University of CINCINNATI

Deltares
Enabling Delta Life

FutureWater

Climate Change Risk Analysis for Projects in Kenya and Nepal

Kabeli-A Run-of-River-Hydroelectric Project
Final Report

WORLD BANK GROUP Water

Korea Green Growth Trust Fund

Climate Change Risk Analysis for Projects in Kenya and Nepal

Kabeli-A Run-of-River-Hydroelectric Project – Final Report

Asphota Wasti (University of Cincinnati)
Patrick Ray (University of Cincinnati)

Title
Climate Change Risk Analysis for Projects in Kenya and Nepal

Client	**Project**	**Attribute**	**Pages**
The World Bank	11202602-000	11202602-000-ZWS-0041	88

Keywords
Climate Change, risk assessment, project appraisal, Kabeli, Nepal, hydropower, run-of-river, Decision Tree Framework

Summary

This is the Final Report for the Kabeli case study of the World Bank assignment number 7187313, *Climate Change Risk Analysis for Projects in Kenya and Nepal*, financed by the Korean Green Growth Trustfund. The case study concerns the application of the Decision Tree Framework (DTF) to assess the climate change risk for the project to construct the Kabeli-A Run-of-River Hydroelectric Project.

This report describes the DTF and the Kabeli-A Run-of-River Hydroelectric Project. The DTF consists of four phases:

1. Project Screening Phase;
2. Initial Analysis Phase;
3. Climate Stress Test Phase; and
4. Climate Risk Management Phase.

This Final Report is an update of the Second Interim Report and describes the results of all four phases. Compared to the Second Interim Report, the findings and stakeholder feedback collected during the visit in June 2019 to Nepal and comments of the World Bank and stakeholders have been incorporated in the text of the report. Furthermore, results of some additional analyses have been included.

References
Wasti, A. and Ray, P., 2019. Kabeli-A Run-of-River Hydroelectric Project, Climate Change Risk Analysis for projects in Kenya and Nepal. Deltares, FutureWater and University of Cincinnati for the World Bank.

The work behind this report has been supported by several technical staff of Deltares, FutureWater and University of Cincinnati, namely Peter Droogers, Johannes Hunink, Marjolijn Haasnoot, Dana Stuparu, Ümit Taner and Marnix van der Vat. This report and previous versions have been reviewed by Ad Jeuken, Deltares.

Status
final

Contents

Appendices

Acronyms and Abbreviations

CRG	International Hydropower Association Climate Resilience Guide
CRU	Climatic Research Unit
Delaware	Global Meteorological Forcing Dataset for Land Surface Modeling, University of Delaware
DHM	Department of Hydrology and Meteorology of Nepal
DTF	Decision Tree Framework
FAO	Food and Agriculture Organization
GCM	General Circulation Model
GPCC	General Circulation Model
GWh	Gigawatt-hour of electrical power
HBV	Hydrologiska Byråns Vattenbalansavdelning hydrologic model
HPRG	Hydropower Resilience Guide
ICIMOD	International Centre for Integrated Mountain Development
IDA	International Development Association
IHA	International Hydropower Association
KAHEP	Kabeli A Hydroelectric Project
KEL	Kabeli Energy Limited
kWh	kilo-watt hour of electrical power
masl	Meters above sea level
NEA	Nepal Electricity Authority
P	Precipitation
PET	Potential Evapotranspiration
PPA	Power Purchase Agreement
ppm	Parts per million
PPB	Parts Per Billion
Princeton	Global Meteorological Forcing Dataset for Land Surface Modeling, Princeton University
Project Team	Deltares – FutureWater - University of Cincinnati
PSD	Particle Size Distribution
Rs	Nepali Rupees
ROR	Run of River hydropower
Tair	Near-surface Air Temperature
Tavg	Average Daily Temperature
Tmax	Maximum Daily Temperature
Tmin	Minimum Daily Temperature
TRMM	Tropical Rainfall Measuring Mission
UC	University of Cincinnati
WBG	World Bank Group
WFDEI	Watch Forcing Data Era Interim

0 Executive Summary

The Kabeli-A Hydroelectric Project (KAHEP) is a proposed peaking run-of-river hydropower with an installed capacity of 37.6 MW, to be located primarily in Panchthar District in the Eastern Development region of Nepal on the Kabeli River, which is a tributary to Tamor River. It is at early stages of construction. KAHEP has a catchment area of 860 km^2 and a mean monthly flow of about 60 m^3s^{-1}. With a gross head of 118.80 m, KAHEP's average annual electrical output is expected to be approximately 205 GWh/year. It is expected to generate electricity to contribute to the national grid for two hours in the morning peak and four hours in the evening peak.

KAHEP is a run-of-river hydropower project with high dependency on consistency of riverine streamflow in a basin with extreme seasonal variability in precipitation (monsoon to non-monsoon), and substantial contribution to streamflow from snowmelt. Its power-purchase agreement (PPA) specifies monthly delivery targets, meaning that KAHEP is susceptible to stiff financial penalties incurred in the event that seasonal or inter-annual precipitation variability (or the timing of snowmelt) are different from that on which the PPA was negotiated. The economic lifetime of the project is 30 years, meaning that financial projections for the project must anticipate streamflow availability to the project through the year 2050, at which point the climate of the Himalayan region is likely to be substantially different from the recent past.

The Project Team (Deltares, University of Cincinnati, and FutureWater) was hired to evaluate the climate change risk to the performance of KAHEP, and to put those risks in context relative to risks of other kinds. The Project Team followed the methods laid out in the World Bank's Decision Tree Framework, and adopted by the International Hydropower Association (IHA) in its Hydropower Sector Climate Resilience Guide (CRG). The methods are founded on bottom-up, robustness-based concepts that respond to deep uncertainty in future climate conditions not by designing for an unknowable "expected" set of conditions, but by ensuring the ability of the project to perform acceptably well over a wide range of conditions that might reasonably be expected to occur within the project's lifetime.

To do so, the Project Team conducted a detailed analysis of all available data regarding observed historical and project future hydro-climatic conditions in the basin in order to understand trends, and climate drivers. The Project Team then developed a series of models (weather generator, hydrologic model, hydropower generation model, financial model) capable of confidently reproducing historical basin conditions, as well as projecting future KAHEP productivity. The models were run using a systematically-generated set of scenarios of possible future scenarios of climate (precipitation and temperature), sediment-flow, and financial (capital and operations and maintenance costs). The fundamental risks facing KAHEP and other similar run-of-river hydropower projects worldwide are: 1) drought; 2) flood; 3) increased sediment load. This project therefore evaluated each those three risks in detail, and summarized findings of the best understanding of the Project Team regarding the magnitude of each risk to the KAHEP investment.

Conclusion on Concerns Regarding Future Insufficiency of Flow: The project is expected to be financially profitable (yield a positive Net Present Value, NPV) for all wetter future scenarios (approximately half of the uncertainty space), as well as drier futures, as long as the precipitation drop is less than approximately 20% and the temperature rise is not more than 3 ^{o}C. Neither condition (precipitation drop greater than 20% or temperature increase greater than 3 ^{o}C) is likely within the next 30 years.

Figure ES-1 illustrates the likelihood of scenarios in which NPV is negative (red area on the plot). A few general circulation models (GCMs) under representative concentration pathway (RCP) 8.5 project potential futures in which conditions in the basin skirt unfavorability, but generally the project appears at low risk of poor financial return. It should be made clear that this analysis accounts only for shifts in average annual conditions. Shifts in extremes are evaluated in the flood risk section, but are not correlated to financial losses. Shifts in seasonality (or seasonal-specific results) were not closely evaluated, as the GCM outputs supporting the likelihood aspects of such evaluations are not of high confidence.

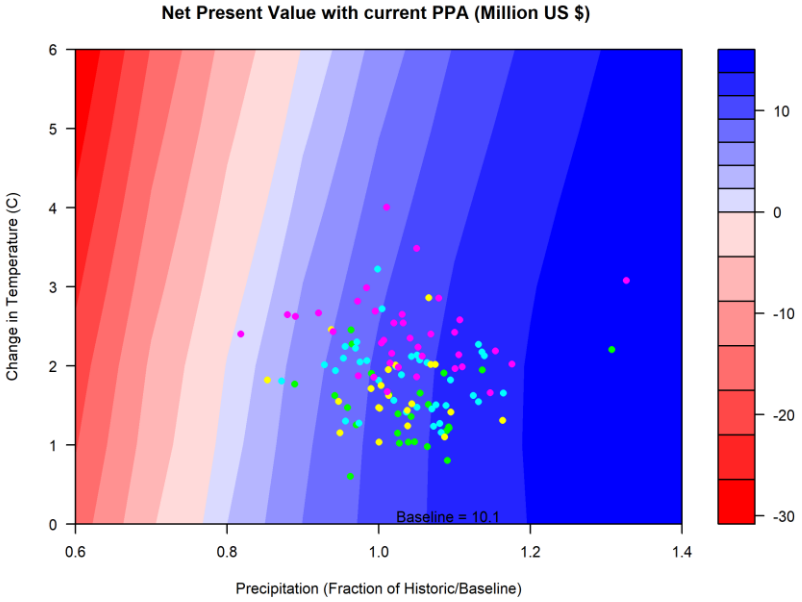


Figure ES-1 Net Present Value response surface for the energy sold each year subject to the maximum limit on the saleable energy per month with power purchase agreement. The dots on the response surface represents the CMIP5 climate change projection (centered on year 2050). Green: Representative concentration pathway (RCP) 2.6; Cyan: RCP 4.5; Yellow: RCP 6.0; Magenta: RCP 8.5.

