博士論文(要約)

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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”This thesis is dedicated to my parents, who were always a source of inspiration and endless support during this journey”

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Abstract

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 were 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.

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Chapter 1

Introduction

Parts of this section will be included in a publication for submission to the Journal of Water Resources Planning and Management, Journal of Geophysical Research: Atmospheres, Geoscientific Model Development and Water Resources Research.

1.1 Motivation

Hydropower is one of the oldest and most stable sources of renewable energy. According to REN21 (2019), at the end of 2018, hydropower was still the primary contributor (15.8%) to the global renewable energy share (26.2%), followed by wind, solar, bio-power and others. In the year 2018 alone, 21.8 GW of capacity was added to the global hydropower capacity, increasing it to 1292 GW (IHA, 2019). This motivated a number of studies to identify and estimate additional potential of hydropower developments both at regional and global scales, with the most recent global scale estimates amounting to 9.49 PWh yr^{-1} (Gernaat et al., 2017; Hunt et al., 2020; Larentis et al., 2010; Moiz et al., 2018; Yi et al., 2010; Zhou et al., 2015). Many of these potential sites are located in mountainous regions where they can take benefit of the topography to achieve higher heads for hydropower generation (Gernaat et al., 2017; Hunt et al., 2020).

Despite the fact that the development of large dams can have significant socio-economic benefits in developing and in least-developed countries (Chen et al., 2016; Tortajada, 2015), in the case of developed countries like Japan, dam construction has been reduced, due to the fact that most of the available hydropower potential has already been developed (World Commission on Dams, 2000). In such cases, the effectiveness of the operation of existing hydropower dams systems is a crucial concern for hydropower dam operators in order to maximize the benefits (Labadie, 2004). This kind of the problem is not only limited to hydropower dams, but also dams built and operated for other purposes such as flood control, water supply, irrigation etc. In order to effectively operate these dams for maximizing their benefits, forecasts of the future river inflows are needed. However, this is quite challenging since many of the hydropower dams are often located in snowfed mountainous watersheds, where meteorological observations are scare and uncertain, which makes hydro-meterological prediction a difficult task. At the same time, the increasing complexity of the dam operation and optimization algorithms makes it very difficult for the dam operators to adopt them, especially in the case of large-scale hydropower systems. Moreover, the increasing complexity of the hydrological models on which the hydro-meteorological systems are based, coupled with complex large-scale multi-dam operation optimization algorithms leads to significant increases in the computation costs which limits their applications in a real-time operational perspective (Clark et al., 2017; Labadie, 2004).

Due to these challenges researchers need to develop methods to deal with the scarcity of meterological observations in mountainous snowfed watersheds, as well as hydrological models which can operate on a real-time basis in such environments. At the same time, efficient and effective dam operation optimization strategies which are capable of being fully integrated with such hydrological models also need to be advanced so as to realize a real-time hydropower decision support system.

1.2 Real-time hydropower decision support system: Concept and issues towards its realization

Figure 1.1 shows the concept of a real-time hydropower decision support system. Real-time meteorological observations are need to drive a hydrological model in real-time in order to update its states, especially the snow and soil states as they contribute to the skill of the hydro-meteorological forecast (Koster et al., 2010; Wood and Lettenmaier, 2008). Ensemble meterological forecasts can then be used ot drive the hydrological model with updated states to generate hydro-meterological streamflow prediction. These predictions can be used to optimize a hydropower-hydrology simulation model which can provide decision support to the decision maker in terms of real-time release sequences. Depending upon the sequences adopted, states of the dams can be updated and then the whole processes repeats itself for the next forecast.

