Maximizing Hydropower Generation with Observations and Numerical Modeling of the Atmosphere

Yabin Miao

Graduate Student, Dept. of Civil and Environmental Engineering, Univ. of Washington, More Hall 201, Seattle, WA 98195.

Xiaodong Chen, S.M.ASCE

Graduate Student, Dept. of Civil and Environmental Engineering, Univ. of Washington, More Hall 201, Seattle, WA 98195.

Faisal Hossain

Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of Washington, More Hall 201, Seattle, WA 98195 (corresponding author).

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DOI: 10.1061/(ASCE)HE.1943-5584.0001405

Introduction

The ongoing drought in California seems to indicate that water managers are now paying greater attention to the use of numerical models of the atmosphere for short-term (7–10 day) weather forecasts. At the time of writing this article, a bill to Congress was being formulated that essentially aims to make the rule curves for large dams more adaptive through the use of numerical models for weather forecast. The use of such models is expected to reduce wastage of impounded water for dam managers and allow more flexibility in water storage and release during periods of anomalous/off-season big droughts or floods. The purpose of this opinion article is to shed light on the current state of hydropower generation in the United States and discuss how the use of such numerical models of the atmosphere can also maximize energy production while conserving water or protecting against floods.

As a clean and renewable energy source, hydropower has been extensively exploited by human beings for over 100 years. According to the *2014 Hydropower Market Report* released by the Department of Energy (DOE), there are 2,198 active hydropower plants with a total operational capacity of 79.64 gigawatts (GW) in the United States. Hydropower accounts approximately 7% of the total power generated in the United States (Uría-Martínez et al. 2015). Unfortunately, hydropower generation capacity has stagnated the last two decades since the 1990s owing to lower economic growth (Hall et al. 2003), stricter environmental regulations, a stagnant energy market, and recent breakthroughs in the shale gas and oil industries (such as fracking). Nevertheless, hydropower remains the single largest source of renewable energy because of its relatively low-cost and sustainable characteristics.

Compared to other renewable energy sources, hydropower has several unique advantages (USBR 2005). For example, a dam, which is normally considered an expensive investment to build, has a long service life spanning at least 50–100 years. Hydropower remains a more stable and durable source compared to wind or solar power, which are vulnerable to changing or unpredictable weather conditions. Hydropower production is relatively easier to ramp up or scale back depending on the transient nature of power demand. There are also no greenhouse gas emissions as byproducts during hydropower generation.

A few U.S. states that are gifted with abundant water resources and topography have already harnessed hydropower as a clean and reliable electricity generation source, such as Washington, Oregon, and California (Fig. 1). Collectively, these three states have the largest installed hydropower capacity, which is equivalent to half of the total installed capacity across the United States. Among these three states, Washington has the largest share with approximately 30.4% of total hydropower generation in the United States, which also amounts to 70% of total electricity generation in the state of Washington. Oregon and California contribute 13.5% and 6.3%, respectively to the national grid in hydropower sector. Compared to the Northwest's large amount of installed capacity, the Northeast has the most hydropower facilities, which typically are aged and small-capacity.

The states that rely more on locally available hydropower apparently have lower electricity price compared to other states that have limited access to hydropower generating resources (Uria-Martinez et al. 2015). Because building a new power plant is expensive, the low prices are usually in the states that have extensive power facilities where owners have already paid off the capital cost. The three northwestern states (Washington, Oregon, Idaho) are clear examples of cheap electricity pricing due to abundant hydropower resources.

Maximizing Hydropower Generation Using Observations and Numerical Models

Every hydropower dam usually adopts a *rule curve* as an operating policy based on the hydro-climatology of the river basin. The rule curve represents reservoir release and storage policies (or targets) as a function of season that maximizes the net benefits of the reservoir system to stakeholders. For example, a hydropower dam may also function as a flood-control dam requiring, as a rule curve policy, to keep the pool below a maximum specified level during the onset of a flood season. This way, the expected flood storage can be held inside the reservoir and gradually routed downstream for flood mitigation. Similarly, a hydropower dam serving the needs of water supply/irrigation will need to keep the pool at the highest level to maximize storage during the season of peak water demand (e.g., growing or irrigation season). Such a rule curve is shown in Fig. 2, for the Hungry Horse Dam in the United States.