Conclusion on Concerns Regarding Increasing Flood Risk: The design flood for the KAHEP facility is the 1000-year streamflow. Because we do not have available estimates of the consequences (either to the structure or to the downstream population) of exceedance of the 1000-year flood, we cannot evaluate all aspects (impact and likelihood) of flood risk to the KAHEP facility. However, Figure ES-2 shows that the magnitude peak annual streamflow, and the 1000-year flood, in particular, appears to be increasing throughout the period of historical record (since the middle of the past century), and is likely to further increase in the future (Figure ES-3). GCMs cannot be consulted directly for credible information on the future behaviour of extreme precipitation. However, when the local historical trends in extreme precipitation and streamflow are evaluated; and the information from the subset of GCM that capture the monsoon processes well are reconciled, we observe that the magnitude of flood peaks is increasing in the basin.

The current design flood magnitude is likely to correspond to a much smaller return period, i.e., it may occur every 500 years in the hydro-climate of the next century instead of every 1000. When the structure was designed for what the designers understood to be a 1000-year return period flood, the designers anticipated a risk characterized by a chance of “not-failure” of the structure during the project life of $.999^{30}$, or about a 3% chance that a 1000-year flood would happen within the project lifetime. Accounting for the historical climate trend, as well as somewhat qualitative information from the GCMs, we see that the magnitude of what was historically a 1000-year flood better corresponds to a 500-year return period flood in the project lifetime. The probability that the flood magnitude would be exceeded during the project life-time is now $1-0.998^{30}$, or about 6%.

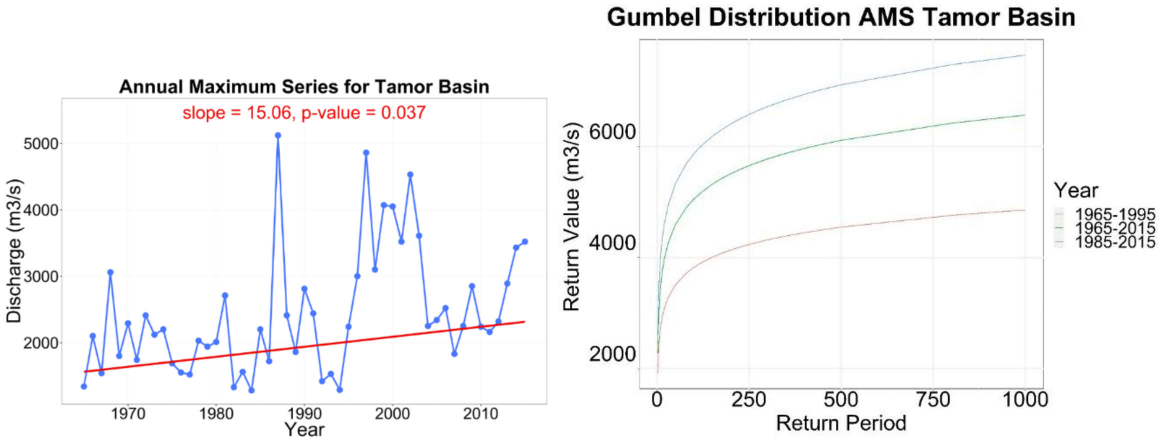


Figure ES-2 Annual Maximum Time Series for Tamor Basin Station 690 (left); Comparative plots of Gumbel distribution fitted to the annual maximum streamflow time series for Tamor Basin. The red, green and blue are the analysis on 1965-1995, 1965-2015 and 1985-2015 respectively (right)

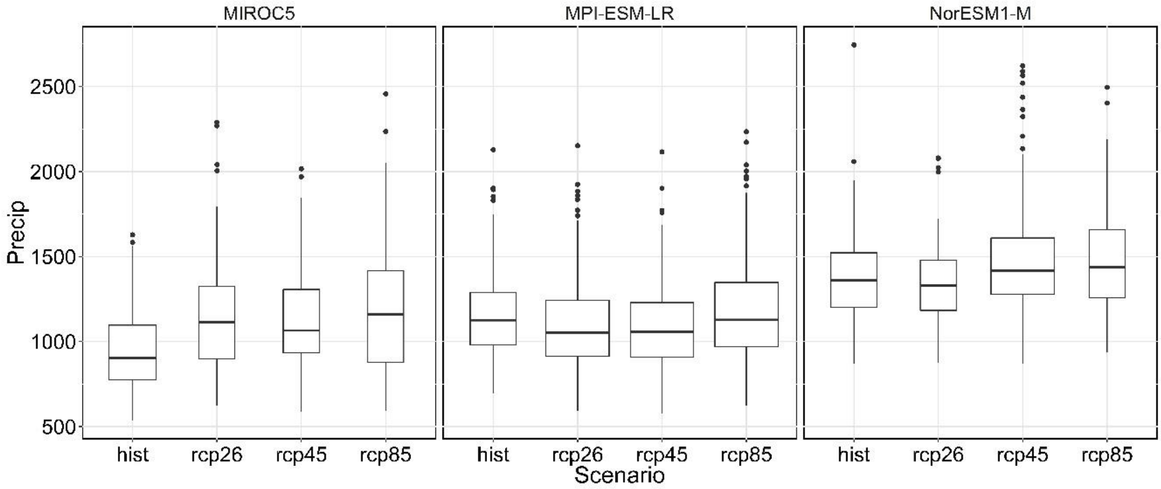


Figure ES-3 Maximum monthly precipitation for the project area abstracted from the GCMs identified by Sharmila et al. (2015) to capture the Asian monsoon processes well in CMIP5.

Conclusion on Concerns Regarding High Sediment Load: The sediment load impact on the annual energy production was analysed by calculating the number of days the power plant would be shut down due to excessive sediment in the river. This was accomplished by using an empirical relationship between streamflow and suspended sediment derived as part of this project. The analysis does not take into account rolling bed load. Figure ES-4 shows the response of project operating cost to climate-change-induced changes in sediment concentration.

With an increase of precipitation by 20%, a reduction of 2.7 GWHr of annual energy production is predicted, which in terms of financial terms would be $170,100 per year. Moreover, with an increase of precipitation by 20%, up to a 50% increase in the average annual sediment concentration is expected, which could more than double the expected cost for turbine replacement in the project lifetime.

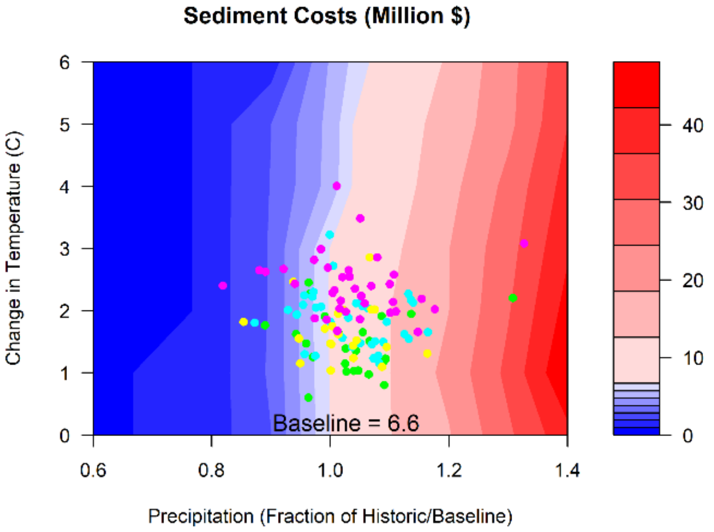


Figure ES-4 Response surface of total non-discounted cost due to sediment concentration with decrease in turbine efficiency and power plant shutdown.

Conclusion to Multidimensional Risk Assessment: When the impacts of uncertainty in sediment load, electricity selling price, capital and O&M costs, and discount rate are evaluated alongside uncertainty in future average annual precipitation and temperature, the project appears to be more sensitive to changes in the capital costs and the energy selling prices than to shifts in temperature and precipitation. An increase in the capital cost by 50% would result in a large loss to the project (Figure ES-5).

