論文の内容の要旨

Thesis Summary

論文題目 (Title of Dissertation)

Optimizing cascaded hydropower dam operations in a snowfed mountainous watershed
(積雪山岳流域でのカスケード式水力発電ダムの運用最適化)

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Hydropower, despite being an old technology, is one of the most stable and reliable sources of renewable energy. It is still the primary contributor to the renewable share of the global electricity mix. Even with the increasing number of hydropower installations every year, it is important to improve the efficiency of the existing installations as well, through more efficient dam operations. Predicting river inflows received by a particular reservoir is crucial to guide dam operators in a way such that benefits from hydropower generation can be maximized in addition to other benefits such as flood control, water supply, irrigation, environmental flows etc. Hydrometeorological forecasts, derived by forcing distributed hydrological models (DHMs) with weather (meteorological) forecasts, have been used in the past to provide support to dam operators for effective real-time decision making by using optimization techniques. However, such studies are limited in snowfed mountainous watersheds where cascaded hydropower dam systems are often located to take advantage of the high head and snowmelt runoff. This is partly because reliable real-time meteorological forcings are scarce in snowfed mountainous watersheds. In addition, development of an optimization framework for cascaded hydropower dam operations integrated with DHMs is a challenge, largely due to gaps between the water resource management community and hydrological modeling community, the complexities inherent to hydropower optimization problems and the associated computational costs. Compounding these with the requirement that their solution should be applicable on a real-time basis, to be of value in practice, further adds to the challenge. Motivated by these research challenges, the aim of this study is to develop a computationally efficient model-data driven real-time optimization framework to support hydropower dam operators in snowfed mountainous watersheds.

Multi-layer distributed energy-balance based snowmelt hydrological models have been used in the past to simulate basin hydrology and have demonstrated value over lumped empirical models. From a water resources management perspective, the computational costs associated with these models further increases the computational expense of solving the already complex hydropower operation optimization problem. From a hydrological modeling perspective, the use of these data-intensive models in mountainous regions with scarce and unreliable precipitation observations, and scarce air temperature observations, can add to the uncertainty in the estimates of the hydrological model state leading further to unreliable hydrometeorological forecasts. Previous studies have made use of DHMs and short-term quantitative precipitation forecasts to generate hydrometeorological forecasts for optimizing integrated flood control dam operations, however, such studies have never before been conducted for cascaded hydropower dam operations, largely due to the complexities (large number of decision variables) and computational constraints posed by such problems, especially when considering their real-time applications. To investigate and develop solutions to these problems, the following objectives are set forth in this thesis: (1) to develop a spatially distributed parallelized multi-layer energy balance snow model and verify the model physics by application to a snowfed watershed; (2) to develop and evaluate an auto-correction scheme for a radar-gauge system in Japan at high elevations, which can provide high resolution real-time precipitation estimates; (3) to evaluate the applicability of reanalysis vertical temperature profiles (VTP) in order to extrapolate air temperature observations at high elevations for real-time hydrological modeling applications; (4) to integrate a cascaded hydropower simulation model with a DHM and optimize its operation; (5) to develop and evaluate a real-time short-range prediction

system using downscaled numerical weather forecasts and a DHM for optimizing operations of a cascaded hydropower system. This research is novel, as it the first to develop and demonstrate the application of a real-time operational optimization framework for cascaded hydropower dam operations using short-range hydrometeorological forecasts while considering the challenges associated with snowfed mountainous watersheds.