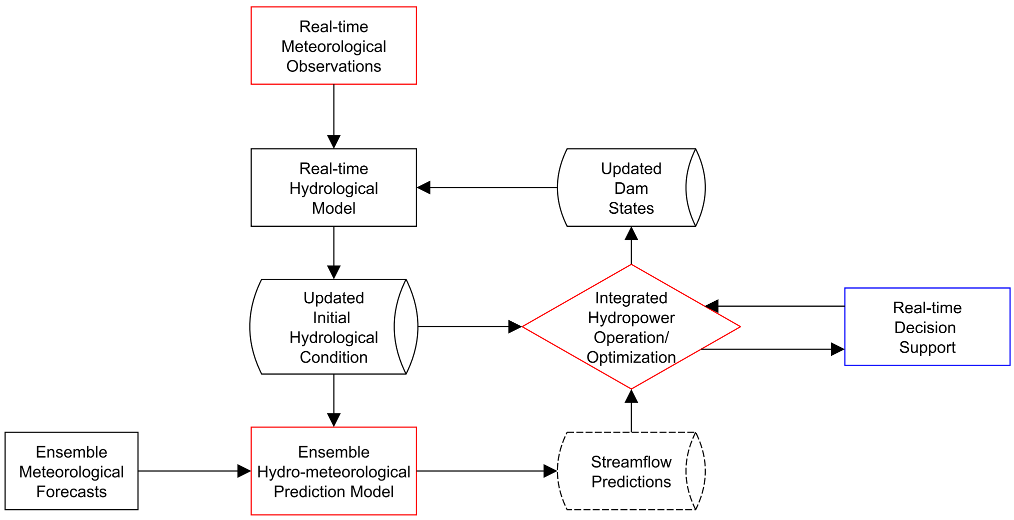

Figure 1.1: Concept of a real-time hydropower dam operation decision-support system

There are however several issues towards the realization of this real-time system. Firstly snowfall observations in mountainous regions are generally scarce and uncertain and as such need to be corrected. Secondly, the air temperature observations are also scarce at high altitudes and also need to be extrapolated. Both these two forcings must be available in real-time so that the state of the hydrological model can be updated in real-time. Moreover, a computationally efficient hydrological model with advanced snow physics is needed that can be driven by ensemble meteorological forecasts relatively quickly so that timely ensemble hydro-meteorological forecasts are available for hydropower dam operation optimization. Moreover, the hydropower dam system needs to be completely integrated with this efficient distributed hydrological model so that the decision variables of the optimization problem can be solved for fairly quickly for effective decision-support. Previous efforts to deal with these challenges are reviewed in the following sections.

1.3 Previous Contributions

1.3.1 Snowmelt modeling and the associated computational performance

This section will be included in a publication for submission to Geoscientific Model Development.

1.3.2 Snowfall estimation/correction in mountainous regions

This section will be included in a publication for submission to Journal of Geophysical Research: Atmospheres.

1.3.3 Air temperature lapse rate estimation and air temperature correction in mountainous regions

This section will be included in a publication for submission to Journal of Geophysical Research: Atmospheres.

1.3.4 Dam operation simulation/optimization and their integration with hydrological models

This section will be included in a publication for submission to Journal of Water Resources Planning and Management and Water Resources Research.

1.4 Research Objectives

Keeping in view the research gaps highlighted in the previous sections the main goal set forth in this study is the development of a computationally efficient model-data driven real-time optimization framework to support hydropower dam operators in snowfed mountainous watersheds. To achieve this goal the following specific objectives are defined:

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. Evaluate applicability of reanalysis vertical temperature profiles in order to extrapolate air temperature observations at high elevations for real-time hydrological modeling applications
4. To integrate a multi-dam hydropower simulation model with a distributed hydrological model and optimize its hydropower generation

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

1.5 Novelty of this research

This section will be included in a publication for submission to Journal of Water Resources Planning and Management and Water Resources Research.

1.6 Dissertation Outline

Chapter 2 reviews the physics of the original WEB-DHM-S model followed by the development of WEB-DHM-4cS and a discussion of improvements in computational performance along with model physics verification.