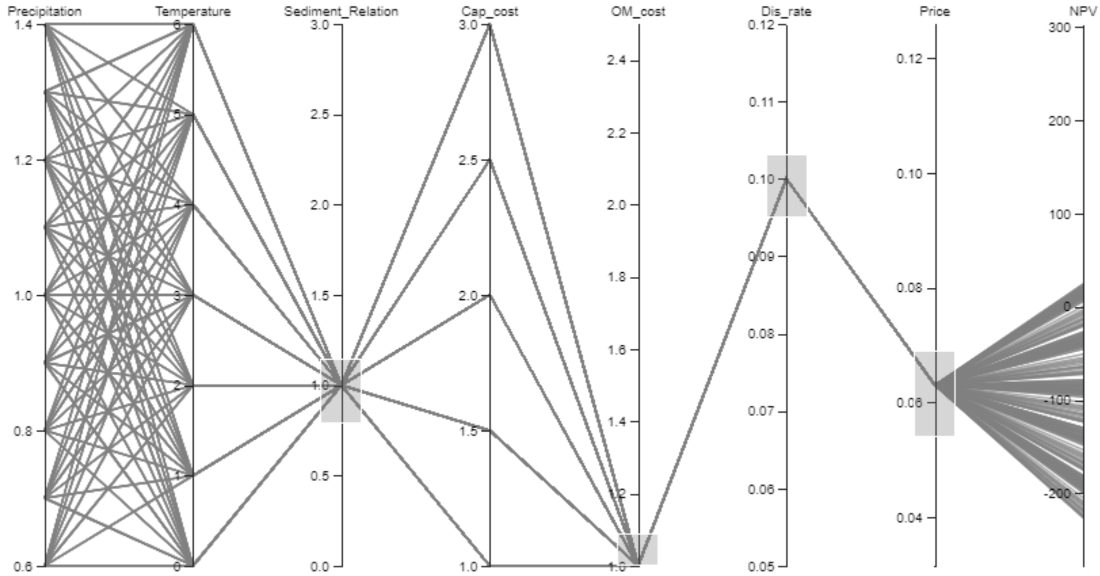


Figure ES-5: Demonstration of the Impact of uncertainty in capital cost on the NPV of the project. Whereas the range of NPV when accounting only for climate change was approximately +$20M to -$40M, the potential losses stretch to over $200M if capital costs occur at the upper range of possibility (in this case, 3x the baseline estimate).

Recommendations for Climate Change Adaptation: No climate change adaptation measures are recommended to manage risks associated with low flows. For flood risk, though we cannot evaluate the trade-offs between flood risk management options in the absence of cost information regarding flood impacts, the Project Team recommends careful consideration by the design engineers of the costs of floods ranging from 100-year to 500-year occurrence intervals, which this analysis shows are much more likely in the next 50 years than they were in the past 50 years. In response to the risk of increased sediment load, this report proposes installation of coated turbines, which would increase the initial investment by 40%, but could help reduce the potential loss in the energy with power plant shutdown. In addition to reduction of shutdown days, coated turbines also reduce the efficiency loss associated with sediment erosion, though these improvements were not explicitly quantified in this analysis.

Finally, as one of the initial pilot demonstration projects of the International Hydropower Association's (IHA's) Climate Resilience Guide (CRG), this report presents feedback to the IHA on the experience of the Project Team applying the principles in the guide. In short, for all its strengths, the CRG is weak on safety concerns, reflecting a current state of the science that has not matured on design considerations for the risks of increased peak precipitation from climate change. This Kabeli case study takes a comprehensive approach to the evaluation of historical trends and GCM projections of peak annual precipitation (and in the case of historical observations, trends also in streamflow). However, because of the lack of skill of GCMs in the reproduction of historical precipitation extremes, it is difficult to apply a decision-scaling-style impact/likelihood assessment to risks of increasing streamflow extremes. The recommendation of this report is that additional research of both the scientific community and the community of hydropower design engineers be applied to methods for the estimation of likelihood of increasing precipitation extremes.

There are a few promising beginnings to this research which rely not on GCM skill in estimation of extreme precipitation, but rather on GCM skill in estimation of regional-scale pressure-based weather regimes.
Examples include the work of Steinschneider et al. (2019) with the California Department of Water Resource and the US Army Corps of Engineers, and Schlef et al. (2019) with the Department of Defence in the Ohio River Valley.

One further recommendation for the IHA CRG based on this case study is to put an emphasis on selection of a simple and effective hydrologic model that can be run multiple times with minimal computational effort. The bottom up approach is based on the sensitivity analysis of the project performance under a number of climate and non-climate factors and thus quick and effective hydrologic model is a central part to the evaluation. In the experience of this research team (and as demonstrated using the HBV model in this analysis), it is not necessary to sacrifice quality (or spatial resolution) in hydrologic modelling in order to achieve speed and calibration efficiency.

1 Overview of this Final Report Document

Under World Bank Contract 7187313, the Decision Tree Framework (DTF – see Box 1) has been applied to two planned investment projects of the World Bank Group, here referred to as Task 1 and Task 2. According to the Terms of Reference:

- “The overall objective of the consultancy for Task 1 is to quantitatively assess the climate change risk vis-à-vis other identified risks unrelated to such change, followed by guidelines for a phased adaptation leading to increased resilience of the integrated **Nzoia River** Flood Program and irrigated expansion using the DTF”.
- “The overall objective of this consultancy for Task 2 is to assess the vulnerability of the **Kabeli Project** to current or potential changes in the baseline (climate and other) conditions under which the proposed design is to be based and to develop adaptation strategies through iterative risk assessment and risk management methodologies consistent with the potential sensitivity of the project to climate and other risks applying the WBG’s Hydropower Sector Climate Resilience Guidelines. Based on this, a second objective is to provide feedback on the applicability of the Guidelines.” It is understood that these Guidelines are a dedicated version of the DTF containing specific guidelines for hydropower.

This Final Report provides final recommendations by the Project Team on Task 2. The document is organized as follows:

1. The Project Overview, describing the tasks involved in application of the Decision Tree Framework to the case of Kabeli A.
2. The final version of the Timeline and Deliverables.
3. A description of data collection and analysis.
4. A complete Phase 2.
5. A complete Phase 3 with subsections on the weather generator, the hydrologic model, and three applications of the stress test (financial, sediment, and multidimensional). Flood risks were evaluated in terms of likelihood only, as data informing an impact analysis were not provided by project stakeholders. A supplementary analysis is provided to demonstrate the effectiveness of historical-trace-only (in the absence of a stochastic weather generator) stress tests to provide meaningful information on climate change risks to the project.
6. Phase 4 with responses to stakeholder concerns, and special attention given to the risks of increased sediment load with climate change.
7. A summary of the International Hydropower Association’s Climate Resilience Guide, including description of the modifications it made to the Decision Tree Framework on which it was based, with commentary on its strengths and weaknesses.
8. A conclusion that summarizes findings of the report, identifies limitations, and recommends actions in response to report findings (including topics in need of further study).
9. Annexes to the report provide: a) meeting minutes from the two missions to Nepal; b) a description of the SPHY hydrologic model originally used for this analysis, but abandoned in favor of a faster and more easily calibrated model; c) a supplemental section on resilience, sustainability, and other performance metrics; and d) R scripts for calculation of the response surface for NPV and performance metrics.

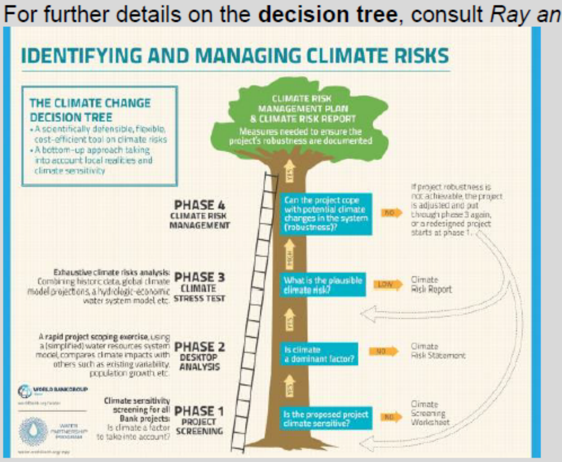
Textbox 1 The Decision Tree

The **decision tree** framework provides resource-limited project planners and program managers with a cost-effective and effort-efficient, scientifically defensible, repeatable, and clear method for demonstrating the robustness of a project to climate change. At the conclusion of this process, the project planner is empowered to confidently communicate the method by which the vulnerabilities of the project have been assessed, and how the adjustments that were made (if any were necessary) improved the project's feasibility and profitability. The framework adopts a "bottom-up" approach to risk assessment that aims at a thorough understanding of a project's vulnerabilities to climate change in the context of other non-climate uncertainties (for example, economic, environmental, demographic, or political). It helps to identify projects that perform well across a wide range of potential future climate conditions, as opposed to seeking solutions that are optimal in expected conditions but fragile to conditions deviating from the expected.

