1. Motivation

Renewable Energy Sources (RES) are playing an increasing role in global energy consumption. Governments are introducing policies to bolster RES as the human civilization is looking for an effective solution to climate change (The World Bank, n.d.). Traditional fossil-fuel based energy systems have centralized generation. The fuel supply, hence, the generation can be controlled until the resource is exhausted. In contrast, RES rely on perpetual resources of water, solar radiation, and wind. However, the intermittent nature of these resources pose additional challenge as electricity supply must meet demand at any instant.

Among the RES, hydropower accounts for a bulk of electricity production (60 % in 2018 (REN 21, 2019). Hydropower systems can be broadly divided into reservoir-based (storage) or run-of-river. Both forms of hydropower rely on precipitation in the catchment area of the reservoir/weir for their operation. Ideally, a reservoir-based hydropower operator desires to have high water levels to maximize power generation, but it needs to be prepared for an increase in water level due to future precipitation event. Hence, information in future rainfall, hence information on future reservoir inflow is essential for efficient reservoir operation (Doug McCollor & Stull, 2008a). Since traditional run-of-river projects do not have additional flow control capabilities other than the weir, future inflow information seems redundant. However, short range (1-2 days) information on power generation helps the utility plan its resources to match demand and supply. Furthermore, the generators could use this information to make profitable bids in a competitive electricity market.

Weather forecasts using Numerical Weather Prediction (NWP) can be used to obtain future inflow information. NWP models can forecast precipitation over a watershed. The forecasted precipitation is used as one of the inputs for hydrologic model, which provides inflow information for the hydropower system. Province of British Columbia (BC) and Nepal both rely heavily on hydroelectricity. Nepal generates 94% of its energy from hydropower[1], predominantly through run-of-river projects). The figure is 91% for British Columbia, mainly through storage-based systems[2](Canada Energy Regulator, 2020). Hence, numerical precipitation forecasts can benefit both the regions. NWP forecasts have been actively used by BC Hydro for of NWP has been actively used by BC Hydro for operational decision making (D. McCollor, 2004). However, its applications have been limited to storage-based systems only. On the other hand, NWP has not been implemented for applications in the energy sector in Nepal.

[1] Asian Development Bank, 2017
[2] Canada Energy Regulator, 2020

2. Research Question

The adoption of NWP for run-of-river in both regions will depend on the accuracy of the forecasts and the associated economic aspects. The purpose of the thesis is to answer questions in these two thematic areas:

1) How reliable are the NWP forecasts for Nepal and BC?
2) What is the economic value of the forecasts for a decision maker?

3. Literature Review

Numerical Weather Prediction - Introduction

Numerical weather prediction involves solving the equations of motion of an air parcel. The equations of motion are based on the fundamental laws concerning momentum conservation (Newton's 2nd law), energy conservation (1st law of thermodynamics), mass conservation (continuity equation), moisture conservation and the ideal gas law (Warner, 2010). These equations form a system of non-linear coupled partial differential equations, which do not have an analytic solution, except for the most simplified cases (Stull, 2017). These equations can be solved using different *numerical methods*[3], which has given rise to the different NWP models that are in use today.

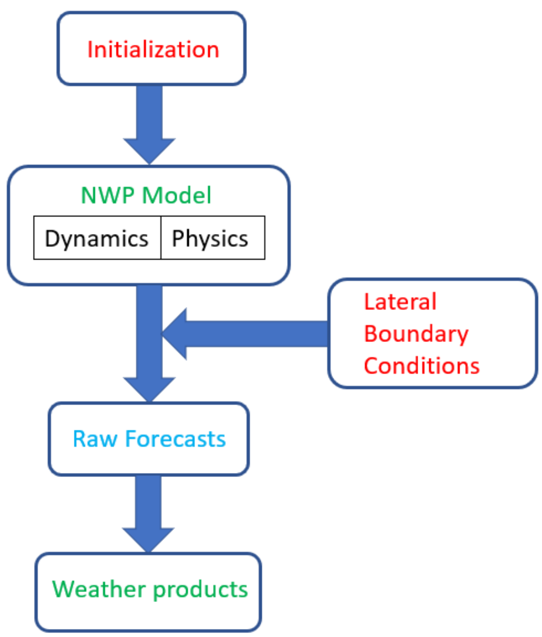

Figure 1: NWP forecast process. Final step weather products include probabilistic forecasts, weather charts or meteograms (Source: own illustration based on (Warner, 2010)