Chapter 3 takes advantage of the computational improvements in WEB-DHM-4cS and explains the development of an auto-correction scheme for Radar-AMeDAS snowfall by optimization of two snow correction factors. Followed by the use of corrected Radar-AMeDAS snowfall for bias correction of Downscaled JRA55 (DSJRA55) and its evaluation using WEB-DHM-4cS simulations for the case of Kurobe River Basin, Japan.

Chapter 4 investigates the application of reanalysis vertical temperature profiles for snowmelt modeling using WEB-DHM-4cS and the snowfall auto-correction algorithm developed in Chapter 3.

In Chapter 5 a simulation model is developed by integrating the Kurobe hydropower cascade with WEB-DHM-4cS. An optimization strategy is devised for maximizing hydropower production and end of the horizon water level assuming perfect forecasts.

In Chapter 6 a real-time hydro-meterological forecast system is developed using downscaled ensemble meterological forecasts for forcing WEB-DHM-4cS and the value of the system for optimizing hydropower dam operation is assessed.

Chapter 7 concludes this thesis, followed by limitations and recommendations for future research.

Chapter 2

Development of a 4-Component Water and Energy Budget based Distributed Hydrological Model with improved Snow physics (WEB-DHM-4cS)

This section will be included in a publication for submission to Geoscientific Model Development.

Chapter 3

Auto-correction Scheme for Correcting Radar-AMeDAS Snow Precipitation Estimates

This section will be included in a publication for submission to Journal of Geophysical Research: Atmospheres.

Chapter 4

Elevation Correction of Air Temperature using Reanalysis Vertical Temperature Profile

This section will be included in a publication for submission to Journal of Geophysical Research: Atmospheres.

Chapter 5

Hydropower Dam Operation Optimization Scheme

This section will be included in a publication for submission to Journal of Water Resources Planning and Management and Water Resources Research.

Chapter 6

A Real-time Ensemble Short-range Hydro-meteorological Prediction System

This section will be included in a publication for submission to Journal of Water Resources Planning and Management and Water Resources Research.

Chapter 7

Conclusions

7.1 Summary

Hydropower is an integral part of the global renewable energy mix. Cascaded hydropower dams are often located in snowfed mountainous watersheds to take advantage of the high heads and snowmelt runoff. These dams needs to be operated in a way so that the maximum benefit can be delivered to the society. The release for these dams is normally planned based on historical inflows so as to maximize their generation. However, in case of flood events, their operation efficiency is often compromised which can lead to increased spills and a loss of hydropower revenue. Recently, weather forecasts are increasingly being used to guide the operation of dams so as to maximize their benefits. However, these studies are limited in snowfed mountainous watersheds. This is partly due to the limited reliable real-time meteorological forcings in such watersheds. In addition to this, the complex nature of hydropower optimization problems limit their integration with state-of-the-art distributed hydrological models due to the added computational cost. This further limits the real-time application of such systems. This dissertation addresses the aforementioned issues by developing a computationally efficient model-data driven real-time optimization framework to support hydropower dam operators in snowfed mountainous watersheds. The developed framework has been applied to the case of a cascade of dams located in the Kurobe River Basin, a snowfed mountainous watershed in Japan.

In chapter 2, the benefits of advanced process based distributed multi-layer energy balance snow hydrology models are reviewed and a new model called the 4-Component Water and Energy Budget based Distributed Hydrological Model with improved Snow physics (WEB-DHM-4cS) as been developed. The model builds upon the previously developed WEB-DHM-S model and inherits its advanced snow physics. However, in the new WEB-DHM-4cS the computational efficiency of the model has been significantly improved my employing parallel programming (using OpenMP). WEB-DHM-4cS was first applied to the case of Kurobe River Basin, at both point and basin scale to validate the model physics in comparison with the original WEB-DHM-S model. It was found that WEB-DHM-4cS was able to achieve a speed-up of roughly 5-6 times as compared with WEB-DHM-S. In addition to this, a new restart feature was also added to the new WEB-DHM-4cS to enable initialization of snow and soil states for hydro-meterological forecasting applications.

