Cairo University

OPTIMAL PLANNING AND DESIGN OF RUN-OF-RIVER HYDROELECTRIC POWER PROJECTS

By

Mohamed Gomaa Abdelfattah Ibrahim

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
In
IRRIGATION AND HYDRAULICS ENGINEERING

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Title of Thesis:

Optimal Planning and Design of Run-of-river Hydroelectric Power Projects

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Hydropower; run-of-river; genetic algorithm; optimization; Guder River

Summary:
The research presents an optimal planning and preliminary-design model (OPD) that maximizes the net annual benefit of developing the hydropower potential of a given stream by identifying multiple optimal, non-overlapping RoR projects. For each project, the OPD model determines intake location; penstock diameter and length; and type, number, and discharge of turbines. The OPD model applies genetic algorithm in two stages. The first stage optimizes design of individual potentially overlapping projects densely spaced at uniform intervals along the stream and the second stage determines the set of non-overlapping projects that maximizes the net hydropower benefit. Results of the OPD model compared favorably to results of previous models for a hypothetical case study. Further application of the OPD model to idealized case studies with different stream elevation profiles and with tributary flows indicated that the model gives reliable results. The OPD model was used to identify optimal RoR projects for the Guder River, Ethiopia. The OPD model identified 22 optimal RoR projects covering ~49 km of Guder River. The total annual generated energy from the identified projects is ~ 540 GWh and the installed capacity for individual projects ranges between 1 MW and 21 MW.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Mohamed Gomaa Abdelfattah Ibrahim Date: …./…/2019

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Nomenclature

OPD, Optimal Planning and Preliminary-Design Model

RoR, Run-of-River

GERD, Grand Ethiopian Renaissance Dam

BCM, Billion Cubic Meters

GW, Giga Watts

kW, kilo Watts

kWh, kilo Watt hours

MW, Mega Watt

MWh, Mega Watt hours

HPP, Hydropower Projects

GIS, Geographical Information System

DEM, Digital Elevation Model

GA, Genetic Algorithm

ANB, Annual Net Benefit

AB, Annual Benefit

AC, Annual Cost

CRF, Capital Recovery Factor

$ATCC$, Total Capital Cost

LM, Lagrange Model

HBMO, Honey Bee Mating Optimization model

IRR, Iranian Rial

USGS, United States Geological Survey

SWAT, Soil & Water Assessment Tool

MIF, Minimum Instream Flow

KP, Kaplan Turbine

FR, Francis Turbine

Abstract

Compared to storage-based hydropower generation projects, run-of-river (RoR) projects are considered better alternatives with less severe adverse environmental impacts. RoR projects do not require storage of water but divert a fraction of the river flow through a penstock to a powerhouse for generating electricity. For maximizing the utilization of hydropower potential of a stream using run-of-river (RoR) projects, it is important to select optimal project locations and design parameters.

This research presents an optimal planning and preliminary-design model (OPD) that maximizes the net annual benefit of developing the hydropower potential of a given stream by identifying multiple optimal, non-overlapping RoR projects. For each project, the OPD model determines intake site; penstock diameter and length; and type, number, and discharge of turbines. The OPD model applies a genetic algorithm in two stages. The first stage optimizes design of individual projects densely spaced at uniform intervals along the stream and the second stage determines the set of non-overlapping projects that maximizes the net hydropower benefit extracted from the stream.

Results of the OPD model compared favorably to results of previous models for a hypothetical case study. Further application of the OPD model to idealized case studies with different stream elevation profiles and with tributary flows indicated that the model gives reliable results. The OPD model was also used to identify optimal RoR projects for the Guder River to provide alternatives to the traditional large storage hydropower projects proposed on the Blue Nile River. The OPD identified 22 optimal RoR projects covering ~ 49 km of the 127-km-long Guder River. The total annual generated energy from the identified projects is ~ 540 GWh and the installed capacity for individual projects ranges between ~1 MW and ~21 MW.

Chapter 1 :Introduction

1.1. General

Hydropower is an important renewable energy resource that is sustained by the natural hydrologic cycle. Water is lifted by evaporation, is precipitated on land at high elevations, and is then transported down gradient in streams to lower elevations. Hydroelectric power projects are developed on these streams to convert the potential energy of flow to electric energy (Wagner and Mathur, 2011). Hydroelectric power projects have the highest efficiency among all electricity generation systems (Rojanamon et al., 2009). Hydroelectric power projects also have the least adverse environmental impacts with no emission of carbon dioxide and other gases that harm the environment (Paish, 2002).