Most large hydropower dams, especially if they are federally operated, are required to adhere to this rule curve by minimizing the deviations even though actual storage and release can be quite different from the targets set in the rule curve. This is where there exists, in our opinion, considerable room for maximizing hydropower generation through the use of observations and numerical

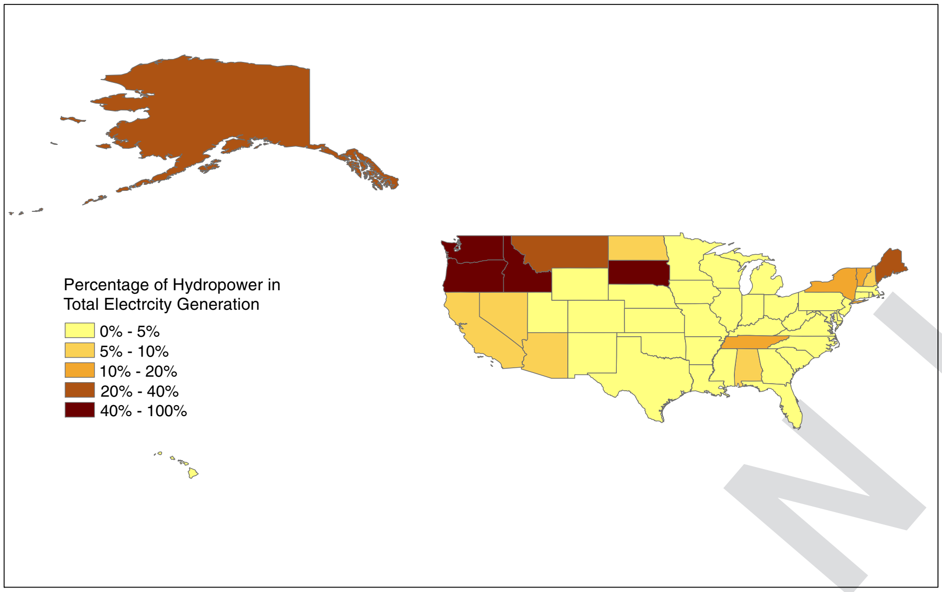

Fig. 1. Percentage contribution of hydropower to total statewide electricity production in 2014 (reproduced from the U.S. Energy Information Administration 2015)

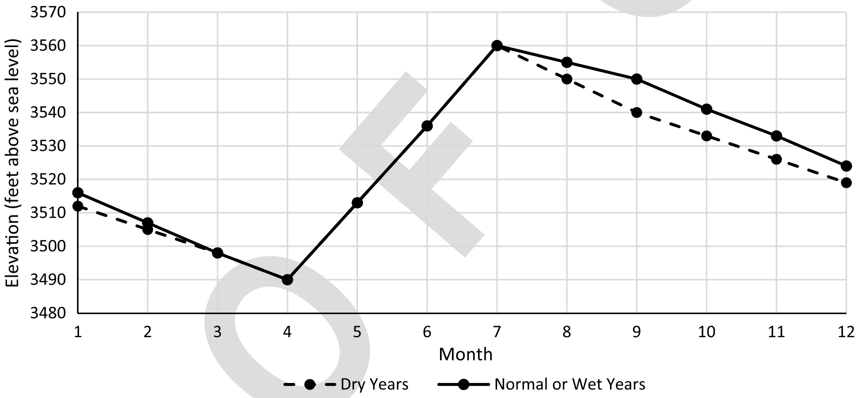

Fig. 2. Operating rule curve of Hungry Horse Dam (USA)

atmospheric model without compromising other benefits or flood risks of a multipurpose hydropower dam. For example, a particular month of a flood season may be unusually less flood-intensive than what climatology may suggest, thereby making the need to lower the pool to the rule curve-recommended levels quite redundant. Vice versa, an unusually flood intensive period of a flood season may warrant the pool to be lowered more in advance to accommodate the additional flood storage not accounted for in the rule curve storage target. Either way, the dynamics of the pertinent weather system and the season should dictate how the reservoir should be operated. Since streamflow forecast is closely related to the forecast of precipitation patterns, it therefore makes more sense to forecast the weather patterns up to 7–14 days in advance to *adjust* for a more *dynamic* rule curve or for a more transient storage/release policy based on the situation. Considerably more hydropower could be generated by keeping the pool at a slightly higher level than the rule curve policy if an intense storm is not forecast within the horizon.