[3] Finite difference, finite volume, spectral or finite element

The equations of motion are formulated by considering atmosphere as a continuous, compressible fluid (Tribbia, 1997). The continuous field has to be *discretized* so that it can be stored in a computer's memory. Hence, a region of forecast is divided into smaller volumes called grid cells. Some of the atmospheric processes are either complicated or much smaller in scale than a grid size. These processes such as cloud formation, which is vital to forecast precipitation, are *parameterized*. The parameterized sub-grid scale processes in NWP models are also referred to as *physics*. Model *dynamics* comprise of the variables, and the associated processes that can be resolved in the grid scale (Stull, 2017). These are variables such as temperature, humidity and they are solved using the fundamental forecast equations.

Solving a system of partial differential equations require initial and boundary conditions. The initial condition is the 'present' state of the atmosphere after which we are seeking a forecast. Ideally, the initial state is captured through the weather instruments such as radars and radiosondes (for upper atmosphere measurements). However, the weather stations are not equally dispersed, and they are not in the exact locations as the simulation grid point. So, the observations are interpolated to desired locations and remaining data gaps are filled using previous forecast. This process, *analysis*, is used as initial condition in NWP models. The boundary conditions would be upper atmosphere and lower atmosphere (usually surface) for *global models*. *Limited Area Models* require lateral boundary conditions in addition to the upper and lower boundaries.

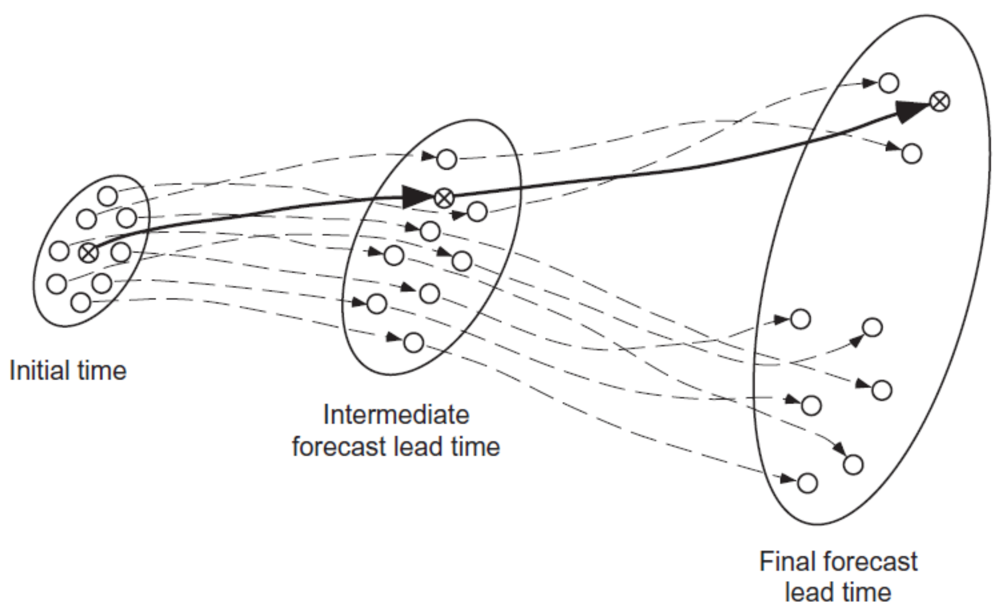

Figure 2: The concept of ensemble forecasting. The circular regions denote all the possible states of the atmosphere. Note the small circle at initial time. Even the initial state cannot be exactly determined due to measurement errors and inadequate distribution of measurement devices. A single weather model run (solid black line) would have given one possible state of the atmosphere, which could be very inaccurate. Hence, having multiple members (dotted lines), i.e., forecast combinations, allows us to capture the possible states of atmosphere more accurately. If majority of the members converge towards a particular state (region within the oval), then the forecast has higher predictability. [from (Wilks, 2020)]

Final step in an NWP model run is called *post-processing*. It involves additional processes to minimize the random and the systematic errors. The bias-corrected forecasts are then used to produce weather maps and charts. Forecasts are verified with measured observations for their quality. Statistical methods such as Kalman filter and Model Output Statistics (MOS) are used to minimize systematic errors (Warner, 2010). Random errors can be reduced by using an ensemble approach. *Ensemble forecasting* involves running NWP models for the same period, but with different conditions such as different grid resolution, initial conditions or parameterizations (see Figure 2). Ensemble forecasts are calibrated to give *probabilistic forecasts*, which allow user to make decisions under uncertainty (e.g. 10% chance that the precipitation will be below 5 mm) (Stull, 2017).