In objective 1, the concept of a new 4-Component Water and Energy Budget-based Distributed Hydrological Model with improved Snow physics (WEB-DHM-4cS) is presented. This model is a new iteration in the WEB-DHM model series and has been developed to serve three main purposes. Firstly, to allow fasters simulations to deal with the computational constraints highlighted above. Secondly, to allow for representation of complex snow process physics as in the WEB-DHM-S model iteration. Thirdly, to allow the model to update its initial state (snow and soil moisture) using real-time observations before the issuance of each new forecast. 4-Component model concept is based on the idea of separation of the four core model components in the model source code, these being (1) Land Surface Model (LSM), (2) Vertical Soil Moisture Scheme, (3) Hill Slope Runoff Processes, and (4) a River Routing Scheme. Upon these 4 core components additional modules can be added to model other processes. The model uses Simple Biosphere 2 (SiB2) to model the turbulent transfer of water, energy and CO2 fluxes. The vertical soil moisture scheme redistributes the soil moisture from SiB2 into finer soil layers. The hill slope runoff processes are based on the Geomorphology Based Hydrological Model's (GBHM) subgrid parameterization. The river routing scheme is based on Kinematic Wave Routing along a virtual river. The model further inherits state-of-the-art snow processes representation from the WEB-DHM-S model iteration by the incorporation of the three-layered snow scheme from the Simplified Simple Biosphere 3 (SSiB3) model and the prognostic albedo scheme from the Biosphere Atmosphere Transfer Scheme (BATS) as modules in the LSM component, which allows reliable simulations of snow depth, snow density, snow water equivalent (SWE), snow albedo, snow surface temperature and snowmelt runoff. The first two of the four core components are fully distributed and spatially independent and take up roughly 97% of the computation time. The other two components being pseudo distributed take up only 0.9% of the computation time. OpenMP protocol was used in this study to parallelize the first two components in space, which led to a speed up of roughly 5 times on a 10 core (20 thread) system. In addition, the snow physics of the WEB-DHM-4cS model were successfully validated for consistency by comparing against the original WEB-DHM-S model on both point and basin scale for the case of Kurobe River Basin, a snowfed watershed, in Japan. A restart feature was also added to allow the model run to be initialized from previously saved state variables. The reason for using WEB-DHM model series in this thesis is that firstly it employs state-of-the-art snow physics from WEB-DHM-S which allows applications to regions with heavy snowfall. Secondly, the subgrid hillslope parameterization and the virtual river routing schemes keep computational costs to a minimum in the two components which are difficult to parallelize. The results of this objective primarily contribute to improved computational efficiency of WEB-DHM-4cS and allows its application to real-time hydrometeorological prediction and optimization. While this contribution is largely significant to the WEB-DHM user community, this study clearly highlights the usage of parallel programming along with pseudo distributed hydrological sub-components for real-time hydrometeorological forecasting and reservoir optimization. A similar approach can also be explored for other state-of-the-art sophisticated distributed hydrological models.

In objective 2, I developed a two-parameter auto-correction scheme for snowfall precipitation estimates of Radar-AMeDAS by using WEB-DHM-4cS, satellite snow cover observations from MODerate resolution Imaging Spectroradiometer (MODIS) and an evolutionary optimization algorithm called the Shuffle Complex Evolution developed by the University of Arizona (SCE-UA). Radar based precipitation products offer the benefit of large spatial coverage, high resolution, and real-time availability. However, there are large biases in theses datasets especially when considering solid precipitation. Here, I show that instead of using a single correction parameter to linearly scale precipitation, the use of two correction parameters above and below the Constant Elevation Plan Position Indicator (CAPPI) at 2km elevation can lead to improved hydrological simulations. The notion behind this correction is that above the CAPPI, echoes from higher radar beam angles are used which can lead to erroneous precipitation estimates in mountainous regions above the CAPPI. The correction parameters were estimated for the case study of Kurobe River Basin, by minimizing both the discharge errors and snow cover errors based on WEB-DHM-4cS simulations. The results of this study clearly demonstrated that the two-parameter correction approach outperformed the single-parameter approach with a Nash-Sutcliffe model efficiency (NS) of 0.85 and PBIAS of -10.29% for a four year simulation (2011-2014). The single-parameter approach did perform better in some years in terms of discharge; however, this was at the cost of a gross over-estimation in the snow cover simulations. Using this corrected high-resolution (1km) product, a Downscaled Japanese ReAnalysis (DSJRA-55) was bias corrected for the first time to facilitate long-term hydrological simulations. These corrections lead to an increase in the NS from 0.70 to 0.75 and a reduction in the PBIAS from -10.65% to 0.9% for the 2000-2006 discharge simulations. Long-term snow depth simulations (1981-2011) also exhibited significant improvements with the PBIAS reduced from 54.19% to 27.18%. The findings of this objective contribute towards improved real-time and historical snowfall estimates, both of which are important not only for the improved hydrological modeling but also for hydrometeorological forecasting.

In objective 3, I evaluated the applicability of VTP from reanalysis for elevational correction of air temperature at locations where ground air temperature observations are not available. In contrast to traditional approaches relying on linear regression-based lapse rates, VTP can be used to extrapolate scarce ground point observations of air temperature. Through extensive experimentation employing both the two-parameter snowfall correction approach developed in objective 2 and the use of VTP, it was found in this study that use of VTP for extrapolating air temperature from only a single point observation can lead to large differences in the snowfall correction factors. Surprisingly, the use of multiple observations points did not significantly improve the discharge simulations and led to poorer snow cover area simulations. In addition, the snow depth was also underestimated in these cases due to large temperature differences at low elevations, caused by steeper lapse rates obtained by VTP as compared with traditional methods. A hybrid technique was also developed which combined linear regression-based lapse rates at elevations, where station observations are available, with VTP at higher elevations, where station observations are not available. This approach led to improved discharge simulations and snow depth simulations. Additionally, a scenario was also considered which involved only reanalysis-based datasets, which led to reasonable discharge simulations. However, snow depth was underestimated at lower elevations in these cases. The findings of this study contribute towards improved real-time snowmelt modeling in mountainous regions where air temperature observations are scarce, augmented with auto-corrected snowfall estimates. These findings are also important for obtaining reliable hydrological model states in real-time for hydrometeorological prediction.