The **decision tree** employs a stress test for project/system climate change risk assessment, and advanced analytical tools for climate change risk management. In addition to addressing the fundamental science issues, the **decision tree** was designed with the economic use of human and financial resources in mind. The goal was to develop a tool that would be applicable to all water resources projects, but to *allocate effort to projects in a way that is consistent with their potential sensitivity to climate risk*. To do so, the process was designed to be hierarchical, with successive stages or phases of analysis triggered only if shown to be warranted during the explorations of the previous phase. The procedure consists of four increasingly intensive phases: Phase 1 Project Screening; Phase 2 Initial Analysis; Phase 3 Climate Stress Test; and Phase 4 Climate Risk Management. The result is that risk management effort is expended in proportion to the need (see **Error! eference source not found.**).

The **decision tree** has been applied to five World Bank projects to date: the Upper Arun Hydropower Project, Nepal, the Mwache Multipurpose Reservoir, Kenya, the Cutzamala Water System, Mexico, and the Poko Hydropower Project and Matenggeng Pumped Storage Project, Indonesia. The pilot demonstrations of the **decision tree** framework were accomplished under World Bank Contract 717 4462: Including Climate Uncertainty in Water Resources Planning and Project Design – Decision Tree Initiative. A new study of the resilience of the urban water system under the jurisdiction of SACMEX in Mexico City, Mexico, is now commencing. The World Bank TTL has requested an additional pilot study application of the **decision tree** to resilience assessment of the flood protection works and irrigation development area on the Nzoia River, western Kenya and the development of hydropower in Nepal.

For further details on the **decision tree**, consult *Ray and Brown* [2015].



Decision tree illustration

2 Project Overview

This section presents an overview of the methodology applied to this study. The methodology is based on that agreed in the signed contract, with minor modifications highlighted throughout, in response to the Inception Workshop (see Annex A for Inception Workshop Meeting Summaries). According to stakeholders and experts consulted over the course of the June 2018 Inception Workshop:

1. All available hydro-climatologic, sediment, cost and price data were provided to the project team.
2. Results were requested in both financial and non-financial terms. Stakeholders request the opportunity to review the possible impact of climate change on streamflow alone, hydropower production (as a direct run-of-river function of streamflow), and finally, financial indicators such as net present value (NPV) or internal rate of return (IRR). While financial terms are useful to understand the value of the potential impact of climate change on the project, financial terms are often distorted by discount rates and uncertainty regarding capital costs and selling price.
3. Sediment data provided by KEL did not include rolling bed load. The methodology adopted here evaluates the potential impact of only the suspended sediment load to the turbine erosion.
4. Special attention was requested to be given to natural variability, and the ability to forecast the subsequent month’s hydropower production, for hydro-banking purposes. In response, the methodology adopted here is evaluating the sensitivity of the Kabeli project to at least 30 traces of stochastically generated natural climate variability.
5. It was suggested by officers at the Department of Electricity Development that the Kabeli project may be inundated by a large storage project under consideration just downstream. Because this project is not confirmed by the Government of Nepal, it is recommended that the stress test approach adopted by the project team explore the critical time length of operation in order to justify capital costs.
6. The Kabeli project is designed for a very small (1000 yr) flood risk. Stakeholders request that the Project Team evaluate questions regarding the sufficiency of the use of the 1000-year event, or if greater flood robustness is justified by possible climate change?

The methodology outlined in the Project Workplan (the signed contract) included:

- Task 1 Problem Description and Definition of Risk Context;
- Task 2 Development of a glacio-hydrologic model and water resources system model;
- Task 3 Multidimensional stress test with emphasis on climate-change-specific risks;
- Task 4 Multidimensional stress test extended to non-climate risks;
- Task 5 Probabilistic inference informed risk assessment and management;
- Task 6 Feedback loop

Each subsection here expands on the approach developed for each of the tasks. The Tasks approximately follow the flow of the International Hydropower Association Climate Resilience Guide (released in May 2019), which include Phase 1 Project Risk Screening, Phase 2 Initial Analysis, Phase 3 Climate, Stress Test, Phase 4 Climate Risk Management, and Phase 5 Monitoring, Reporting and Evaluation.

2.1 Task 1 – Problem Description and Definition of Risk Context

The Kabeli-A Hydroelectric Project (KAHEP) is a proposed peaking run-of-river hydropower with an installed capacity of 37.6 MW. The KAHEP is located primarily in Panchthar District in the Eastern Development region of Nepal on the Kabeli River, which is a tributary to Tamor River (see Figure 2-1). It is at early stages of construction.

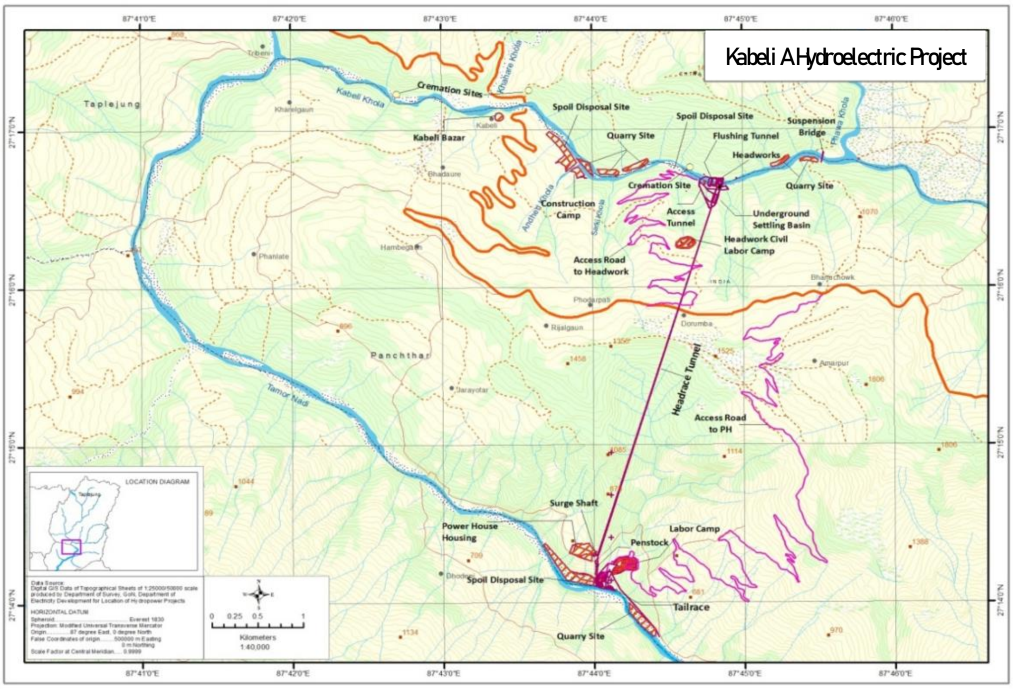


Figure 2-1 Schematic Diagram of the Proposed Project Layout

The KAHEP has a catchment area of 860 km^2 and a mean monthly flow of about 60 m^{3}s^{-1}. With a gross head of 118.80 m, the electrical output of the project is expected to be approximately 205.2 GWh per year. The project is expected to generate electricity to serve the demand of the national grid for two hours in the morning peak and four hours in the evening peak.