Ensemble Forecasting

An ensemble mean is on average more skilful than a single deterministic forecast (Sene, 2016). A multi-model ensemble has been known to outperform an ensemble with variations of a single model. Higher resolution models are desirable for precipitation forecasts as they can capture the surface effects due to the variation in terrain better. However, forecasts in complex terrain such as the mountains of British Columbia and Nepal benefit from addition of coarse resolution NWP models in an ensemble. (Doug McCollor & Stull, 2008a). Accordingly, different forecast centres have adopted these findings in their operational forecasting operations. The concept of ensemble forecasting has been further extended to ensemble streamflow forecasts that incorporate ensemble precipitation forecasts with hydrology models (Boucher & Ramos, 2018) (Sene, 2016) (Bourdin et. al., 2014; Bourdin & Stull, 2013).

Quality of forecasts is an important determinant of the value of forecasts, which determines the usefulness of weather forecasts (R. W. Katz & Murphy, 1997). Forecast *verification* is the process of assessing forecast quality by quantifying the relationship between forecast(s) and corresponding observation(s) using statistical approaches. (Murphy, 1997) breaks down forecast quality into ten aspects. The importance of each of these forecast quality aspects has led to the use of more than one forecast verification measures in the meteorology community. (Wilks, 2020) describes commonly used approaches for forecast verification. Most of these techniques were used to verify precipitation forecasts across different locations in British Columbia in (Doug McCollor & Stull, 2008a).

NWP in Nepal

NWP in Nepal is relatively young, with the operational forecasts having started in 2015 (Meteorological Forecasting Division, 2018). NWP research activities have been mainly based on the Weather Research and Forecasting (WRF) model. Besides precipitation, NWP research in Nepal have covered topics such as wind resource assessment (Regmi & Maharjan, 2013), aviation (Regmi, 2015) and moisture flow (Acharya et al., 2015). (Maharjan & Regmi, 2015) simulated a record high precipitation event on the foothills of the Himalayas using WRF and compared it with rain gauge measurements. (Shrestha et. al., 2017) performed WRF runs using 4 different bulk microphysics parameterization schemes, where they tried to simulate a convective storm event that occurred in 2011 at Nagarkot, a town in Nepal. While most of the works have focused on simulating a historical precipitation event across different locations in the country, none of the works have investigated the various aspects of quality of forecasts as presented by (Murphy, 1997).

Value of Weather Forecasts

The economic justification to produce weather forecasts and associated products have led to various approaches. One approach is to perform impact assessment studies of a high-impact weather event (e.g. typhoon) and evaluate the amount of losses that could be avoided if it was forecasted and essential early warning measures were implemented. Another method is to evaluate the value of the weather forecast information. (Johnson & Holt, 1997) highlight two different aspects: i) value of weather information to individual decision makers and ii) value of weather information at the market level.

For an individual decision maker such as hydropower operator or grid utility, the most common value assessment approach has been the cost-loss (C/L) scenario (Murphy, 1976). This was implemented by (Doug McCollor & Stull, 2008b) to evaluate the economic value of forecasts for hydroelectric reservoir operators. They found that different users require different precipitation forecast probabilities, which would trigger them to take protective action. The triggering precipitation probability depends on a hydro operator's C/L ratio, which in turn depends on factors such as reservoir dimensions, or presence of other reservoirs upstream/downstream. Another common approach is using Bayesian decision-analytic methods. In this method, expected outcome from possible future scenarios is represented by a utility function. A decisionmaker is assumed to always choose a decision that maximizes the utility function. (Wilks & Murphy, 1985) used this approach to evaluate the value added by NWP forecast against climatological forecasts for a haying/pasturing problem.