The traditional schemes for hydroelectric power generation are storage schemes where water is impounded by dams. Water is predominantly stored in reservoirs behind dams during high-flow periods and released year-round for energy production. Having water storage for electric energy generation increases system reliability and reduces the impact of natural fluctuations in stream flow caused by hydrologic variability. However, formation of reservoirs may inundate large areas of land that have high economic value, may require resettlement of population, may adversely affect flora and fauna, and may disrupt navigation (Singal et al., 2010).

A recent alternative for storage-based hydropower development is to generate electricity using the so-called Run-of-River (RoR) projects that have minimal storage. In RoR projects, a fraction of the stream flow is diverted through penstocks to a powerhouse for generating electricity and is then returned to the stream (Rojanamon et al., 2009). The main advantage of RoR projects is that large reservoirs are not required. In addition, the construction time and overall cost of RoR projects are significantly less than for projects with storage reservoirs of similar power capacity (Najmaii and Movaghar, 1992). The main disadvantage of RoR projects is that power generation fluctuates with river flow (Najmaii and Movaghar, 1992). This limitation is typically resolved by using RoR projects together with other types of power generation facilities that can easily be brought online when power from RoR projects is unavailable or taken offline when power from RoR projects becomes available (Warnick, 1984).

The main components of RoR projects are civil works and electromechanical installations. The civil works typically include an intake for diverting water from the stream, a penstock to convey water from the intake to the turbines, a powerhouse for housing the turbines, and a short tailrace for returning diverted water to the stream (Figure (1-1)). Electromechanical installations mainly include turbines and generators for converting hydraulic power to electricity (Wagner and Mathur, 2011).

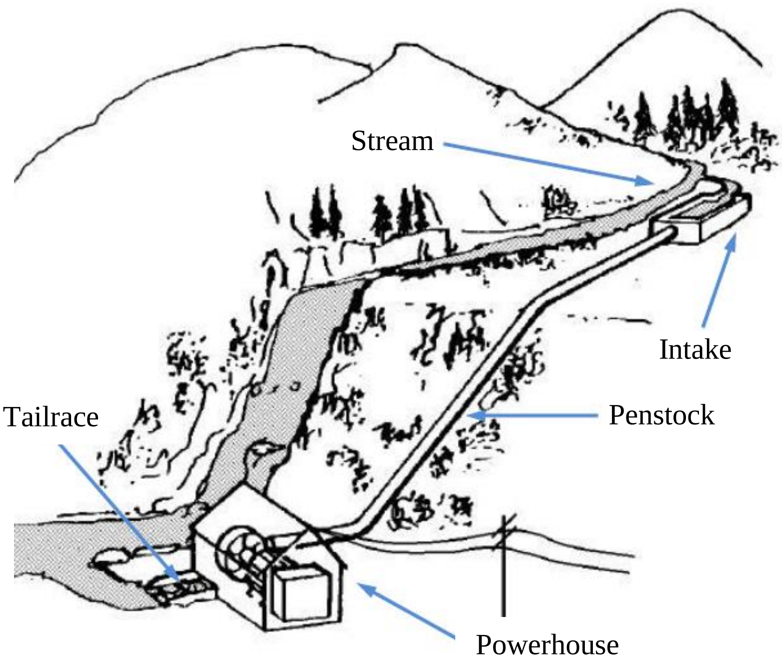

Figure (1-1): Typical layout of a RoR hydropower project (Copyright © 2018 greenbugenergy.com)

The cost of RoR project components depends mainly on power generation capacity of the powerhouse, maximum flow rate, and gross head of the power plant. Several previous studies analyzed the cost of RoR project components and gave empirical cost formulas (Aggidis et al., 2010; Gordon, 1983; Singal et al., 2010). As explained later, some of these formulas were used in this study to determine costs for optimizing planning and design of RoR projects.

1.2. Motivation

In shared river basins where rivers cross national boundaries and multiple countries share the river basin, large water storage projects in upstream countries may have significant adverse effects on downstream countries. These adverse effects are mainly due to reduction of river runoff volumes to downstream countries during initial and subsequent filling of reservoirs in upstream countries. This runoff reduction may even lead to drought in downstream countries during dry years with low precipitation in head water countries.

There are numerous examples around the world of water storage projects that adversely affect downstream countries in shared basins. An example is water storage projects in the basins of the Tigris and Euphrates Rivers which are shared between Turkey, Syria, and Iraq. Extensive water storage projects in the upstream country Turkey reduce flow to the downstream countries Iraq and Syria which depend heavily on the Tigris and Euphrates Rivers for their water supply (Haftendorn, 2000). Conflicts between Iraq and Syria also increased due to filling of Lake Assad by Syria, resulting in reduction of downstream flow in the 1970's.