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Master's thesis

Forecasting River Discharge for Hydropower Production in Central Himalaya, Nepal

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Abstract

Write an abstract

Abstract

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Preface

Here comes your preface, including acknowledgments and thanks.

Chapter 1

Introduction

[**bhattaraiImpactCatchmentDiscretization2020**]

1.1 Motivation

The water supply from the Himalayan and Tibetan Plateau is of great importance for millions of people [4]. The water from this region provides drinking water, supports agricultural demands, is used for hydropower generation and other agro-economic activities [25]. The countries in the High Mountain Asia (HMA) region have a huge potential for developing hydropower making the shift towards a greener economy more feasible. The Bundhi-Gandaki catchment is located in the Gorkha district of Nepal. The catchment has a high mean annual precipitation of 1495 mm and a substantial spatial variation in elevation [11]. For example, the lowest point is at 479 meters above sea level (m.a.s.l.) at Arughat hydrological station and the highest at Manaslu mountain 8163 m.a.s.l. The combination of high precipitation rate and steep gradients in elevation makes the region of superior interest for hydropower. The installed capacity is 1200 megawatt (MW) with an average energy generation of 3383 gigawatt-hours (GWh). However, the hydropower potential is dependent on the climatic conditions in precipitation, evaporation, temperature and snow/ice in the catchment [13]. Climate change has serious implications fro hydropower production [10]. Changing rainfall pattern and increased temperatures will affect power generation. The retreat of glaciers, expansion of glacial lakes and changes in the seasonality and intensity of rainfall is identifies as factors that will affect the power generation in the future [10]. The region is also threatened by Glacial Lake Outburst Floods (GLOFs), that can cause devastating floods downstream [10]. In addition, the extremely heterogeneous topography of the catchment makes it challenging to get accurate measurements of meteorological variables [26]. The scarcity of data makes the discharge predictions, which lies the foundation for hydropower, prone to errors. It is impossible to make observations at all high levels, especially for snow. For this reason, satellite observations and reanalysis data sets important for decision-making processes. Furthermore, different precipitation patterns on the leeward and windward sides of the catchment needs to taken into account in simulations.

1.2 Aim and objectives

1.3 Scope

1.4 Thesis outline

Chapter 2

Background

Chapter 3

Study area

3.1 Geography

The Budhi Gandaki catchment is located in central Nepal (between 27°50' and 29°00' N latitudes, and 84°30' and 85°10' E longitudes [22]). The catchment is part of the larger Narayani River Catchment originating in Tibet to the north, and is encompassing parts of the Gorkha and Dhading districts of Nepal [11]. The Budhi Gandaki catchment is one of the main tributaries of the Trishuli River in Nepal which in turn is a major tributary to the Gandaki River that meets the Ganges in India [17]. The Budhi Gandaki catchment is about 113 km long and between 15 and 30 km wide [22]. The catchment area upstream of the gauging station at Arughat bazaar is 3871.38 km^2 [18]. About 56 % of the catchment area is in Nepal and 44 % lies in China. The catchment elevation ranges from green hills (479 m.a.s.l.) at the gauging station in the south to the snow covered Manaslu mountain peak (8029 m.a.s.l.) [17]. The catchment contains several climatic zones due to the extreme elevation changes within the catchment. The climate changes from tropical (below 1000 m.a.s.l.) to sub-tropical zone ($1000 - 2000$ m), temperate zone ($2000-3000$ m), subalpine zone ($3000-4000$ m) and alpine zone ($4000-5000$ m) [18]. The zone above 5000 m is characterized by permanent snow and no human habitation.

3.1.1 Hypsograph

3.1.2 Land use

3.2 Climate

3.2.1 Temperature

The mean temperature ranges from 6 °C during winter to 35 °C in summer measured near the Budhi Gandaki Hydropower Project proposed dam site [11].

