Improving Climate Resilience of Vulnerable Communities and Ecosystems in the Gandaki River Basin, Nepal

Annex 2b:

Reconciliation of Water Model for Entire Gandaki River Basin

1. Introduction

The Gandaki River Basin (GRB) is a very large transboundary basin extending from Tibet in the north to India in the south and Nepal in the middle occupying 72 percent of the total basin area (46.300 sq.km). The GRB has seven major tributaries namely Kaligandaki, Setigandaki, Madi, Marsyangdi, Daraudi, Budhi Gandaki, and Trishuli. There are many smaller rivers and rivulets that are draining into the Gandaki river. There is a wide variation in terms of elevation, topography, climate and vegetation[1].

The population of the GRB is mostly rural and heavily dependent on natural resources and the ecosystem services they provide. Degradation of the environment resulting from natural and human pressures reduces the flow of ecosystem services including water and protection from landslides and floods and increases vulnerability of people and ecosystems to climate change. Vulnerability is further worsened by poverty as it reduces livelihood opportunities that are necessary for increasing adaptive capability and reducing exposure and sensitivity to climate impacts. Many young men are migrating to escape the vicious circle of vulnerability that is exacerbated by climate change, leaving fewer people (mainly women and elderly) to manage the land[2].

For the GRB the geographical features extend from the tropical lowland Terai (200m above sea level (asl)) to the high mountains and beyond to the cold and dry Trans-Himalayan region (above 4,000m asl), with peaks exceeding 8,000m[3].

2. Climate Change Impacts

Nepal has a diverse array of landscapes and ecosystems. The risks of climate change across the country are consequently varied, and include: i) increased temperatures; ii) rainfall variability; and iii) increased frequency of extreme weather events.

Like in other parts of the world, climate change impacts have become highly visible affecting different aspects of human society and ecosystem in Nepal. The Central Bureau of Statistics (CBS) of the National Planning Commission (NPC) of Nepal[4] has reported that Nepal has experienced direct impacts of climate change and is one of the most vulnerable countries to climate change in the world.

The data trend from 1975 to 2005 show that the mean annual temperature has been increasing by 0.06°C. This rate of increase is higher in the mountains than in other regions. One of the visible impacts of temperature increase is the melting of snow on the mountains which is observed in the glaciers and glacial lake in an unprecedented rate. In another study conducted by the Ministry of Population and Environment in 2012, it was found that Himalayan glaciers are retreating fast with the annual rate of about 10 to 60 m, which has caused vanishing of small glaciers of less than 0.2 km^2 [5]. Long-term data (1971-2014) analysed by the Department of Hydrology and Meteorology (DHM) (2017)[6] has reported that warm days and warm nights, and the duration of warm spells are increasing. It has further reported that cool days are decreasing while cool nights and duration of cold spells are increasing.

[1] ICIMOD, 2017. The Gandaki Basin Maintaining Livelihoods in the Face of Landslides, Floods, and Drought

[2] IUCN, 2018. Improving Climate Resilience of Vulnerable Communities and Ecosystems in the Gandaki River Basin, Nepal: Feasibility Study.

[3] MoFSC. (2016). *Forest Sector Strategy 2015.* Kathmandu: Ministry of Forests and Soil Conservation.

[4] CBS, 2016. National Climate Change Impact Survey 2016. Central Bureau of Statistics, Kathmandu.

[5] MoPE, 2012. Mountain Environment and Climate Change in Nepal: National Report prepared for the International Conference of Mountain Countries on Climate Change, 5-6 April 2012, Ministry of Environment, Kathmandu, Nepal.

[6] DHM, 2017. Observed Climate Trend Analysis of Nepal (1971-2014). Department of Hydrology amd Meteorology, Kathmandu

DHM (2017)[7] in its long-term data analysis report has shown that number of rainy days and consecutive wet days are increasing. It has further reported that very wet days and extremely wet days are decreasing. MOPE (2012)[8] has also reported that the increased high intensity rain for shorter period of times has caused increased frequency of disasters including flash floods posing more than 1.9 million people to high vulnerability and exposing additional 10 million people to the risks of climate induced disasters.[9]

The Mountain and Hill regions have the highest number of rainy days (106 days in a year on average) while the Trans-Himalaya has the lowest number of rainy days (16 days in a year on average). The rate of change in number of rainy days was negative in Terai and Trans-Himalaya regions, but positive for Hill and Mountain regions. The analysis of precipitation trends for different seasons across different agro-ecological zones revealed that the monsoon precipitation is increasing whereas precipitation in other seasons is decreasing, although most of these trends for 1981–2012 are not statistically significant. The trends for annual precipitation indicate that the dry parts of the basin (Trans-Himalaya and Mountain) could become even dryer as there is a decreasing trend and the wet parts (Hill region) could become even wetter as they show an increasing trend. Both of these patterns can affect the livelihood of the people in the region.