In chapter 3, taking advantage of the computational benefits of WEB-DHM-4cS model developed in Chapter 2, I developed a two parameter auto-correction scheme for Radar-AMeDAS snowfall precipitation in Japan. Snow precipitation is scarce and uncertain in high elevation mountainous regions. The measurement of snow precipitation is especially poor in case of radars. Previous research has used only a single linear scaling parameter for auto-correction of Radar-AMeDAS. However, recent research has suggested that different correction factors should be used above and below the Constant Elevation Plan Position Indicator (CAPPI) of the radar. This research is the first which takes benefit of the computationally efficiency and snow process modeling capability of WEB-DHM-4cS, to consider two parameters for the two elevation bands in order correct snow precipitation estimates of Radar-AMeDAS. To achieve this I minimized the discharge errors and snow cover errors between the simulation, gauge measurements and satellite measurements respectively. I quantitatively compared this scheme with other correction schemes using only one parameter for Radar-AMeDAS correction and applying basin-wide correction to gauge precipitation estimates. This analysis was conducted for Kurobe River Basin. While the Radar-AMeDAS corrected with one parameter performed well in terms of discharge simulations (NS improved from 0.46 to 0.80), snow cover areas were grossly over estimated (OE=0.098) at low elevations. On the other hand, base-wide gauge corrected precipitation tended to reproduce the snow cover area well, but significantly underestimated the discharge (NS=0.58). The two parameter scheme for Radar-AMeDAS correction on the other hand performed well in terms of both discharge simulations (NS improved from 0.46 to 0.85) and snow cover simulations (OE=0.052). I further used these corrected estimates to bias correct long-term downscaled reanalysis based product and found that the corrected product improved both discharge and snow depth simulations. This is the first study to achieve such a correction, and can be very useful for Ensemble Streamflow Prediciton (ESP) in basins where long-term datasets are not available. Moreover, the real-time corrected radar snowfall estimates are critical for obtaining real-time estimates of hydrological states for hydrometeorological forecasting in snowfed mountainous watersheds.

Air temperature observations while more certain, are very scarce at high altitudes. Recently, several studies have used reanalysis Vertical Temperature Profiles (VTP) to estimate the air temperature at high altitudes. Previous attempts have been made to use single point air temperature observations along with VTP for extrapolation. In chapter 4, I used the framework developed in Chapter 3, to make a quantitative assessment of the use of VTP in conjunction with uncertain precipitation. This study is the first to find that the use of single ground observations with VTP can lead to differences in corrected snowfall estimates by as much as 20%. I then developed a hybrid lapse rate which combines the station based lapse rates (at low elevation) with the VTP based lapse rates (at high elevation) and checked its implications on snow process modeling. I found that in case if the stations are well representative of the basin lapse rates, then the use of VTP offers limited value. However, if the stations are sparsely located (as may be the case for real-time measurements such a AMeDAS) then these hybrid lapse rates do offer some value. Discharge NS improved from 0.83 to 0.85 and the snow depth RMSE reduced from 0.45m to 0.27m at the low elevation stations. I also considered a situation where only reanalysis is used after applying elevation correction and I found very reasonable results in case of both JRA55 and ERA5 with the exception of low elevation regions. However, JRA55 outperformed ERA5 due the steeper lapse rates associated with ERA5. Nonetheless, the framework presented in this study is unique as it analyzed the corrections in air temperature and snow precipitation simultaneously. The results of this chapter allow the development of elevation corrected real-time air temperature observations in mountainous environments which are essential to estimate real-time hydrological states for hydrometeorological forecasting.