3.2.2 Prcipitation

Long-term annual catchment precipitation (1983-2012) is 1301 mm (maximum of 278 mm in July and minimum of 11 mm in November [23]). The annual precipitation varies from greater than 2500 mm at Arughat gauging station to less than 700 mm in the Tibetan part of the catcment [21]. The hydrological regime is greatly influenced by the seasons [2]. The four seasons are defined as winter (December to February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to November) [1, 30]. The catchment receives about 80 % of the annual precipitation during the monsoon season [18]. The maximum relative humidity is also reached during the monsoon season. The rainfall decreases from west to east during this period, while the greatest rainfall intensity intensity is occurring on the south facing slopes of the mountains. The catchment is among the tributaries to the Narayani river that are monsoon fed (those in the middle and high mountain regions), in contrast to the glacier and snow melt fed (those originating in a higher Himalayan region) [2].

3.2.3 Wind

3.2.4 Relative humidity

3.2.5 Radiation

3.2.6 Snow

3.2.7 Hydrology

The observed stream flow at Arughat seem to closely follow the precipitation pattern [23]. The mean annual flow near the Budhi Gandaki Hydroelectric Project (BGHEP) dam site is estimated at 222 m/s [12].

Percentage of Seasonal PPT, show pie chart

Show annual trends

Monthly average rain days, temperature

Radiation duration

Rating curve

Maximum discharge pr month

Chapter 4

Data and methods

4.1 Meteorological forcing data

Forcing data are used to drive the hydrological model. Shyft needs precipitation, relative humidity, temperature, wind speed and incoming shortwave radiation as input data. Table 4.1 gives a summary of the forcing data used in this study.

Table 4.1: Summary of the forcing datasets

Forcing dataset	**Data period**	**Spatial resolution**	**Temporal resolution**	**n**	**Reference**
WFDE5	1990-2019	$0.5^\circ \times 0.5^\circ$	Hourly	9	[9]
ERA5 + TopoScale	1999-2015	$0.5^\circ \times 0.5^\circ$	Hourly		[15]

4.1.1 Reanalysis and regional climate data

WFDE5

The bias-adjusted ERA5 reanalysis data for impact studies (WFDE5) is generated through applying the WATCH Forcing Data methodology to surface meteorological variables from the ERA5 reanalysis [9]. Reanalysis data is a combination of model data and worldwide observations into a globally complete and consistent dataset using the laws of physics [15]. The WFDE5 dataset contains 11 variables with an hourly temporal resolution on a regular longitude-latitude 0.5 degree grid. The dataset has a global coverage, but is only defined at land and lake points. The WFDE5 dataset is spanning from January 1979 to the end of 2019, and has been adjusted using an elevation correction and monthly-scale bias based on Climatic Research Unit (CRU) data (for temperature, diurnal temperature range, cloud-cover, wet days number and precipitation fields). The datasets used for monthly bias-correction are CRU TS4.03 from CRU [14] from 1979 to 2019 for all variables, and the GPCCv2018 full data product [29] for rainfall. The dataset is distributed by the Copernicus Climate Change Service (C3S) through the Climate Data Store (CDS) as monthly netCDF files that are downloaded as zip-files or compressed tar files [6]. NetCDF files are self-describing data that are machine-independent. The netCDF format supports creation, access, and sharing of array-oriented scientific data. The data can be downloaded via the CDS API or through the C3S Climate Data Store.

Table 4.2 shows the names and units of the near-surface variables from WFDE5 used in this study.

