Benefits and limits of seasonal forecasts for hydropower production: a global analysis

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Motivation

- Synoptic assessment of the value of seasonal forecasts for global hydropower production is lacking
  - Potential of seasonal forecasts only demonstrated for specific river basins
- Limited knowledge on how forecast skill and reservoir characteristics translate into forecast value
Our approach

- Global analysis on 1,593 hydropower reservoirs
  - Develop seasonal inflow forecasts for each reservoir leveraging teleconnections between large-scale climate drivers and local hydrology
  - Simulate hydropower production under 3 operating schemes (perfect forecasts, realistic forecasts, no forecast)
  - Explain how reservoir design properties and forecast skill affect value of seasonal forecasts
    - Made possible due to the wide range of climatic conditions and dam characteristics available in our database
    - Identify key geographical regions that would benefit the most from forecasts
Data

Hydropower data

- 1,593 hydropower reservoirs—about 40% of global hydropower capacity
  - General properties: location, purpose
  - Physical properties: storage, surface area, dam height
  - Hydropower properties: installed capacity, hydraulic head, maximum release through turbines
  - Compiled by Ng et al. (2017) with original data retrieved mainly from
    - Global Reservoir and Dam (GRanD) database, and
    - International Commission on Large Dams (ICOLD) database

Data

Hydro-climatological data

- 4 large-scale climate drivers
  - ENSO (El Niño Southern Oscillation)
  - PDO (Pacific Decadal Oscillation)
  - NAO (North Atlantic Oscillation)
  - AMO (Atlantic Multidecadal Oscillation)

- 2 local variables
  - Monthly soil moisture (ERA-40 reanalysis product)
  - Lagged inflow (WaterGAP model using WATCH 20th century forcing data)
### Methods

**Reservoir model**
- Storage dynamics represented by mass-balance equations
- Environmental flow requirements included

**Dam inflow prediction model**
- Monthly prediction model based on climate and local drivers
- Principal component linear regression model

**Operating schemes**
- **Benchmark: control rule**
  - Release decisions based on observed storage, season, inflow
- **Perfect forecast-informed operations**
  - Release decisions based on 3-month streamflow forecast
- **Realistic forecast-informed operations**

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Methods

Performance evaluation

Expected improvement from perfect forecast-informed operations:

\[ I_{PF} = \frac{H_{PF} - H_{ctrl}}{H_{PF}} \times 100\% \]

Expected improvement from realistic forecast-informed operations:

\[ I_{DF} = \frac{H_{DF} - H_{ctrl}}{H_{PF}} \times 100\% \]

Potential improvement between realistic and perfect forecast-informed operations:

\[ I = \frac{H_{DF} - H_{ctrl}}{H_{PF} - H_{ctrl}} = \frac{I_{DF}}{I_{PF}} \]

- Explained likelihood of attaining high \( I_{PF} \) and high \( I \) using logistics regression with forecast accuracy and reservoir characteristics as predictors
Accuracy of dam inflow prediction model
Prediction accuracy for 1-month ahead inflow

- Average weighted KGE is 0.31 for 1-month ahead predicted inflow
- Prediction accuracy decreases with lead time (0.22 and 0.17 for 2-month and 3-month ahead predicted inflow)
Performance of forecast-informed operations
Performance of perfect forecast-informed operations

- 96% of reservoirs have greater hydropower production, collectively contributing to an additional 219 TWh per year of hydroelectricity
Performance of realistic forecast-informed operations

- 51% of reservoirs have greater hydropower production, collectively contributing to an additional 69 TWh per year of hydroelectricity
Evaluation of prediction accuracy and reservoir characteristics
Explaining potential of perfect forecasts using reservoir characteristics

- Large dams are unlikely to benefit from forecasts as large storage capacity acts as a buffer against inflow uncertainty.
- Dams whose hydraulic head is highly dependent on reservoir depth are more likely to benefit from forecasts.

![Diagram](image.png)

- Ratio of maximum reservoir depth to maximum hydraulic head
- Ratio of reservoir storage capacity to the maximum turbine release rate
Explaining potential of realistic forecasts using reservoir characteristics and forecast accuracy

- Dams with high forecast accuracy are likely to benefit from realistic forecast.

- Dams with hydraulic head dependent on reservoir depth can benefit from realistic forecast only when forecast accuracy is high.

- Dams that fill quickly and have large fraction of time in which inflow exceeds the maximum turbine release are likely to benefit from realistic forecasts—even when forecasts are not very accurate.
Classification of hydropower dams
### Classification of hydropower dams

Based on potential to benefit, forecast accuracy, and design specifications

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<th>Group</th>
<th>High potential to benefit from perfect forecasts</th>
<th>High forecast accuracy</th>
<th>Design specifications complement forecast</th>
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Group AI can reap immediate benefits by switching from control rules to forecast-informed operations.

Group CI can achieve increased hydropower production if investments are made to improve forecasts.
Conclusions

- 51% of the hydropower dams evaluated worldwide may benefit from seasonal forecasts conditioned on hydroclimatic predictors

- Potential benefits are predominantly modulated by forecast skill and reservoir characteristics
  - Planned dams with appropriate characteristics (e.g. run-of-the-river hydropower dams in the Amazon and Mekong basin) should consider adopting forecast-informed operations

- Dams in North America, Southeastern South America, Europe, and East Asia can increase hydropower production if more accurate forecasts are developed
Acknowledgements

- This project is supported by Singapore’s Ministry of Education (MoE) through the Tier 2 project ‘Linking water availability to hydropower supply—an engineering systems approach’ (Award No. MOE2017-T2-1-143)
Thanks!

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Water Systems & Society Research Group
https://wss.cee.wisc.edu/
References


- Lee, D., J.Y. Ng, S. Galelli, P. Block (2020). Global Hydropower Simulation - Forecast, HydroShare, https://doi.org/10.4211/hs.2b38ecee5ba40c1a88a242e8c18fafe
Appendix
23%, 30%, 23%, and 18% of dams have inflow significantly correlated with ENSO, NAO, PDO, and AMO, respectively.

78% of dams exhibit significant 1-month lead inflow autocorrelation.
Performance of forecast-informed operations for each group