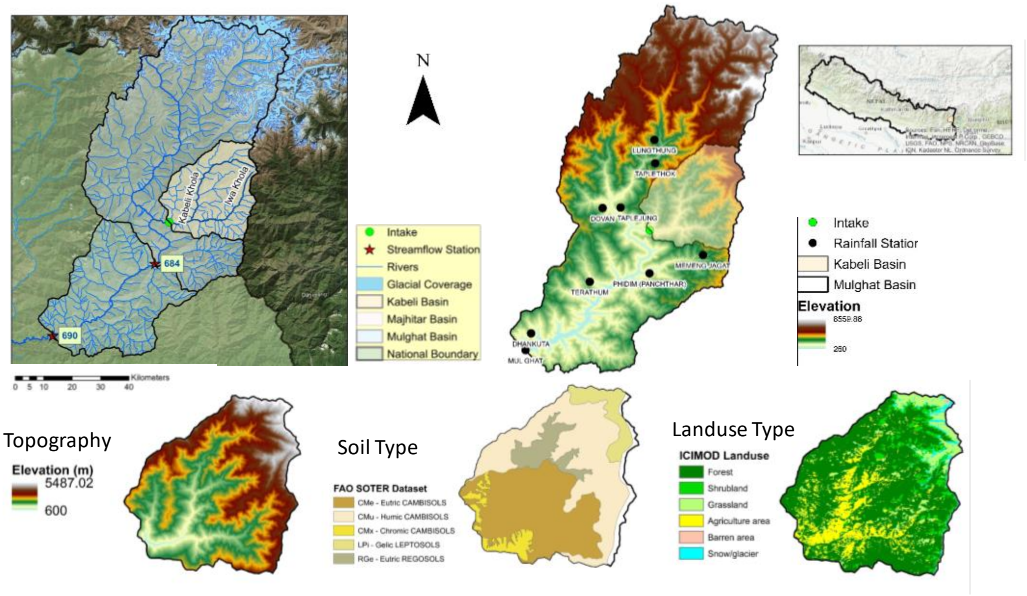


Figure 2-2 Catchment of Kabeli-A Hydroelectric Project

Presented in Figure 2-2 is the catchment of Kabeli A Hydroelectric Project with relevant data available on the catchment characteristics. The topographic map shows elevations in the catchment ranging from 600 meters above sea level (masl) to 5487 masl. From the land use map, it is seen that more than 70% of the catchment is covered with forest, and the remaining area is agricultural land and shrub-land. The agricultural land may require larger quantities of irrigation water in a warmer future, and attention is therefore given to potential non-stationarity in the projected agricultural water demand. In the event that agricultural water users require a larger allotment of the total flow, a decrease in water available to the Kabeli A Hydropower Project could result during the dry season. However, no such increase is projected based on the Ecological Reports. Twenty six percent of the catchment area is above the elevation of 3000m (Figure 2-3), with less than 1% area above 5000m indicating a year-round snow line (a common practice in Nepalese catchments, though subject to change with a warming climate). Thus, snowfall has historically contributed to the precipitation in the basin especially in the winter months, however the monsoon precipitation is dominant is the basin. This may change in a warmer future. No glacier area has been identified within the Kabeli catchment using Randolf Glacier Inventory (RGI Consortium, 2017). The larger Tamur Catchment (of which the Kabeli catchment is a part) includes glacier area outside of the Kabeli boundary (see the Figure 2-2 upper left).

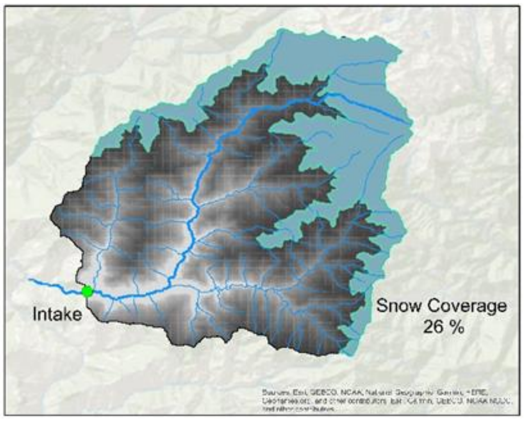


Figure 2-3 Hypsometric curve showing area above 3000m in the Kabeli Catchment

As of the IDA17 replenishment (December 2013), the World Bank must subject its potential investment in the KAHEP to a climate change and natural hazards risk assessment. This project therefore applies a multidimensional risk assessment approach to the uncertain factors potentially affecting the performance of the Kabeli A Hydroelectric Project (KAHEP) throughout its economic lifetime. As a pilot demonstration project of the International Hydropower Association's (IHA) Hydropower Sector Resilience Guide, (published in May 2019), the methodology includes aspects (e.g., sediment, flood risk) of particular concern to hydropower projects, and results of the analysis was presented to the IHA for consideration in refinement of the Guide.

The Kabeli project, as a long-lived (> 20 year design life) water infrastructure project relying directly on streamflow for its functionality, is "hydrologically sensitive" and therefore also "climate sensitive", and passes in the DTF from Phase 1 to Phase 2. As part of Phase 2, a rapid project scoping is conducted, in which the streamflow is perturbed in ways informed by historical trends (trends identified by examination of the local precipitation and streamflow records). The performance of the Kabeli run of river hydropower facility is evaluated using the perturbed streamflow, by way of a direct mathematical conversion (see Ray et al. (2018) for example equation). As the performance of the facility is demonstrated to be potentially vulnerable to climate change in Phase 2, Phase 3 was initiated.

The Phase 3 methodology centers on a detailed "stress test", which is a computational vulnerability analysis based on stochastic weather generation. The approach uses computer algorithms that probe a numerical model of the system to identify the conditions or combination of conditions that would cause the project to not meet objectives. Climate change projections are used only in a "posterior" analysis, to assess whether the problematic climate conditions that have been identified in the stress test are likely to be of concern in the future.

In this application, the approach explores uncertainties in future climate, sediment, and economic factors, with a process described as a "climate stress test" to identify the vulnerabilities of the proposed project. Climate change projections are used to determine if these vulnerabilities are likely, and thus require adaptive response (adaptation) or whether they are too unlikely to be a concern.

The DTF approach to climate change risk assessment applied to KAHEP uses four modelling subsystems (see Figure 2-4): 1) a climate model that applies to simulated changes in natural variability of climate and plausible climate variations in the future, based on a climate/stress testing algorithm; 2) a hydrologic model (which translates weather into streamflow), 3) a water resources system model (which translates streamflow into hydropower and other water uses), and 4) a financial model to evaluate the performance metrics (in this case NPV). The climate/weather stress tester generates weather sequences consistent with current climate and with a range of climate changes.

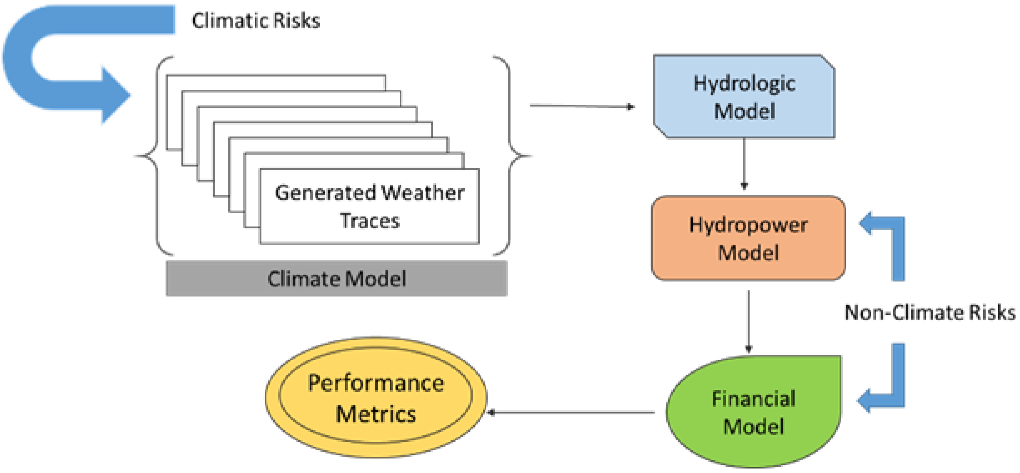


Figure 2-4 DTF approach to climate change risk assessment applied to KAHEP

Those sequences are used as input to the hydrologic model, the output of which then becomes input to the water infrastructure system model. The water infrastructure system model produces the output of interest to the risk assessment, in this case hydropower and its financial value. The intermediary and final output of the modeling chain is then analysed to predict how the proposed project performs under climate change.

2.2 Task 2 – Development of a glacio-hydrologic distributed model and water resources system model

The HBV model (Bergström, 1976, 1992) is a conceptual rainfall-runoff model, which describes the water balance in the catchment with the following equation:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + lakes]$$

Equation 2-1

Where,
P = precipitation
E = evaporation
Q = runoff
SP = snow pack
SM = soil moisture
UZ = upper groundwater zone
LZ = lower groundwater zone
Lakes = lake volume

The HBV model consists of different subroutines for processes in the hydrologic cycle such as snow accumulation and melt, estimation of evaporation, soil moisture accounting, runoff generation and rainfall routing. The model structure of HBV-96 ((Lindström et al. 1997) is presented schematically in Figure 2-5. The diagram describes the simplified working mechanism of the HBV model.