Table 4.2: WFDE5 variables

Variable name	Description	Units	Data for monthly bias correction
Wind	10 m wind speed	m s^{-1}	Nil
Tair	2 m air temperature	K	1)
PSurf	Pressure at the surface	Pa	Nil
SWdown	Downward shortwave radiation flux	W m^{-2}	2)
Rainf	Rainfall flux	kg m^{-2} s^{-1}	3)
Snowf	Snowfall flux	kg m^{-2} s^{-1}	3)
Qair	2 m specific humidity	kg kg^{-1}	Nil

1) CRU TS4.03 temperature and diurnal temperature range

2) CRU TS4.03 cloud and effects of inter-annual changes in atmospheric loading

3) ERA5 ratio of rainfall/precipitation and snowfall gauge correction

Shyft requires the units of the forcing data to be converted into standard input units. Temperature was converted from Kelvin (K) to Celsius degrees (°C) by simply subtracting 273.15 from the absolute temperature. Similarly, the surface pressure was converted from Pa to hPa by multiplying with 0.01. Precipitation was converted to mm h^{-1} by summing the snowfall flux (kg m^{-2} s^{-1}) and the rainfall flux (g m^{-2} s^{-1}), and then multiplying the sum with 3600 (s h^{-1}).

The relative humidity was calculated using the MetPy package in Python [24]. The relative humidity function in this package calculates relative humidity from total atmospheric pressure (hPa), air temperature (°C) and specific humidity (kg kg^{-1}). The formula is based upon [31] and [27].

The units of wind (m s^{-1}) and global radiation (W m^{-2}) were not converted.

$$RH = \frac{q}{(1-q)w_s} \tag{4.1}$$

where RH is relative humidity as unitless ratio, q is the specific humidity and w_s is the saturation mixing ratio. The saturation mixing ratio is the ratio between the density of water vapor and the density of dry air [16].

ERA5

The ERA5 dataset is the fifth generation reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) [15]. The dataset provides hourly estimates for a large number of atmospheric, ocean-wave and surface quantities. The data is available from 1950 to present, and has been regridded to a regular lat-lon grid of 0.25 degrees. The dataset is updated daily, and can be downloaded in either GRIB or netCDF format from the CDS API or the C3S Climate Data Store.

4.2 Topographical Data

The SRTM 1 Arc-Second Global elevation data from the NASA's Shuttle Radar Tomography Mission (NASA-SRTM) provides a worldwide coverage of void filled data filled with a resolution of 1 arc-second ($\sim$ 30 meters) [7]. The Digital Elevation Model (DEM) data can be downloaded from the coverage map in the USGS Earth Explorer. Each GeoTIFF file covers 1 degree tiles, and is about 25 MB each.

Table 4.3 shows the DEM data that was downloaded for this study.

Table 4.3: SRTM 1 Arc-Second Global

Projection	Geographic
Horizontal datum	WGS84
Vertical Datum	EGM96 (Earth Gravitational Mode)
Vertical Units	Meters
Spatial resolution	1 Arc-second ($\sim$ 30 m)
Raster size	1 degree tiles
Tiles	N25-31 E82-88
C-band wavelength	5.6 cm

The DEM files were merged into one DEM file in QGIS. This DEM file was then opened in Python using the Rasterio package which reads and writes GeoTIFF files, and provides a Python API based upon Numpy N-dimensional arrays and GeoJSON. The coordinate points from the forcing data were then sampled in the DEM file to get the elevations needed for the Shyft input data.

4.3 Land Cover Data Sets

The Land Cover Classification System (LCCS) Land Cover Map Fine Resolution V2.3 Global dataset from the GlobCover Portal provides global composites and land cover maps [3]. The GlobCover products have been processed by ESA and by the Université Catholique de Louvain using input observations from the 300 m MERIS sensor on board on the ENVISAT satellite mission. The land cover maps covers December 2004 - June 2006 and January - December 2009. The surface reflectance mosaic products are projected in a Platé-Carré projection (WGS84 ellipsoid) with a 1/360° pixel resolution. The land cover classes as defined by a set of classifiers.

4.4 Validation datasets

4.4.1 Observed river discharge

Daily stream flow data from the period 2000-2015 is obtained from The Department of Hydrology and Meteorology, DHM. The flow gauging station is located at Arguhat bazaar (485 m.a.s.l) at 28.043611° N and 84.816389° E. The station has been operating since 28 November 1963.