4. Methods

Watershed Identification

The first step in the research will be identifying a watershed of interest. Ideally, the subject watershed would have the following characteristics:

i) It houses a major run-of-river project or multiple run-of-river projects.
ii) Availability of ground-based precipitation measurement stations

For British Columbia, there is a list of IPP projects with whom BC Hydro have an Electricity Purchase Agreement (EPA) (BC Hydro, 2020). Similarly, for Nepal the Department of Electricity Development has a list of hydropower projects, which have received a generation license (Department of Electricity Development, 2020). A possible approach is to plot the run of river projects in a map and identify possible site of interest.

Weather Forecast Models

The Weather Forecast Research Team (WFRT) led by Dr. Roland Stull at the University of British Columbia runs ensemble forecasts at two initialization times 0000 UTC and 1200 UTC. The UBC ensemble consists of four models:

i) WRF Advanced Research core (WRF-ARW),
ii) WRF Nonhydrostatic Mesoscale Model (WRF-NMM),
iii) Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)
iv) Model for Prediction Across Scales (MPAS)

These models are run at nine different grid lengths ranging from 1.3 km to 108 km. Further ensemble members are created by using six initial conditions from five different weather agencies around the world. The forecast domain covers entirety of British Columbia. So, the main task for British Columbia will be to interpolate the gridded forecasts to the region where the watersheds are located.

The operational forecasts run by the Nepali meteorology department runs at grid size of 12 km and 4 km (Meteorological Forecasting Division, 2018). There are global models such as the North American Ensemble Forecast System (NAEFS), which cover Nepal as well. Furthermore, the regional model run by the Indian meteorology office also covers Nepal. However, I still need to investigate if and how I can get access to the data from the different sources. Finally, to have high resolution outputs in the ensemble, a WRF run over the basin of interest with a small grid size can be done to better simulate convective processes.

Ground based measurements

Details on surface measurement stations across Canada is available through the meteorological station catalogue (Environment and Climate Change Canada, n.d.).

Similarly, DHM – Nepal has an online database of the meteorological stations across Nepal (Department of Hydrology and Meteorology, n.d.). The next step would be to check the availability of the weather stations and recorded data in the regions of interest.

Economic value

Both Nepal and BC have vertically integrated utility. Furthermore, the electricity trade between power producers and the utility is through Feed-in tariffs (FiTs) in both regions. In this scenario, the inflow forecasts do not add value to the plant operators as flow control measures are limited. The only possible benefactor is the utility, who can use the future inflow information to better optimize the hydro facilities. An example would be to maximize use of run-of-river operations and save water in storage facilities, which can be later used to trade at higher prices or meet peak demand.

Further research can be done to evaluate the value in multiple scenarios:

1) Introduction of Peaking Run-of-River (PRoR) projects
   PRoR is a newly trending concept in Nepali energy industry. Such plants have storage capacity of a few hours. So, they can run in full capacity during the peak demand, where they get paid more as well.

2) Implementation of bidding market
   FiT is a common approach towards subsidizing renewable energy. However, there are many markets which employ day-ahead bidding. Research can be done on how the economic value of forecasts would change of both jurisdictions implemented the day-ahead bidding for energy.

The two scenarios are preliminary ideas. A good understanding of energy markets would be required for both these scenarios. I need to do further research to understand the prerequisites that would be needed to explore these scenarios.

5. Future work

For the final part of this proposal, I have prepared a list of my tasks for the summer term 2020:

Meteorology

1) Decide a watershed of interest for both regions based on the criteria mentioned in Section 4.
2) Learn how data can be accessed from the UBC ensemble
3) Learn the techniques required to interpolate forecasts to regions of interest
4) Check the availability of ground-based precipitation stations in British Columbia
5) Investigate how to gain weather stations data and NWP data from Nepal.

6) Investigate the specifications (run times, availability, grid resolution) for global/regional models that cover Nepal.
7) Explore different methods to create an ensemble forecast for the region of interest in Nepal

Economics

1) Build foundation in economics
2) Research more on the energy markets and renewable energy-meteorology nexus.
3) Read through 'Hydropower Economics' by (Førsund, 2015), recommended by Dr. Werner Antweiler.

6. Acknowledgement

This work is done as a part of the Weather Forecast and Research Team (WFRT) led by Dr. Roland Stull. The primary funding for this work has been through a MITACS funding in partnership with BC Hydro.

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