In chapter 5, I presented the first hydropower dam operation optimization scheme which is fully integrated with a distributed hydrological model and can consider the impact of the releases of upstream dam on the downstream cascade. This was achieved by using the computationally efficient WEB-DHM-4cS model (developed in Chapter 2) along with the real-time corrected snow precipitation product (developed in Chapter 3) and the real-time elevation correction air temperature product (developed in Chapter 4). Since hydropower dam operations are represented by functions which are non-convex, non-linear, often non-differentiable and discontinuous, the optimization of hydropower dam operations poses challenges. In case of flood control, previous research has fully integrated dam operations with distributed hydrological models by assuming that the ratio of outflow to inflow is a constant for each dam. However, this assumption is not valid for hydropower dams since release from hydropower dams depends upon the storage and demand as well. This however, can make the problem too computationally costly to solve, when integrated with distributed hydrological models. However, by taking advantage of the new WEB-DHM-4cS model's computational efficiency, this target was achieved for the first time. At first I develop a simplified simulation model which only requires the release sequence for the upstream dam and validated it. Then I setup an optimization objective which maximizes the hydropower revenue of the whole cascade and minimizes the difference between the end water level and a target water level to promote water conservation. I then successfully tested this optimization scheme assuming short-term (39 hours) perfect forecasts for the flood events of 2011 and 2018 which resulted in an increase in the hydropower revenue by upto 5.8% and 1.26% respectively. The end water level increased by 0.29 m and 0.92 m respectively. The application of the optimization scheme for the two other cases of flood events in 2013 and 2019 was also considered and the discrepancies were discussed. The new optimization scheme presented in this study is key for hydropower decision support in snowfed mountainous watersheds as it can use short-range hydro-meterological forecasts for hydropower optimization and takes only 10-15 minutes for execution as each new forecast issued. This also showed that parallelization of the LSM component in WEB-DHM-4cS along with the subgrid hillslope parameterization and virtual river routing scheme do play a crucial part for dispensing timely release sequences for real-time cascaded dam operations.

In chapter 6, the optimization scheme developed in chapter 5 is tested by using actual hydrometeorological forecasts. A new short-range ensemble hydrometeorological forecasting system was developed for this purpose. The value of the short-range hydro-meterological forecasts was determined in comparison with perfect forecast. As expected, the perfect forecasts did outperform actual forecasts, however the ensemble mean of the hydrometeorological forecast was still valuable as it increase the resulting hydropower revenue by as much as +1.01% in case of the 2019 flood event, compared to the case when no forecasts are used. In addition to this the spilled volume was also reduced. Moreover, when considering the entire ensemble for optimization, it was found that not all ensemble members are valuable for optimization, which shows why the use of ensemble forecasts is more beneficial as compared with deterministic forecasts.

7.2 Key Contributions

7.2.1 WEB-DHM User and Research Community

- A new hydrological model called WEB-DHM-4cS has been developed which combines the advanced snow process modeling capabilities of WEB-DHM-S with improved computational efficiency achieved thourgh parallel programming of its sub-components. The new model contributes significantly to the WEB-DHM user and research community by enabling faster simulations in snowfed watersheds, allowing computationally intenstive experiments to be conducted.

7.2.2 Hydrological Science Community

- A new method for correcting real-time radar snowfall precipitation estimates for mountainous regions has been developed and was found to lead to improved discharge and snowcover simulations. While the technique was tested using the WEB-DHM-4cS model simulations, it can be used with other state-of-the-art distributed snowmelt models.

- A method for extrapolating air temperature from a sparse network of real-time ground observations and reanalysis based vertical temperature profile has been developed for the first time. This method exhibited improved hydrological simulations using WEB-DHM-4cS in snowfed mountainous environment and can be used with other distributed hydrological models as well in basins where data-scarcity is an issue.

- A scheme which is capable of optimizing cascaded hydropower dam operations in snowfed mountainous watersheds using real-time short-range weather forecasts has been developed for the first time. This scheme enabled the operation of cascaded hydropower dams with increased hydropower revenues and reduced spillages. It was also demonstrated that the improved computational efficiency of WEB-DHM-4cS achieved through parallel programming and its inherent pseudo distributed sub-components enabled the application of this scheme under real-time constraints. The application of these key characteristics can also be explored for other hydrological models for real-time dam operation optimization.