4.4.2 Snow Products

The High Mountain Asia (HMA) snow reanalysis data set from the NASA Snow and Ice Data Center (NSIDC) covers the period 1 October 1999 to 30 September 2017 with a daily temporal resolution and 16 arc-seconds x 16 arc-seconds spatial resolution [19].

4.5 Pre-processing of data

4.5.1 TopoScale

4.5.2 Catchment Discretization Technique

4.6 Hydrological Modeling Framework

Shyft is an open-source cross-platform hydrological toolbox built to provide a computation framework for spatially distributed hydrologic models [5]. Shyft is developed for operational, regional-scale hydropower inflow forecasting. The platform is developed by Statkraft AS, the largest generator of renewable energy in Europe, in cooperation with the research community at the University of Oslo. The objectives of Shyft are to i) provide a flexible forecasting toolbox for operational environments, ii) facilitate computationally efficient calculations of hydrologic response at the regional scale, iii) enable the use of multiple hypothesis to quantify forecast uncertainties, iv) allow for multiple model forcing configurations, and v) promote expeditious implementations of the findings from research into operational modeling.

One of the strengths of Shyft is that multiple models may be built through the creation of hydrologic algorithms from a library of well known routines or by the construction of new routines [5]. The user of Shyft can get access to all of the components of the framework via Python through an application programming interface (API), while still having high computational performance as the algorithms are implemented in modern C++. This API set-up enables rapid use of different model configurations and selection of an optimal forecast model.

The primary model forcing variables in Shyft are precipitation, atmospheric temperature, wind speed, shortwave radiation and relative humidity.

Table 4.4: Forcing data and validation data

Input	**Units**	**Source**	**Temporal resolution**
Input for model simulations in Shyft			
Precipitation	mm h^{-1}	WFDE5	Hourly
Temperature	°C	WFDE5	Hourly
Wind speed	m s^{-1}	WFDE5	Hourly
Relative humidity	-	WFDE5	Hourly
Global radiation	W m^{-2}	WFDE5	Hourly
Data used for validation			
Discharge	m^3 s^{-1}	DHM	Hourly
Snow cover	per pixel	MODIS	8-day