There is no significant trend on the summer monsoon arrival but there is a significant trend toward delay in departure (about a half day per year), therefore, the duration of the monsoon is increasing at the rate of five days per ten years. There is predicted to be an increase in the amount of precipitation during the monsoon period which may increase the severity of water-induced disasters, such as landslides in the Hill region and floods in the lowland region of the basin. An increased frequency and intensity of extreme precipitation events may also cause flash floods. The fragile and sensitive geology, deforestation and the heavy precipitation make the Hill region very susceptible to soil erosion and landslides. The decreasing post-monsoon precipitation may adversely affect paddy rice production as this time coincides with the sensitive stage of the paddy (season for spikelet formation, fruiting and ripening) that demands more water. In addition, the decreasing winter precipitation may lead to failure of winter crops such as wheat, barley and potatoes. The farming system is strongly dependent on the timely arrival of monsoon rain and its distribution. Rising temperatures in combination with increasing precipitation anomalies can influence soil moisture, ultimately affecting the crop production and livelihood of the people depending upon rain-fed agriculture.

The World Bank (2017)[10] provides the following summary of climate change for Nepal.

- Mean annual temperatures are projected to increase between 1.3-3.8°C by the 2060s and 1.8-5.8°C by the 2090s, and this warming is expected to occur more rapidly during the dry months (December-May).
- Winters are projected to be drier and monsoon summers wetter, with some estimating a threefold increase in monsoon rainfall. This could result in more frequent summer floods and winter droughts.
- Currently, it is not possible to get a clear picture of precipitation change, due to large model uncertainties. However, increases in rainfall are more consistent for south-east Nepal.

There are some basin specific studies done by modelling hydrological behavior.

[7] DHM, 2017. Observed Climate Trend Analysis of Nepal (1971-2014). Department of Hydrology amd Meteorology, Kathmandu

[8] MoPE, 2012. Mountain Environment and Climate Change in Nepal: National Report prepared for the International Conference of Mountain Countries on Climate Change, 5-6 April 2012, Ministry of Environment, Kathmandu, Nepal.

[9] CCP, 2011. Climate Change Policy 2011. Government of Nepal.

10 Climate change country profile for Nepal. Retrieved 2017, from http://sdwebx.worldbank.org/climateportalb/doc/GFDRRCountryProfiles/wb_gfdrr_climate_change_country_profile_for_NPL.pdf

3. Hydrological Models

Hydrological models are developed for many Nepalese basins such as Bagmati[11], Dudhkoshi[12], Karnali[13], Karnali-Mohana[14], Koshi[15]; Roshi[16], Tamor and Seti[17], etc.

In the GRB, the specific studies carried out were for Narayani[18],[19],[20], Kaligandaki[21],[22], Setibeni Sub-basin[23], Watersheds in Gandaki Province[24], Marshyangdi[25], Madi[26], and Budhigandaki[27]. Based on these studies, vulnerability of sub-watersheds in the GRB is summarised in the following table.

Criteria	Sub-watersheds	Vulnerability rank
Exposure		
Risks from Rainfall and Temperature	Upper Kaligandaki	Very high
	Myagdi Khola and Taman Khola	High
	Daram Khola _Kaligandaki, Bhabil Khola_Budhi Gandaki, Modi Khola, Upper Badigad Khola, Nisi Khola and Budi Gandaki	Moderate
Ecological Risk	Trishuli_Koplu Khola, Middle Trishuli, Bhyaure_Trishuli, Marsyangdi, Mahesh Khola_Trishuli, Lower Trishuli,	Moderate
	Budhi Gandaki, Lower Kaligandaki, Marsyangdi	Very high
	Upper East Seti, Ridi Khola, Upper Kaligandaki	High

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[14] Pandey V.P., Dhaubanjar S., Bharati L., Thapa B.R. (2019). Modelling hydrology in large basins using multi-site calibration approach: A case of Karnali-Mohana basin, Western Nepal. Journal of Hydro-Environmental Research (Under Review).

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[21] Manandhar S., Pandey V.P., Ishidaira H., Kazama F. (2013) Perturbation study of climate change impacts in a snow-fed river basin. Hydrological Processes, 27 (24), 3461-3474.