In objective 4, I integrated a complex cascaded hydropower dam network with WEB-DHM-4cS to optimize the operation of the system using a Model Predictive Control (MPC) framework. The integrated framework was tested on the case of Kurobe River's dam cascade through idealized experiments assuming perfect forecasts. Only short-term forecasts (upto 39 hours lead) were assumed. A multi-objective function which maximized the hydropower revenue and the end water level was formulated and optimized using SCE-UA with the resampled release sequence (6 hourly) from the largest upstream dam as the decision variable vector. Application of this system to the flood events of 2011 and 2018 exhibited increases in the revenue by as much as 5.8% when compared with the current operation, while still maintaining a higher water level at the end of the forecast horizon. In both cases, spillages where significantly reduced throughout the dam network. In situations, where the water level was higher than the target water level, the optimization framework successfully lowered the water level to match the target water level, such as in the case of the 2013 flood event. This result highlights that this optimization scheme can allow higher target water levels to be set in the future during flood season, by taking advantage of pre-releases. The optimization framework was also tested in situations where the simulated water levels were very low as compared to the target water levels such as in the case of the 2019 flood event. This highlighted the importance of considering long-term value of the stored water for hydropower generation, indicating that in future research long-term optimization strategies should be coupled with the short-term optimization strategy presented in this study. Introducing artificial overestimations and underestimations by scaling precipitation forecasts by upto three times still led to increased revenues with reduced spillages, when comparing with current operations. The findings of this objective are key contributions for effective water resources management considering a cascade of hydropower dams and short-term predictions during floods. This framework also contributes as a test bed for future optimization experiments considering imperfect forecasts. Moreover, this framework is also applicable on a real-time basis in practice due to the very short computation times.

In objective 5, I further extended the framework developed in objective 4 for application using actual weather forecasts. A real-time short-range (39 hour lead) ensemble hydrometeorological prediction system was developed using downscaled Global Spectral Model (GSM) forecasts, real-time corrected Radar-AMeDAS precipitation estimates (objective 2), real-time air temperature observations extrapolated by using VTP (objective 3) and WEB-DHM-4cS (objective 1). Application to the flood event in 2019 demonstrated that the use of ensemble (32-member) mean forecast led to an increase in the hydropower revenue by about 0.89% in comparison with the current operation. As expected, this is lower than the perfect forecasts, the use of which led to 1.5% increase in the revenue. In both cases the spilled volume was reduced. The hydrometeorological predictions were further improved by merging the short-term ensemble forecasts (39 hour lead) with very short-range deterministic forecasts (6 hour lead). The basis for merging these very short-range deterministic forecasts is that these are based on the extrapolation of Radar-AMeDAS precipitation estimates and hence can provide more reliable precipitation forecasts, initialized in real-time. Use of these merged forecasts for optimizing dam operations indicated a slight increase in the hydropower revenue and lower spillages compared with the case where only GSM based forecast is used. These findings clearly contribute towards improving hydropower operation decision support in real-time for effective water resource management using only short-range forecasts.

Overall, this research realized a model-data driven real-time cascaded hydropower decision support framework using short-range hydrometeorological forecasts and successfully demonstrated its application and associated benefits for the case study of Kurobe River's cascaded hydropower system. Significant contributions were made for the WEB-DHM user and research community by improving its computational efficiency while considering applications to snowfed mountainous watersheds and furthering applications to real-time hydrometeorological predictions. New techniques were developed for radar snowfall correction and air temperature extrapolation considering data scarcity in mountain regions and real-time constraints for water resources management. These new techniques offer contributions to the hydrological science community by providing reliable estimates of snowfall and air temperature in mountainous regions, leading to improved hydrological simulations, which are necessary to enhance our understanding of the hydrological processes in these regions. These new techniques also contribute towards effective water resource management, by offering reliable hydrological state estimates for hydrometeorological predictions. Moreover, these techniques can also be used with other state-of-the-art distributed snowmelt models as well. Finally, a new optimization framework has been developed which makes use of short-range ensemble weather forecasts for optimizing cascaded hydropower dam operations during flood season by maximizing hydropower revenue and water conservation, while minimizing spillages. This new framework furthers the state-of-the-art in water resource management as the first which enables provision of short-term decision support to hydropower dam operations in mountainous snowfed watersheds. The new framework also holds value for current practice, as demonstrated through application to an actual case study while considering real-time constraints and can be used to provide timely and effective decision support to hydropower dam operators.