. (2010), which uses a combination of hydrologic, topographic, and environmental criteria to rate the suitability of candidate SHP sites. Using a case study area in South Korea, a small set of promising locations for reservoir and run-of-river type SHPs is identified by performing a series of geospatial data processing steps.

Installation decisions are considered independently in almost every proposed methodology. An exception is Larentis, Collischonn, Olivera, and Tucci (2010), where the interactive effects of hydropower dams are considered. The proposed methodology treats total hydropower in a basin as a system, where the siting of a dam reduces the generation potential of upstream sites by raising the water surface depth (the so called "backwater" effect explained in more detail in Section 2.3). Maximum hydropower potential within a basin is estimated by siting dams in series along a river course, such that each dam lies outside the length of the backwater curve produced by the dam downstream.

Of particular relevance to our current work is the study by Ziv, Baran, Nam, RodrÃguez-Iturbe, and Levin (2012). Rather than employ a typical GIS approach, the authors examine in detail the ecological impacts of hydropower development within the Mekong River Basin. Their framework, which incorporates spatially-explicit fish dispersal and population growth models, is designed to explore trade-offs between hydropower, fish abundance, and biodiversity. Trade-off curves are produced by enumerating all possible dam development scenarios, which invariably limits the scalability of their approach to problems involving small numbers of possible dam locations.

Another relevant study is one carried out by the UK's Environment Agency (EA), which looked into the potential for expanding renewable energy production from small scale hydropower across England and Wales (EA, 2010). All known weirs were considered as possible hydropower plant locations. Using a variety of methods to estimate flow, weirs were assessed for their hydropower potential and subsequently categorized based on their environmental sensitivities (i.e., presence of fish key fish species or areas of special conservation concern).

To our knowledge, Chang, Liaw, Railsback, and Sale (1992) is only existing example in the literature to propose a formal optimization framework for selecting hydropower development alternatives. Their methodology takes into account potential reductions in water quality (measured in terms of dissolved oxygen concentrations) caused by the installation of hydropower dams. Using a case study of the upper Ohio basin, they investigate trade-offs between power generation and water quality.

1.2. Barrier mitigation planning

While there are few examples involving the use of optimization techniques for locating new hydropower dams (Chang et al., 1992), optimization has been applied frequently in the context of cost-effectively removing dams and other river infrastructure to improve river connectivity. Some examples include: Paulsen and Wernstedt (1995), O'Hanley and Tomberlin (2005), O'Hanley (2011), O'Hanley, Wright, Diebel, Fedora, and Soucy (2013), and Neeson et al. (2015). A key feature of these studies and other similar optimization based approaches is the explicit consideration of the spatial structure of barrier networks and the interactive effects that barrier removal decisions have on longitudinal connectivity.

One study dealing specifically with hydropower is Kuby, Fagan, ReVelle, and Graf (2005), who propose the use of a multi-objective optimization model for prioritizing the removal of large hydropower dams. Their model quantifies trade-offs between ecological gains for migratory fish, economic losses from reduced hydropower generation, and water storage capacity. The use of a multi-objective framework is noteworthy in that it offers decision makers a means of identifying alternative portfolios of dam removal that vary in terms of their ecological and socioeconomic benefits. This, in turn, can help to inform negotiations among managers and different stakeholders.

Zheng, Hobbs, and Koonce (2009) propose a mixed integer linear programing model for optimizing the net benefits of removing multiple dams in the Lake Erie basin. The model is multi-objective and aims to maximize a combination of ecological (e.g., native species biomass) and socio-economic (e.g., recreational and commercial harvesting) goals subject to a budget constraint. Zheng and Hobbs (2012) extend the model proposed by Zheng et al. (2009) by adding the additional goal of reducing the risk of dam failure.

A detailed review of procedures and techniques related to evaluating and prioritizing the mitigation of fish passage barriers can be found in Kemp and O'Hanley (2010). Given multiple and often conflicting environmental and economic goals, they recommend the use of optimization models and multi-criteria decision making techniques as an objective and efficient means for prioritizing barrier repair and removal decisions.

The remainder of the paper is organized as follows. In Section 2, we present the hydropower plant location problem. Specifically, in Section 2.1, we present a basic nonlinear model and in Section 2.2 a linear reformulation. In Section 2.3, we talk briefly about the backwater effect caused by siting a dam. This is followed in Section 2.4 by the development of an extended version of the hydropower plant location problem, where backwater effects are considered. In Section 3, we apply our methodology to a case study of England and Wales and discuss key findings. Finally, in Section 4, we give some concluding remarks.

2. Hydropower plant location problem

The aim of the hydropower plant location problem (HPLP) is to select sites for installing dams to maximize potential hydropower generation while keeping longitudinal river connectivity at or above some threshold. Given a range of dam sizing options for each potential dam location, the hydropower potential w_{ji} (measured in watts) at site j when fitted with a dam of size i is defined by the well-known equation:

$$w_{ji} = \eta_{ji} \rho g Q_j H_{ji} \tag{1}$$

where η_{ji} is the efficiency (in the range 0–1) of the dam's turbine, ρ is the density of water (1000 kilograms per cubic meter), g is the acceleration due to gravity (9.81 meter per second square), Q_j is the river's volumetric flow (cubic meter per second) at site j, and H_{ji} is the hydraulic head (meter) of the dam (i.e., the difference in

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