- This is the first time that short-range weather forecasts are evaluated for their value in terms of hydropower operation. It was found that actual ensemble short-range weather forecasts are valuable for hydropower operations in mountains snowfed watersheds, and their benefit over deterministic forecasts were discussed.

7.2.3 Water Resource Management Practice

- A real-time operational protype to support real-life hydropower dam operation of Kurobe River cascade has been developed. The same framework can be readily applied to other river basins across Japan, since all the regional datasets used are available across Japan. Theoretically, the framework can also be applied to other basins across the globe, subject to the availability and accuracy of the input datasets.

7.3 Limitations and Recommendations

In this study, all applications have only been tested for the case of Kurobe River basin and its cascaded dam system. In order to enhance and generalize the applicability of the real-time hydrometeorological forecasting system and the cascaded hydropower dam operation optimization scheme, it should also be applied to other river basins and other cascaded hydropower systems with different configurations. This will also help highlight any limitations of the methods developed in this study. In addition to this, there are several limitation which also need to be addressed.

At this moment only OpenMP has been implemented in WEB-DHM-4cS. In order to take advantage of the developing computational technology, it may be worth extending the parallelization to multi-node large scale systems by employing MPI along with a distributed IO. In addition, WEB-DHM-4cS does not consider the affect of blowing snow or fall of snow from the canopy which should be addressed in the future as well.

In case of the snowfall correction for the two elevation bands of Radar-AMeDAS, linear scaling factors are used. However, it is possible that in the elevation band above CAPPI, a high beam angle may be used. In this case, it is worth looking into other correction factors which may be functions of the distance from the radar or the elevation. Discrepancies were observed when comparing the WEB-DHM-4cS simulated snow cover and MODIS snow cover using the corrected Radar-AMeDAS. These should be further investigated in the future across different locations. For the correction of long-term downscaled reanalysis precipitation only empirical quantile mapping based on a sample of 5-years was used. In future if such a reanalysis (DSJRA55) is made available after 2012 then a large sample should be used to generate quantile-to-quantile mappings to see if that further reduces the positive bias in the long-term snow depth simulations. Correction of real-time satellite products (such as GSMaP) for snow precipitation should also be explored using a similar framework to enhance applications in data-scare regions.

The use of VTP needs to be examined across basins located in different climate regimes to further validate its value. Another way of validating it would be to use MODIS LSTs to further evaluate the simulated surface temperature using this VTP dataset. The steeper VTP of ERA5 despite its higher space-time resolution needs to be further investigated.

The application of the dam optimization scheme should be compared with the actual case in real-time. In addition, the results for the flood event in 2013 also highlighted some key limitations. Whether if there is a need to consider a buffer below the normal water level should be further tested, when using the optimization scheme presented in this study. Another limitation was also observed when the optimization scheme was applied to the case of flood event in 2019, in which year the winter precipitation was usually low. This leads to very low water levels in the reservoir causing the optimization scheme to conserve more water rather than produce hydropower. To deal with this, long-term optimization should be coupled with short-term optimization in order to guide the end water level while considering the long-term hydropower revenues. In addition, the predictive capabilities of WEB-DHM-4cS should also be utilized fo long-term hydrometeorological forecasting during the snowmelt season to decide the time for refilling the reservoir in a way so that the maximum amount of water can be utilized and water levels can be kept sufficiently lower to avoid spills during the flood season. Moreover, since WEB-DHM-S does not require snow cover maps as inputs for hydrological simulations, it can be used with climate change projections as inputs in order to simulate how the climate change in the future might affect the dam operations. This can help in designing dam operations strategies which are more robust considering future climate change. Optimization methods from other areas such as supply-chain management or areas focusing on financial revenues gained by considering the fluctuations in stock markets can also be explored in the future. Moreover, in this research hydropower maintenance requirements of dams, sediment flushing requirements and the constraints affecting the downstream safety have not been considered. These requirements can considerably affect the release from the dam and need to be considered in future research. Another assumption made in this research is that spot market prices are used as a proxy for energy demand and it is assumed that they are perfectly forecasted. In reality the fluctuations in the actual market price forecasts can affect the results. Related to this, in this research it is assumed that hydropower does not compete with other sources of electricity. But in reality, many electric power companies rely on multiple source of electricity such as solar, wind and fossil fuels. A market which balances these different sources with hydropower also needs to be considered in future research. Moreover, in this study, while ensemble based optimization results are discussed from an optimization perspective, it is also important develop guidelines on how to interpret such information in the future. An additional future research could also be to develop simpler parametric rules based on the optimization results presented in this study, so as to enable faster computations and easier application by the general user. The use of machine learning could also be explored to develop faster simulation models based on these optimized results.