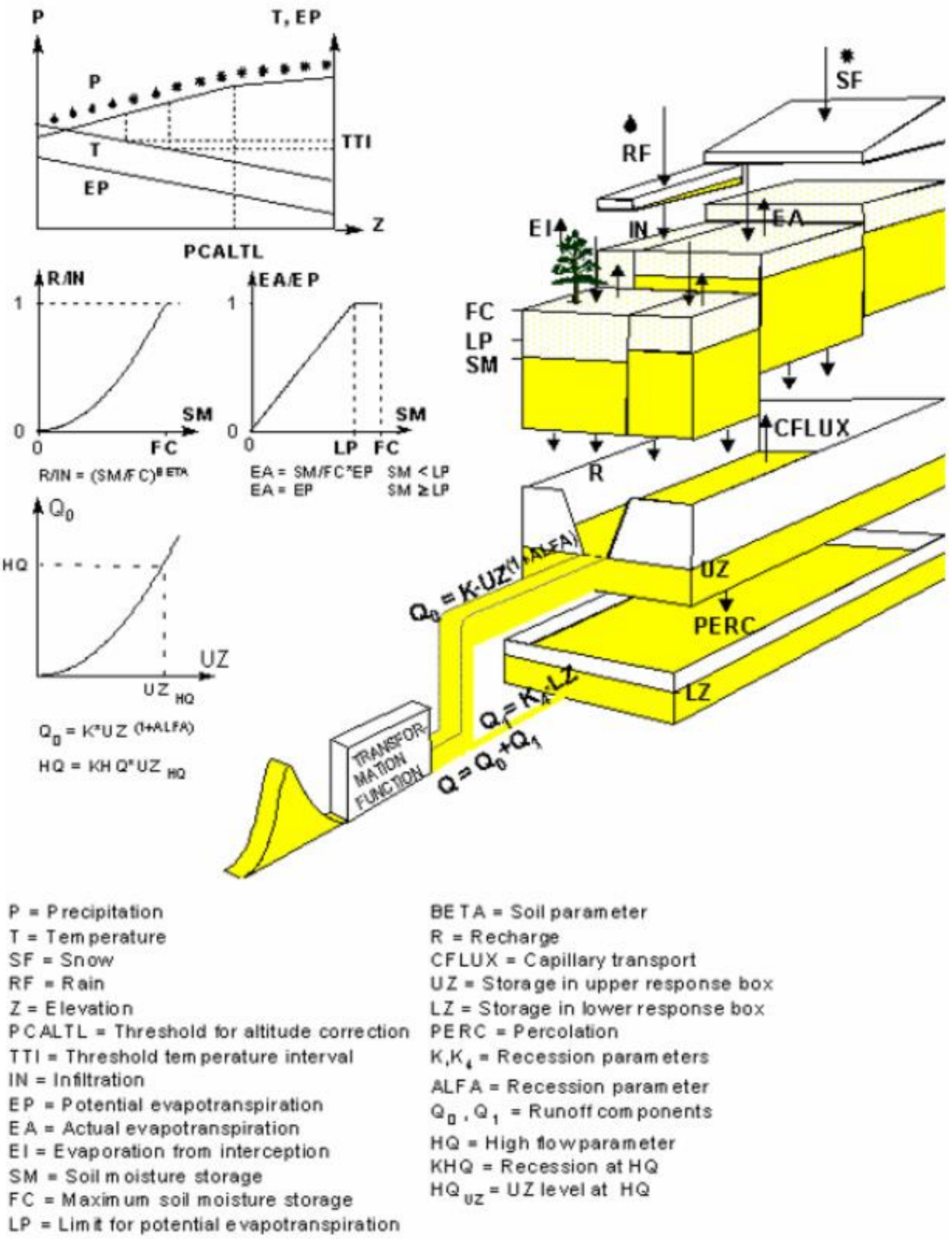


Figure 2-5 Schematic diagram of HBV-96 (Lindstrom et. al., 1997); Snow module (top), soil module(middle) and response module (bottom)

In the application of the HBV model to the Kabeli basin, the following modules were employed:

a) Snowmelt and snow accumulation module: SNOW-17 (Anderson, 2002) is a conceptual model that captures the process of snow melt, ablation and accumulation in the catchment. The Kabeli basin is a highly snow-fed basin thus this module plays a significant role in appropriate model calibration.
b) Evapotranspiration module: Hamon method (Hamon, 1961) is used to derive the potential evapotranspiration (PET) for the basin. The PET in millimeters is computed as a function of daily mean temperature and hours of daylight.

c) Routing module: The rainfall, runoff water balance in the basin is routed to the outlet of the basin (here the intake of the hydropower plant) for model calibration and validation. Lohman routing model is used to describe the transport of water in the channel system using the diffusive wave approximation of the Saint-Venant equation (Lohmann et al., 1998).

In the original iteration of this modelling exercise (see previous versions of this report though the Midterm Report), the Spatial Processes in Hydrology (SPHY) model was used for hydrologic modelling in the Kabeli basin. However, the SPHY model was not a good fit for the requirements of the Climate Stress Test, and was abandoned. The HBV model was adopted instead. The reasons for the switch to the HBV model were:

1 There was no automatic calibration option for the SPHY model, which resulted in difficulty fitting to historical data

2 The raster format of the distributed SPHY model made the many runs required for scenario analysis prohibitively slow.

For record-keeping, a description of the SPHY model (included in previous versions of this project report) has been included in Annex B.

In order to translate changes in streamflow into impacts on hydropower generation and downstream flow conditions, a water resources system model has been developed. Typically, water systems models are either constructed as simulation models, with reservoir operations following prescribed rules, or as optimization models, with reservoir operations guided by an objective function (e.g., maximization of hydropower generation subject to constraints). The model developed as part of this analysis incorporates elements of each.

The water resources systems model is quite simple in this case of run-of-river hydropower with no storage or reservoir operations to be considered. For this purpose, a simple system model has been developed in R, a mathematical programming language (refer to Equation 4-1 and Annex D). The water resources system model computes hydropower generation and its profits under a range of inflow conditions, which are provided by the hydrologic model. The model could be expanded to consider downstream water requirements (agricultural, domestics and/or ecological purposes) and demonstrate trade-offs between alternative water uses, although this is not considered necessary in this analysis.

The impact of sediment accumulation on the project was evaluated outside of the system model. Based on a limited historical record, a relationship between sediment and flow rate was developed.

The sediment accumulation analysis consisted of a sensitivity analysis of the project performance to changes in sediment loading rates. This was done by exploring the uncertainty on the sediment-flow relationship derived later in this report.

2.3 Task 3 – Multidimensional stress test with emphasis on climate-change-specific risks

With the modeling framework in place, the next step is the climate and human development stress test. The stress test is an exhaustive exploration of the effects of climate changes and changes in other key human development factors on the performance of the system. The climate stress test is conducted using a stochastic climate/weather generator that was specifically created for this purpose. The climate/weather generator creates time series of daily weather data for a specified time frame (e.g., 50 years) over a specified spatial area. The climate/weather generator is designed such that the mean climate conditions can be changed and then new weather sequences are generated that represent the changed climate conditions. In this way, an ensemble of weather time series is created that tests the sensitivity of the system to changes in mean climate conditions (e.g., changes in mean precipitation and temperature) and variability effects (the natural variability of day to day weather and longer spells due to the earth’s climate system).

The climate stress test allows efficient and exhaustive sampling of the system response to all climate changes. It does not depend on any downscaling methods, choice of models or emissions scenarios because it explores sensitivity to climate change (rather than sensitivity to a particular climate model’s projection of the future). In addition to climate changes, other uncertain future factors are evaluated. The climate stress test is expanded using a range of values of other variables. These factors include the rate of sedimentation (and resulting lifespan of the project) and financial factors (price of electricity, cost of construction).

2.4 Task 4 – Multidimensional stress test extended to non-climate risks

Climate change is explored using a delta shift technique, conserving historical natural variability but shifting precipitation and temperature in response to possible future climate realizations. In addition to the climate shifts, the following are explored:

1. Non-climate risk factors include: changes to electricity selling price in each season, sediment load (as described in the sediment section below), upstream/downstream water use requirements, earthquake risk (represented as the risk that the structure could collapse premature to its intended economic life), and potential increase in the capital cost resulting from construction delay.
2. Climate risk factors not well represented by shifts in long-term means were explored. The analysis included the observation of historical trends in the precipitation, and streamflow time series and the potential impact of such changes on the floods (1000-year flood for instance).
3. Assessment of other risks was proposed (e.g., Glacier Lake Outburst Flood (GLOF), landslide, changing abstractions upstream), but none were carried out in this analysis, because:
    a. Project owners (KEL) and stakeholders deemed the likelihood of each to be small;
    b. No data on GLOFS, landslides, or trends/projections in upstream agricultural withdrawals were available.

Results are presented using suitable visualizations for a multidimensional risk space (e.g., parallel coordinates plots).

2.5 Task 5 – Probabilistic inference informed risk assessment and management

The final step of Task 3 is the use of climate information, including climate change projections, to assess the level of concern associated with the risk scenarios. For each of the risk scenarios defined in Task 3, a probability estimate is assigned to that scenario based on available information. Since the probabilities are necessarily subjective, the term “level of concern” is used to clarify the purpose of the probabilities. Level of concern for climate risks is estimated based on three factors: 1) theoretical basis for the climate change (i.e. atmospheric science), 2) observations of the climate change (i.e. historical trend) and 3) modelling projections of the climate change (i.e. GCM results).

Level of concern on non-climate risks is generally informed by: 1) historical trends; 2) model projections; 3) expert elicitation. The level of concern is higher when the three factors are in agreement regarding a particular change. A generic example is upstream municipal water demands, where there may be a clear historical trend on population increase (and/or urbanization), projections for population growth and urbanization indicate an expectation that growth continues, and local experts point to social and economic phenomena propelling more people to the cities. Probability estimates may also be applied to other uncertain factors if reasonable means of estimating them are available. In the specific case of this Kabeli project, almost all of our understanding of expectations for future values comes from expert elicitation - earthquakes, prices, costs, and electricity demands.

If adaptation is necessary, a set of possible adaptation plans is to be generated and discussed with the project developer. The adaptations options could be new/modified design or operation rules. The stress test is re-performed to evaluate the system performance with the adaptations that make positive impacts through the reduction of concern associated with the risk scenarios, or the elimination of risk scenarios altogether. A preliminary screening of adaptation options is used the beginning of the project. Using previous projects experience in Nepal, relevant and suitable adaptation options based on the level of concern of identified risks in Task 1 is discussed.