[22] Bajracharya, A. R., Bajracharya, S. R., Shrestha, A. B., & Maharjan, S. B. (2018). Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Science of the Total Environment*, *625*, 837–848. https://doi.org/10.1016/j.scitotenv.2017.12.332

[23] CDKN. 2016. Adaptation to Climate Change in the Hydroelectricity Sector in Nepal. Annex 3.1: Setibeni Sub-basin in Narayani (Gandaki) River Basin

[24] Keshav Basnet, Ram Chandra Paudel, and Bikash Sherchan. 2019. Analysis of Watersheds in Gandaki Province, Nepal Using QGIS. Nepal Engineers' Association. technical Journal. Vol 1, No.1, July 2019

[25] Achut Parajuli, Lochan Prasad Devkota, Tirtha Raj Adhikari, Susmita Dhakal, Rijan Bhakta Kayastha. 2015. Impact of Climate Change on River Discharge and Rainfall Pattern: A Case Study from Marshyangdi River basin, Nepal. Journal of Hydrology and Meteorology, Vol. 9, No. 1

[26] Narendra Raj Khanal. 2004. Floods in mountain watershed: A case of Madi River, Central Nepal. Journal of Hydrology and meteorology. Vol 1. No. 1

[27] H B Khatri, M K Jain and S K Jain. 2018. Modelling of streamflow in snow dominated Budhigandaki catchment in Nepal. J. Earth Syst. Sci. (2018) 127:100

Physical Ecological Risk	Madi, Middle Kaligandaki, Tadi Khola, Arun Khola, Middle Trishuli, Upper Trishuli	Moderate
Combined Ecological Risk	Budi Gandaki, Lower Kaligandaki, Marsyangdi	High
	Middle Trishuli, Upper East Seti, Upper Trishuli, Ridi Khola	Moderate
Combined Multiple Risk	Upper Kaligandaki, East Rapti, Budi Gandaki, Lower Kaligandaki	High
	Daram Khola, Upper East Seti, Marsyangdi, Upper Badigad, Myagdi Khola, Aandi Khola	Moderate
Sensitivity		
Ecological sensitivity	Marsyangdi and Upper Kaligandaki, Lower Kaligandaki, Upper East Seti	Very high
	Ridi Khola-Kaligandaki, Madi_East Seti	High
	Middle Trishuli, Middle Kaligandaki, Tadi Khola, Daraudi, Aandhi Khola, Modi Khola	Moderate
Human sensitivity	Upper East Seti, Lower Badigad Kholamm Aandi Khola, Middle Kaligandaki	Very high
	Mahesh Khola_Trishuli, Kolpu Khola_Trishuli, Ridi Khola, Bhyaure Khola, Middle Trishuli and Tandi Khola	High
	Daraudi Khola, Lower Kaligandaki, Lower Trishuli, Modi Khola and Daram Khola, Upper Trishuli, Upper Badigad, East Rapti and Marsyangdi	Moderate
Combined Sensitivity	Upper East Seti	Very high
	Ridi Khola, Lower Badigad, Middle Kaligandaki, Budhi Gandaki, Lower Kaligandaki, Marsyangdi, Middle Trishuli, Mahesh Khola, Tadi Khola, Kolpu Khola	High
	Upper Kaligandaki, Bhyaure Khola, Daraudi Khola, Modi Khola, Upper Trishuli, Lower East Rapti, Lower Trishuli	Moderate
Adaptive Capacity		
Socio-economic capability index	Madi Khola	Very high
	Upper East Seti, Madi, Aandi Khola, Gorandhi Khola, East Rapti, Upper Badigad Khola, Taman Khola, Daram Khola, Nisi Khola, Upper Kaligandaki	High
	Middle Kaligandaki, Lower East Seti, Trisuliseti, Lower Kaligandaki, Ridi Khola, Lower Badigad Khola, Myrsyangdim Myagdi, Mahesh Khola, Dadraudi Khola, Kolpu Khola	Moderate
Vulnerability		
Combined Multiple Vulnerability index	Budi Gandaki (Dhading, Gorkha, Nuwakot)	High
	Upper Kaligandaki (Baglung, Mustang, Myagdi, Parbat), Upper East Seti (Kaski, Syangja, Tanahun), Lower Kaligandaki (Nawalparasi, Palpa, Syangja, Tanahun), Kolpu Khola (Dhading, Nuwakot), Marsyangdi (Gorkha, Lamjung, Manang, Tanahun, Kaski), Lower Badigad Khola (Baglung, Gulmi), Middle Kaligandaki, Aandhi Khola	Moderate

The above mentioned studies are sub-basin specific among which the results of the Kaligandaki are generally indicative for the GRB as a whole. The Kaligandaki study used the Soil and Water Assessment Tool (SWAT) for a future projection of changes in the hydrological regime of the Kaligandaki basin based on Representative Concentration Pathways Scenarios (RCP 4.5 and RCP 8.5. The model results show a predicted rise in the average annual temperature of over 4°C, and an increase in the average annual precipitation of over 26% by the end of the 21st century under RCP 8.5 scenario with the 1990s reference period. See Annex 2a : Feasibility Study, Section 2.6.2 Climate Change in Nepal for detail.