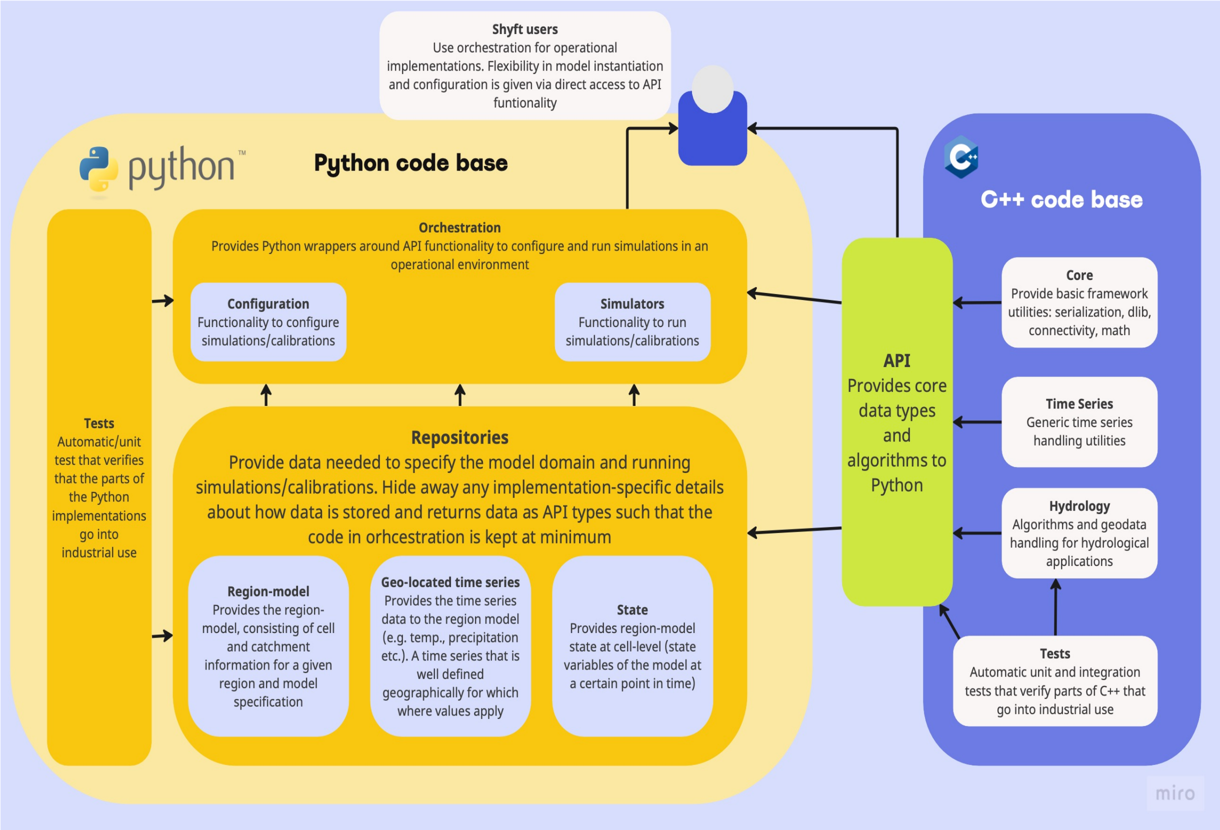

Figure 4.1: Shyft arcitechture. The figure is made using Miro, and it is an adaptation of the figure in [5]