Within the scope of this task, a climate risk management strategy is outlined, if any adaptations were deemed necessary, based on the delineation of risks, assessment of level of concern, and evaluation of possible adaptations. The strategy consists of the concerns related to the project, the uncertain factors that may be considered for further investigation, and any adaptive responses that are recommended. The strategy outlines a set of possible actions and conditions for those actions that are recommended for achieving successful project design and implementation. It represents a translation of the results of the technical analysis into a set of direct recommendations and proposed actions to address any concerns related to climate or other risks that are identified. The consortium, when appropriate, applies the adaptation pathway method [e.g. Haasnoot et al., 2013] to outline potential step wise implementation opportunities of those strategies.

2.6 Task 6 – Feedback Loop

The overall process is described in the International Hydropower Association Climate Resilience Guide (CRG) and is framed as an adaptive management feedback loop. This final phase of the CRG is included to track how resilient the project is in operation and to allow the climate resilience and disaster risk management plan to be monitored, reported on, evaluated and updated. The main stages of Monitoring, Reporting and Evaluation are set out in the flow diagram in Table 1 of the CRG. The final task of this project-level assessment describes for the project planners (owners, investors, etc.) those characteristics of system performance, hydro-climatic indicators (e.g., trends in temperature, streamflow, precipitation, snow accumulation, monsoon seasonality), and water quality metrics (e.g., sediment loads) that should be monitored, and with approximately what frequency, going forward. The Monitoring, Reporting and Evaluation plan to be developed as part of this study assists project operators in vigilant efforts to identify problematic trends, and anticipate problematic system performance.

2.7 Timeline and Deliverables

Project deliverables as described in the TOR include (see also Table 2-1 for a timeline):

a) Inception Report (submitted October, 2018):
   i. Describing how the DTF methodology is going to be applied to the Kabeli project, including scheduling for the workshops and the provision of technical guidance and support to stakeholders and decision makers, including an updated work plan, methodology and models for the rapid project climate and non-climate scoping and timeline as agreed with the Project Team;
   ii. Describing the data collection process, including preliminary findings on data availability, and strategy to adapt the proposed modelling methodology to the limitations of the available data;
b) First Interim Report (submitted December, 2018)
   i. Describing the hydrologic model development process, and presenting results of the first stakeholders meeting and the model calibration as well as preliminary findings of a climate change risk assessment of the hydrology of the system;
c) Mid-term Report (submitted March 2019)
   i. Presenting detailed findings of the Hydropower Model, Sediment analysis and Flood Model, with context on each of Phases 1 through 3 of the DTF;
d) Second Interim Report (submitted May 2019)
   i. Presenting preliminary findings of the climate risk assessment and multidimensional risks analysis, with context on each of Phases 1 through 4 of the decision tree;
   ii. Presenting a strategy for a more detailed set of economic considerations in the DTF (e.g., prices, markets, etc.);
   iii. Presenting a recommendation for modification of hydropower guidelines (if deemed necessary after analysis)
e) Draft of Final Report (submitted June 2019)
   i. Describing the background, problems that prompted the realization of the study, its objectives, methodology, data and models used, and presenting detailed findings and recommendations of the climate risk assessment and resilience analysis, with context on each of adopted Phases 1 through 4 of the decision tree, including the results of the launch and closing workshops, for Client and Bank comments.
f) Final Report (submitted August 2019);
   i. Same content as the Draft Final Report plus an Executive Summary, and including the Client and Bank Team comments and revisions;
g) Other informal communications by e-mail about progress of the study, as agreed with the Project

In addition to the deliverables specified in the signed contract, feedback on the application of the Hydropower Sector Climate Resilience Guide was delivered in two phases:

a) January 2019 London Meeting
    a. A climate stress test of the Kabeli Project has been presented
    b. Lessons learned from application of the CRG to the first three phases of the Kabeli project through the Risk Assessment phase have been described.
b) May 2019 World Hydropower Congress, Paris
    a. Draft final results of the Kabeli Project climate risk management analysis
    b. Lessons learned from application of the Guidelines to all phases of the Kabeli project
    c. Suggestions for revisions to the Guidelines to make them more generally applicable (especially to cases such as the Kabeli Project)

Table 2-1 Project timeline and Deliveries

	2018				2019							
Activity/deliverable	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Working session in Delft with all partners	🟦											
Initial Analysis Phase	🟦											
1st Interim Report	🟩											
Hydrological modeling	🟦	🟦	🟦									
Weather generator		🟦	🟦									
Climate stress test			🟦	🟦	🟦							
Midterm Report					🟩							
London IHA Meeting					🟩							
Climate risk management plan					🟦	🟦	🟦	🟦				
Second Interim Report									🟩			
Paris IHA World Congress									🟩			
Presentation of Results in Nepal										🟦		
Final Report										🟦	🟦	🟩

3 Data Collection, Description, and Analysis

This section presents an analysis of the available historical observations of data relevant to the KAHEP project. The Project Team was provided with streamflow data and precipitation data in the basin by the leader of Kabeli Energy Limited on June 21, 2018 via email. Kabeli Energy Limited (KEL) had bought the data from Department of Hydrology and Meteorology for study and design of the Hydropower Plant. The precipitation data provided was monthly ground station data updated until 2008. The streamflow data provided was daily discharge measurements until 2015 at two gaging stations maintained by DHM further downstream along Kabeli River. The Project Team also met with DHM in Nepal to request recent updates on the hydro-meteorological data.

The motivations of this section are threefold: 1) to confirm the design team’s estimation of historical availability of hydropower-producing streamflow; 2) to evaluate trends in the available historical data that may indicate that future streamflow (and streamflow extremes) are likely to be different to the past; and 3) to initiate an examination of climate change projections to inform expectations regarding future meteorological conditions in the basin.

Generally, previous studies of climate trends and climate projections in the Himalayan region have found temperature to already be increasing (and projected to increase 2-4 ^{o}C by mid-century), with little change in average annual precipitation (observed or projected), but with increasing streamflow between now and mid-century as a result of accelerating melting of highland glaciers (with increasing temperatures) (Immerzeel, 2008; Immerzeel et al., 2010; Shrestha and Aryal, 2011).

The impacts of climate change on water, biodiversity and socio economic activities have been discussed (Xu et al., 2009). A number of studies have explored the climate change resilience of hydropower by evaluating basin-wide changes in hydropower generation potential in the context of changes in hydrology and water resources (e.g. Beyene et al. 2010; Bharati et al. 2014; Christensen et al. 2004; Finger et al. 2012; Giuliani et al. 2016; Hamlet et al. 2010; Ho et al. 2016; Lehner et al. 2005; Majone et al. 2016; Markoff and Cullen 2008; Maurer et al. 2009; Mehta et al. 2011; Minville et al. 2009; Schaefli et al. 2007), the ability of diminishing glaciers to continue to sustain baseflows on which run-of-river hydropower facilities rely (Bolch et al. 2012; Shrestha and Aryal 2011) and the impact of seasonality shifts on hydropower timing (Laghari et al. 2012; Madani and Lund 2010; Sharma and Shakya 2006). Some have found substantial evidence of the effects of climate change on hydropower already: Destouni et al. (2013) in northern Europe; Hanshaw and Bookhagen (2014) in the Andes, Peru; and in Central Asia.

To test the resilience and robustness of hydropower in the context of climate change and other unknown future risks, the DTF has previously been applied in Upper Arun (Ray et al., 2018), Trishuli, and Karnali basins of Nepal.

During the inception visit, the consultant had a meeting with the team leaders from KEL at World Bank Headquarters in Nepal on June 25, 2018 and a follow-up meeting on June 28, 2018. During these meetings, the Project Team was informed of a number of studies that have been carried out for KAHEP, including:

1. Streamflow and Stage Data: KEL maintains a gaging station few kilometers downstream of the project intake site. The gage height measured at the station was provided by the KEL leaders on June 26, 2018 during the inception visit via email. The rating curve established for the gage height measurement was provide later on via email in the form of Discharge measurement report on August 29, 2018.
2. Sediment Data: The Sediment Report prepared by Hydro Lab (2013 & 2014) was provided by the KEL team leaders in early July via email. Further Sediment Sampling and Laboratory Analysis Report (2010, 2011 & 2012) was provided in early January by the KEL team leaders via email. Further sediment reports with a complete record (2010 - 2016) was provided later during the second mission to Nepal in June 2019.
3. ESIA Reports: Pravin Karki provided the ESIA document via Dropbox access on Jun 18, 2018.

3.1 Hydroclimatic Data

Presented below are data collected in the Kabeli Basin for studying the historical climate and observed characteristics of the climatology.