Benefitting from advances in atmospheric science over the past 40 years, numerical weather prediction models are now capable of producing short-term (approximately 7–14 days) global forecasts at large scales with variable accuracy. Such forecast can be downscaled at smaller space-time scales using numerical models of the atmosphere such as weather research and forecasting (WRF). Although the accuracy of the forecast of precipitation at scales relevant for an impounded river basin may be lower, combining the forecasts with observations of snowpack and upstream surface water (from satellite observations) as well as forecasts of other meteorological variables that have higher skill (i.e., temperature and wind) can present a practicable approach for maximizing hydropower operations. Models like WRF are also able to reconstruct a number of big storms in recent history (Tan 2010). Such reconstruction of storms offers physical insights into unique mechanisms of precipitation formation that may be relevant for hydropower operations in a priori mode during extreme events that often send a flood pulse into the reservoir.

Hungry Horse Dam is a gravity dam located in Flathead County, Montana, and operated by the U.S. Bureau of Reclamation. To balance flood control and hydropower generation, a dynamic rule curve based on monthly climatology of streamflow and seasonal weather conditions (Fig. 2) is generally applied to the Hungry Horse Dam operations. Monthly water-supply forecasts indicate that inflows during the period from April 1 to August 31 are

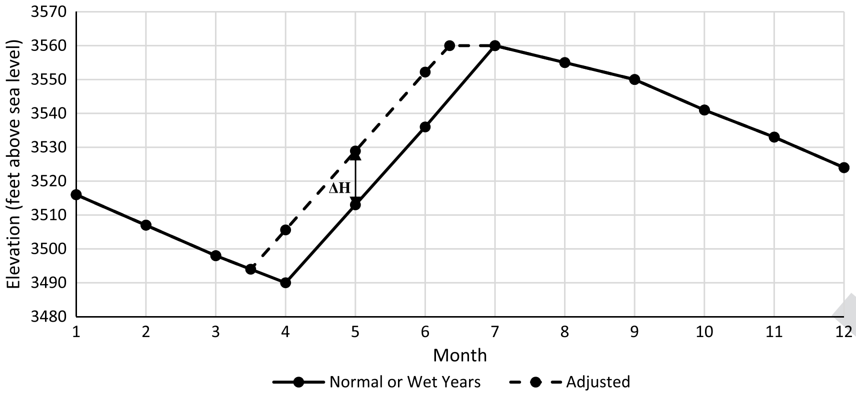

Fig. 3. Adjustment on operating rule curve of Hungry Horse Dam; the delta H is about 16 ft as the difference between model adjusted rule curve (dashed) and the static rule curve (solid)

highest. However, a more dynamic rule curve based on a combination of numerical model forecast of the atmosphere and observations of snowpack and upstream surface water has capability of providing more hydropower potential without reducing the flood risk. For example, Fig. 3 shows the wet year rule curve and adjusted rule curve for use with numerical model-based forecasting of the atmosphere. With assistance from atmospheric modeling, observations on snowpack and temperature and hydrological modeling (to model the anticipated inflow into a reservoir), it may be possible to extend the scheduled date of reaching minimum pool by 14 days. This may translate to an almost 14 more days of hydropower generation at highest potential. With a model and observational-data driven change in the rule curve, the water elevation can be potentially increased by up to 16 ft during the flood season for Hungry Horse Dam and maintained 14 more days during the flood season if no major flood inflow is expected from the model-data forecast system. The additional head afforded by a 16 ft results in an increase in theoretical hydropower by about 3.7% during the flood season for the Hungry Horse Dam. Fig. 4 provides schematic of how an atmospheric model based dynamic rule curve operation could work for a dam to maximize hydropower generation.

To compromise between flood control and hydropower generation, the traditional and static rule curve sacrifices water generation potential at the expense of a false sense of flood security during periods that are anomalously dry or free of extreme events. Based on the current rule curve, maximizing hydropower generation with numerical atmospheric model could be considered as an innovation that takes advantage of the progress made in atmospheric science. An even bolder strategy is to completely get rid of the rule curve and depend exclusively on short-term forecast (approximately 7–14 days) of precipitation and streamflow. However, such a strategy may not work for large dams that impound several years' of annual runoff and are critical to a region's water security (such as Aswan High Dam on the Nile River in Egypt).