4.6.1 Spatial interpolation

4.6.2 Hydrological model

4.6.3 Model simulation

4.6.4 Model calibration

4.6.5 Water balance estimation

4.6.6 Model validation

4.6.7 Model performance evaluation

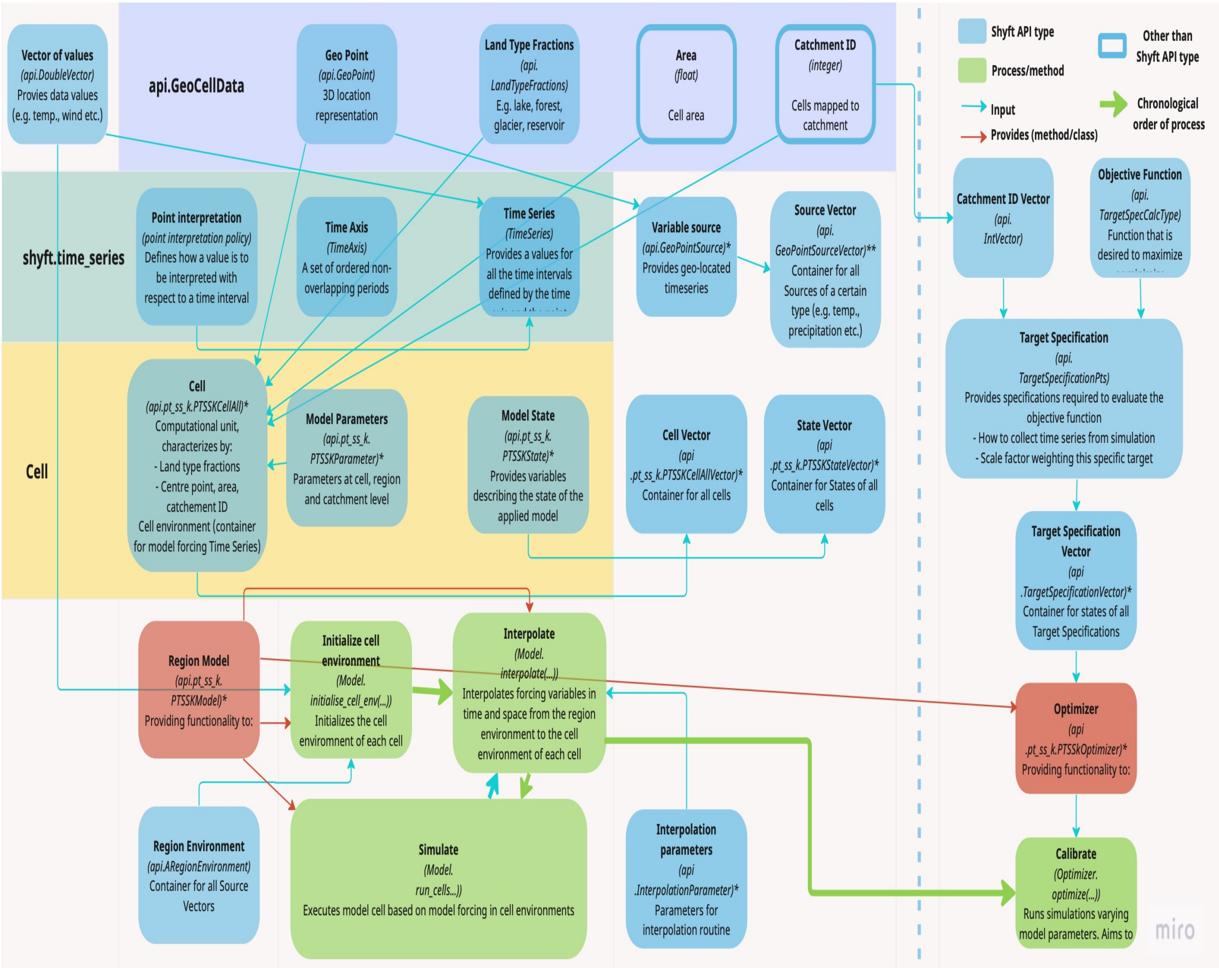

Figure 4.2: Overview of the main Shyft API types. The figure is made using Miro, and it is an adaptation of the figure in [5]

Table 4.5: Model calibration parameters

Parameter	Description and unit	Parameter used in the submodel	Lower limit	Upper limit	Sources
c_1	Outlet empirical coeff. 1 (–)	K	-8.0	0.0	[20, 28]
c_2	Outlet empirical coeff. 2 (–)	K	-1.0	1.2	[20, 28]
c_3	Outlet empirical coeff. 3 (–)	K	-0.15	-0.05	[20, 28]
Prescribed parameters					
ae scale factor	Scaling factor for AE (–)	AE	1.0	1.0	[20, 28]

'K' is the catchment response function and 'AE' is actual evapotranspiration.