4. Reconciliation of water model for GRB

The studies at different sub-basins have used different types of models, calibrated for different time scales, and have not projected future climate for the entire basin. As a knowledge product of this project, a water model will be established for the entire GRB by reconciling various studies conducted in different sub-basins within GRB. This will be useful in preparing the River Basin Management Framework for the GRB.

The sub-basin level studies mentioned avove have used a wide variety of models such as BTOPMC, HBV, HEC-HMS, J2000, SWAT, Tank, etc. Amongst many hydrological models, Soil and Water Assessment Tool (SWAT) is widely used in many basins in Nepal as it is semi-distributed, can simulate both hydrology, water quality, and sediment under variety of scenarios including climate change, and can well capture spatio-temporal distribution in water availability.

SWAT is widely used at different spatial scales to simulate hydrology, sedimentation, and climate change impacts studies, among others[28],[29],[30],[31],[32]. The SWAT model is therefore selected for hydrological simulation of the GRB. Conceptually, SWAT divides a basin into sub-basins and further into Hydrologic Response Units (HRUs). A stream channel connects the sub-basins. Each HRU represents a unique combination of a soil, land use/cover and slope type within a sub-watershed. The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{n}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where, SW_t is Final soil water content (mm); SW_0 is Initial soil water content (mm); t is Time in days; R_{day} is Amount of precipitation on day i (mm); Q_{surf} is Amount of surface runoff on day i (mm); E_a is Amount of evapotranspiration on day i (mm); w_{seep} is Amount of percolation on day i (mm); and Q_{gw} is Amount of return flow on day i (mm).

In case of future climate change, projections under different representative concentration pathways (RCP) scenarios can be obtained from global circulation models (GCMs) and regional circulation models (RCMs). For local-scale basins such as Gandaki, projections from RCMs are considered better than that from GCMs. However, RCM projections are not free of biases due to coarse spatial resolution, and therefore need bias-correction before using for local scale CC impact assessments[33] [34]). Statistical techniques such

[28] Devkota, L. P., & Gyawali, D. R. (2015). Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. *Journal of Hydrology: Regional Studies*, *4*, 502–515. https://doi.org/10.1016/j.ejrh.2015.06.023

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[31] Bajracharya, A. R., Bajracharya, S. R., Shrestha, A. B., & Maharjan, S. B. (2018). Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Science of the Total Environment*, *625*, 837–848. https://doi.org/10.1016/j.scitotenv.2017.12.332

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[33] Maraun, D. (2014). Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue. *Journal of Climate*, *26*(2013), 2013–2014. https://doi.org/10.1175/JCLI-D-12-00821.1

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as empirical quantile mapping (QM)[35] are used for correcting the biases[36] [37] [38]). Additionally, to reduce uncertainties in the projections, bias-corrected RCM outputs will be combined into ensembles representing various climate models. Ensemble time series will be fed to the hydrological model for CC impact assessment. Climate future approach will be used to project future climate at various physiographic regions in the basin. The SWAT model will then be forced, with bias-corrected RCM outputs under different future scenarios, to assess climate change impacts on the hydrological regime and water availability.

Figure 1[39] depicts the methodological framework that will be used in the reconciliation of the water model for the entire GRB. The diversity of approaches used in the past across sub-basins highlights the challenge of reconciling data and understanding across the basin and the institutions and stakeholders involved. The opportunity to consolidate approaches will be used to help create ownership of the consolidated results, and will help to align understanding of impats and responses. This is key to improving the inter-sectoral understanding across different institutions and to help build national climate knowledge.

[35] Maraun, D. (2014). ibid

[36] Berg P., Feldmann H., Panitz H.J. (2012). Bias correction of high resolution regional climate model data. J. Hydrol., 448-449: 80–92.

[37] Shrestha M., Acharya S.C., Shrestha P.K. (2017). Bias correction of climate models for hydrological modelling – are simple methods still useful? Meteorological Applications, 24(3): 531-539.