Appendix A

Rain/Snow Air Temperature Threshold

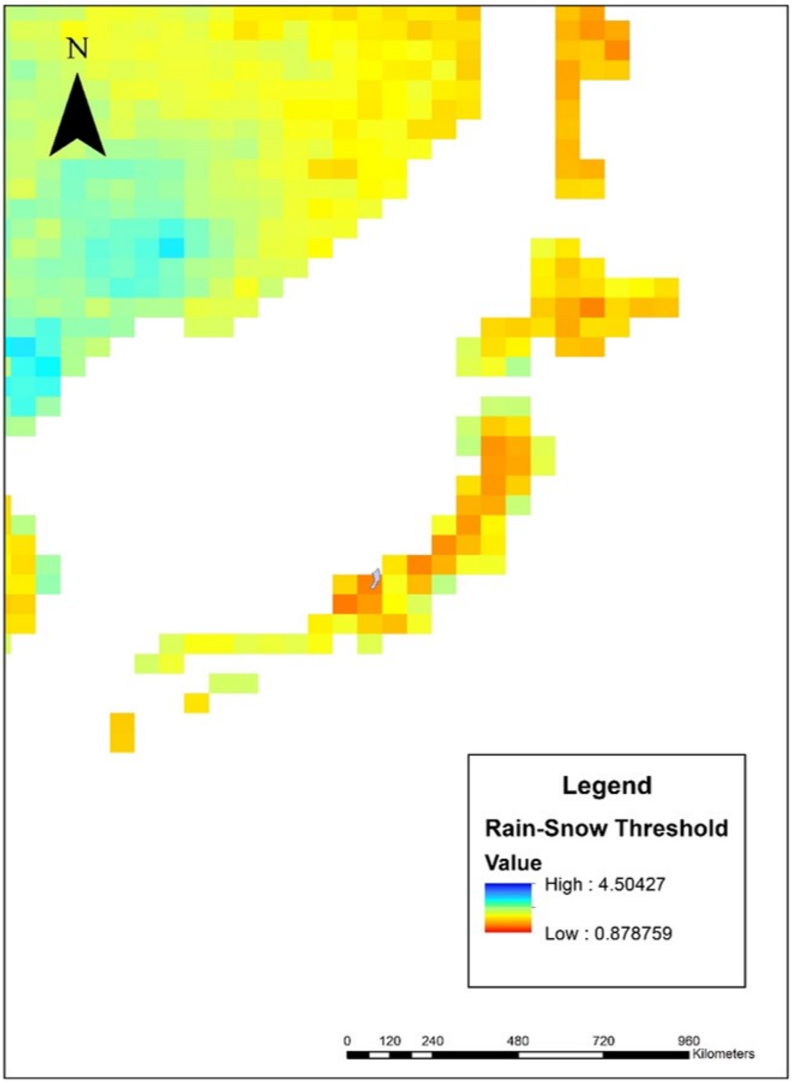

Figure A.1: Rain/Snow Air Temperature Threshold Map of Japan extracted from (Jennings et al., 2018)

Appendix B

Detailed results of precipitation correction experiment series

This section will be included in a publication for submission to Journal of Geophysical Research: Atmospheres.

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