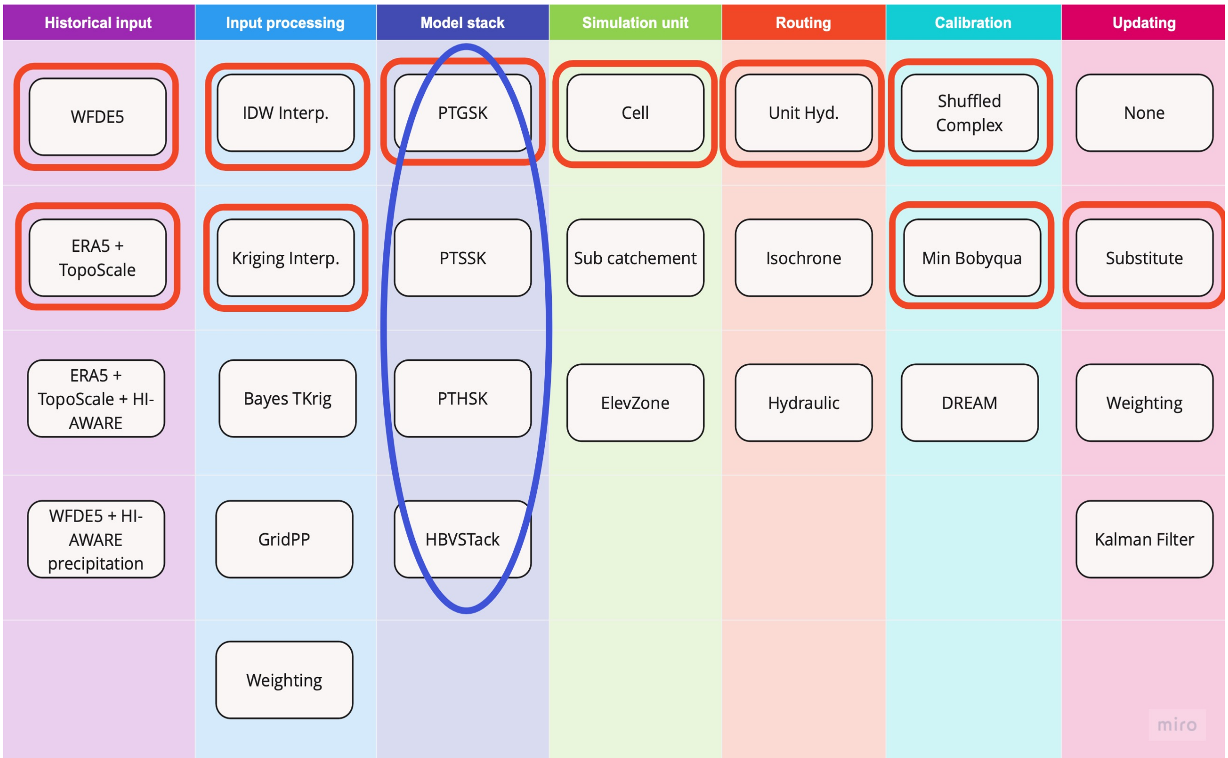

Figure 4.3: Evalutation of multiple configurations. The figure is made using Miro, and it is an adaptation of the figure in [5]