Future of Hydropower Dams

In the last decade, there has not been construction of any large-scale (>500 MW) hydropower dam project in the United States. Insufficient consideration of ecological impact has led to an enormous threat to salmon's existence in Washington State. Many hydropower-rich states (such as Washington) now need to take action to help local tribes claim their fishing rights (Brown et al. 2013). These stricter environmental and ecological regulations and licensing procedures have resulted in a current climate where construction of new hydropower dams is unlikely in the foreseeable future. In such a situation, it makes more sense to optimize current hydropower dam performance so that power generation can be maximized through the use of numerical atmospheric models of weather forecasting.

There is an added benefit to maximizing hydropower generation in states with higher electricity pricing and limited hydropower potential. Georgia is a typical example that experiences high retail price of electricity and is heavily dependent on the fossil fuel. In 2014, 68.83% of electricity in Georgia was generated from fossil fuel thermal power plants and only 2.44% from conventional hydropower. The huge contrast in price and availability between fossil fuel and hydropower makes a good case for increasing the hydropower generation efficiency in the state of Georgia. Assuming the current hydropower share in Georgia could be augmented by 10%

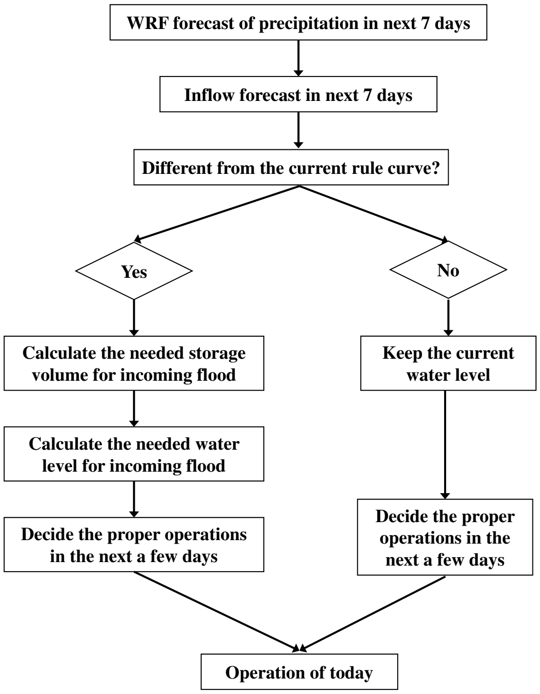

Fig. 4. Dam operation decision flowchart through numerical atmospheric model forecast; the WRF forecast refers to a combination of modeling, data, and observations of snowpack, surface water, and meteorological variables

through optimization with numerical models of the atmosphere, approximately 167,000 short tons of coal, 2,923 billion ft^3 of natural gas, and 4,700 barrels of petroleum could be reduced each year. In the meantime, 522,000 short tons of CO_2 could be eliminated each year. This assessment is based on the information available at the Energy Information Administration.

Another trend now seen is environmental low-impact and stream-reach hydropower developments (Kao et al. 2014). For all new or purposed hydropower projects in the United States, 58% of capacity (or 233 projects) are new stream-reach (non-dam) projects. These are mostly concentrated in the Northwest, especially in Alaska, accounting for 66% of total projects (Kao et al. 2014).

According to another U.S. DOE report, *New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States* (Kao et al. 2014), there are more than 50,000 nonpowered dams that are able to provide another 12 GW of hydropower capacity. Additionally, rivers and streams in United States are able to provide 85 GW of technical hydropower potential capacity. Even excluding the lands protected by federal laws, over 65 GW of potential hydropower capacity that is renewable and carbon-reducing remains untapped today.

Conclusion

The current hydropower situation continues to play an indispensable role in the whole energy generation system of the United States. Although current hydropower is in a low-growth stage and very large-scale dam projects are a thing of the past, more moderate-scale and eco-friendly dams are now being given increasing consideration. Additionally, due to advantages of pumped storage hydropower plants, electricity power companies have a preference of installing this type of power plant, which could be a trend in the future development of the hydropower industry. With such tremendous hydropower potential, both the hydropower industry and the atmospheric science/engineering community should collaborate effectively to design a sustainable blueprint for optimizing hydropower generation, using as a main tool numerical models of the atmosphere to forecast weather patterns (ASCE 2015).

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