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[39] Pandey V.P., Dhaubanjar S., Bharati L., Thapa B.R. (2019). Modelling hydrology in large basins using multi-site calibration approach: A case of Karnali-Mohana basin, Western Nepal. Journal of Hydro-Environmental Research (Under Review).

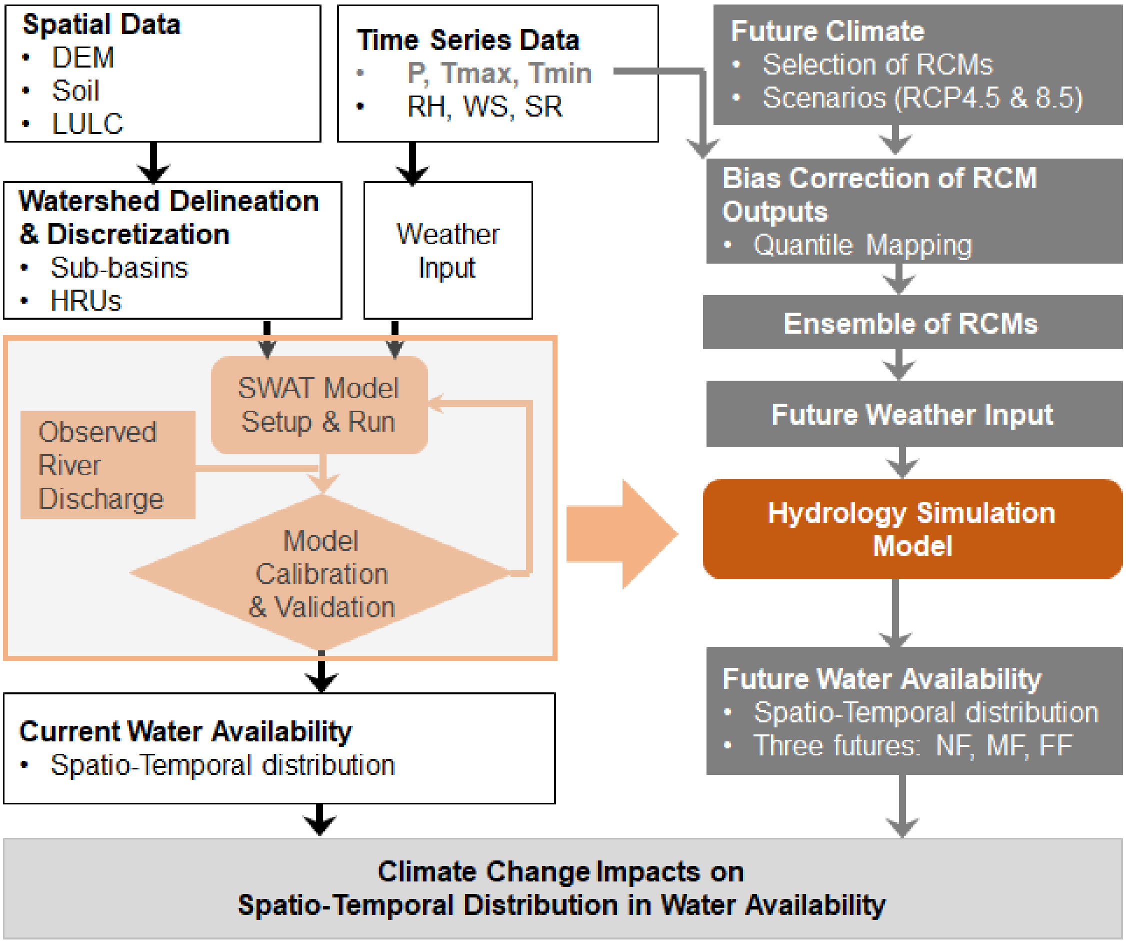

Figure 1: Methodological framework for assessing climate change impacts on water availability. NF, MF, and FF refer to Near-, Mid-, and Far-Futures, respectively; DEM is Digital Elevation Model, LULC is land use/cover; HRU is hydrological response unit (adopted from Pandey et al., 2019)

5. Collaboration with Stakeholders

This activity will be carried-out in collaboration with IWMI Nepal. The project will also engage with other agencies, such as ICIMOD, to ensure that it is working with the most recent scientific support and advice and data. Bilateral and multilateral donors active in Nepal and who are invovled in projects and programmes on climate change or in dealing with climate change impacts will be approached to ensure that this project supports the building of better understnading nationally on climate change. The GRB provides a unique opportunity to demonstrate the potential of alignment of modelling approaches, data, and therefore, appropriate responses to the risks climate change brings for the rest of the country to learn from.