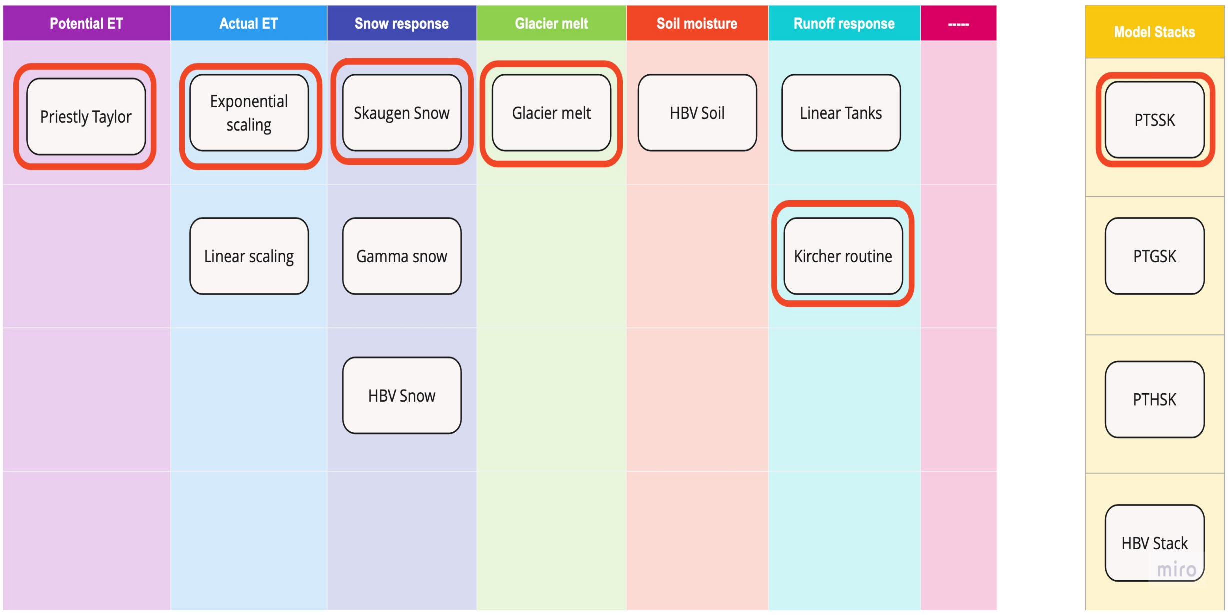

Figure 4.4: Model Stacks components. The figure is made using Miro, and it is an adaptation of the figure in [5]

Chapter 5

Results

5.1 Forcing data analysis

5.2 Evaluation of discharge simulation using different datasets

5.3 Water balance analysis

Chapter 6

Discussion

Chapter 7

Conclusions and outlook

Appendix A

Downloading data from the CDS API

The following Python script describes how the WFDE5 data was downloaded using the CDS API [8].

```
'''
  DOWNLOAD WFDE5 data
  How to download the near-surface-meteorological-variables
  from the CDS API.
  Here version 2.1 is used. Each variable is downloaded
  and saved as a zip file with the name of each variable.
'''

import cdsapi

# Hindu Kush-Himalayan region extent
# (Bajracharya, SR; Shrestha, B (eds) (2011) The status of glaciers
# in the Hindu Kush-Himalayan region. Kathmandu: ICIMOD)

north = 39.31
west = 60.85
south = 15.95
east = 105.04

c = cdsapi.Client()



variables = ['near_surface_specific_humidity',
             'grid_point_altitude',
             'near_surface_air_temperature',
             'near_surface_specific_humidity',
             'near_surface_wind_speed',
             'rainfall_flux',
             'snowfall_flux',
             'surface_air_pressure',
             'surface_downwelling_longwave_radiation',
             'surface_downwelling_shortwave_radiation'
            ]
```

```
for variable in variables:
    if variable == ('rainfall_flux' or 'snowfall_flux'):
        c.retrieve(
            'derived-near-surface-meteorological-variables',
            {   'area': [north, west, south, east],
                'variable': f'{variable}',
                'reference_dataset': 'cru_and_gpcc',
                'year': [
                    '1990', '1991', '1992',
                    '1993', '1994', '1995',
                    '1996', '1997', '1998',
                    '1999', '2000', '2001',
                    '2002', '2003', '2004',
                    '2005', '2006', '2007',
                    '2008', '2009', '2010',
                    '2011', '2012', '2013',
                    '2014', '2015', '2016',
                    '2017', '2018', '2019',
                ],
                'month': [
                    '01', '02', '03',
                    '04', '05', '06',
                    '07', '08', '09',
                    '10', '11', '12',
                ],
                'version': '2.1',
                'format': 'tgz'
            },
            f'{variable}.tgz')
    else:
        c.retrieve(
            'derived-near-surface-meteorological-variables',
            {   'area': [north, west, south, east],
                'variable': f'{variable}',
                'reference_dataset': 'cru',
                'year': [
                    '1990', '1991', '1992',
                    '1993', '1994', '1995',
                    '1996', '1997', '1998',
                    '1999', '2000', '2001',
                    '2002', '2003', '2004',
                    '2005', '2006', '2007',
                    '2008', '2009', '2010',
                    '2011', '2012', '2013',
                    '2014', '2015', '2016',
                    '2017', '2018', '2019',
                ],
                'month': [
```

```
            '01', '02', '03',
            '04', '05', '06',
            '07', '08', '09',
            '10', '11', '12',
        ],
        'version': '2.1',
        'format': 'tgz'
    },
    f'{variable}.tgz')
```

Appendix A. Downloading data from the CDS API

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