3.1.1 Streamflow Data

The Department of Hydrology and Meteorology (DHM) in Nepal maintains two hydrological stations further downstream of the of the KAHEP intake point (Figure 3-1a). Station 684 (Tamor Majhitar) has daily record of discharge since 1996, and Station 690 (Tamor Mulghat) has daily record of discharge since 1965. No station is within the Kabeli boundary, and attribution of streamflow at each site is complicated by contributions from non-Kabeli tributaries within the broader Tamor basin.

A gaging site was established in 2010 near the KAHEP head works. Gage height is measured at the gaging site twice daily (05/15/2010 – present). Kabeli Energy Limited (KEL, owner and operator of KAHEP) provided the Project Team with a report on the discharge measurement and the records of gage height at the site. In the report, two rating curves are established for the gage station and are shown in Equation 3-1 and Equation 3-2, respectively. Both of the rating curves were developed based on the river discharge measurement from the same period: Nov 16, 2011 to May 14, 2015. The results from the rating curves are comparable.

$$Q = 27.612 * (H + .302)^{2.306}$$

Equation 3-1

$$Q = 37.507 * (H + .173)^{2.021}$$

Equation 3-2

The Long-term average daily flow for these different stations are plotted together in Figure 3-1b.

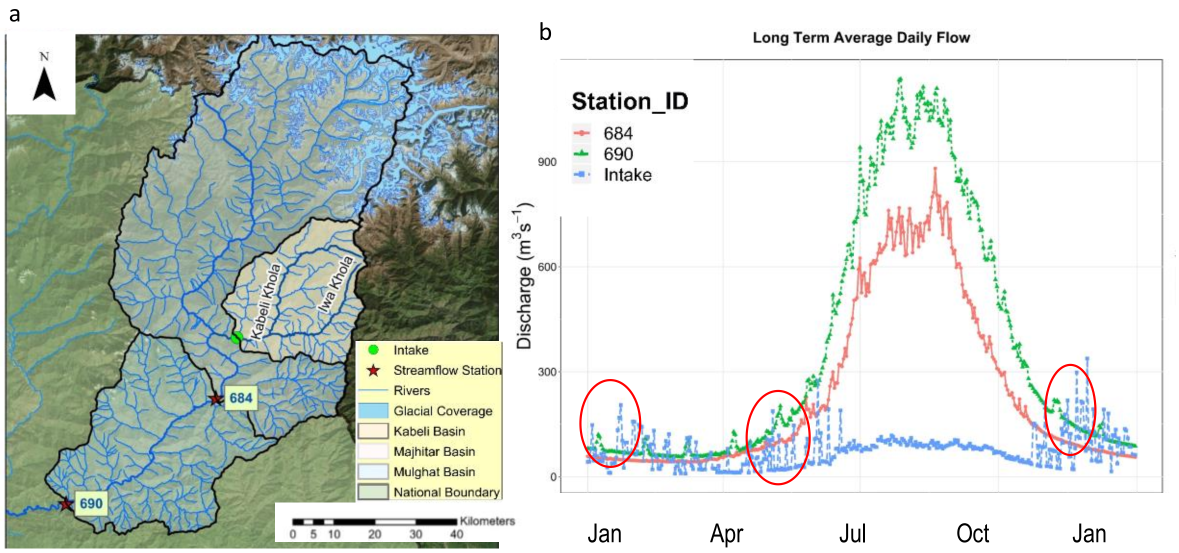
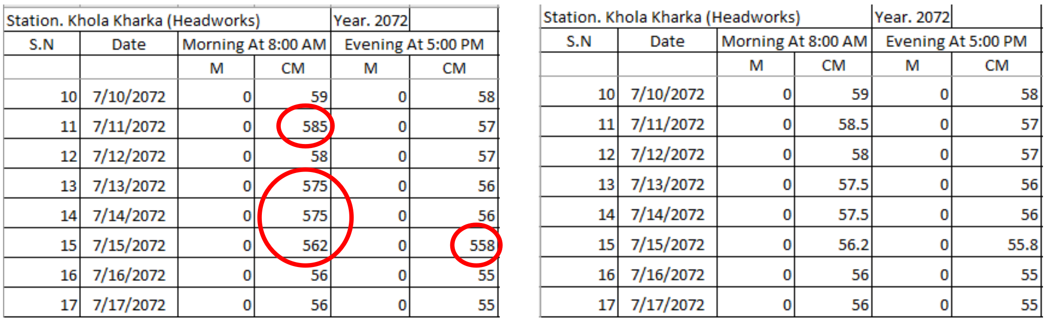


Figure 3-1 a) Location of intake and streamflow stations in the project area b) Long-term average discharge at different stations in and around Kabeli Catchment. The red circles highlight the parts of the hydrograph where the base flow is exceptionally high and irregular.

Figure 3-1b shows irregular discharge measured at the KAHEP intake. The monsoon discharge (June- August) is smaller and flatter in comparison with the noisy values in the base flow period. The base flow (during drier months November-June) is higher, sporadic, and greater than the flow measured in gage stations established downstream along the same river with larger catchment area. This is contrary to a physical-science understanding of the behaviour of base flow versus monsoon flow, and almost certainly is erroneous. The base flow of a hydrograph should represent the groundwater (or, where applicable, the snow/glacier melt) contribution to the streamflow during the dry season. The base flow should be fairly constant, and cannot credibly be said to exceed the peak flow of the seasonal hydrograph; such flashy nature of the graph observed for this site is not easily explainable.

Digging deeper into the data, we found that for some days the gage height measurements in the morning and evening were drastically different. It is suspected that the observed values containing 3 digits were, as a rule, entered with omission of the decimal point. They appear as cm, but are actually mm. One of such case is illustrated in Figure 3-2. The table on the left is the actual recorded values and on the right is the corrected values.



Station. Khola Kharka (Headworks)				Year. 2072	
S.N	Date	Morning At 8:00 AM		Evening At 5:00 PM	
		M	CM	M	CM
10	7/10/2072	0	59	0	58
11	7/11/2072	0	585	0	57
12	7/12/2072	0	58	0	57
13	7/13/2072	0	575	0	56
14	7/14/2072	0	575	0	56
15	7/15/2072	0	562	0	558
16	7/16/2072	0	56	0	55
17	7/17/2072	0	56	0	55

Station. Khola Kharka (Headworks)				Year. 2072	
S.N	Date	Morning At 8:00 AM		Evening At 5:00 PM	
		M	CM	M	CM
10	7/10/2072	0	59	0	58
11	7/11/2072	0	58.5	0	57
12	7/12/2072	0	58	0	57
13	7/13/2072	0	57.5	0	56
14	7/14/2072	0	57.5	0	56
15	7/15/2072	0	56.2	0	55.8
16	7/16/2072	0	56	0	55
17	7/17/2072	0	56	0	55

Figure 3-2 Gage height measured in the gaging station established at the head works. The table on the left is the record measurement and on the right is the corrected data

The complete dataset was checked for such errors and corrections were applied.

Figure 3-3 shows the hydrograph plotted with the corrected dataset.

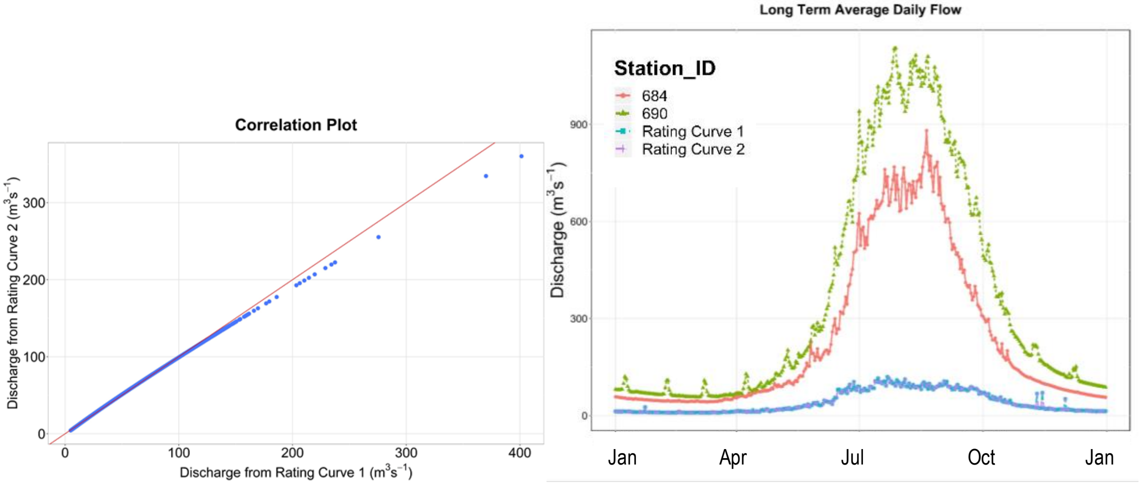


Figure 3-3 Long Term Daily Average Flow at Intake of Kabeli Hydroelectric Project after data quality check. Two hydrographs plotted using Rating Curve 1 and Rating Curve 2 agree well.

Thus, after performing data quality check, it has been concluded that there were errors during data entry and correction is thus applied for the purposes of this project. It is also observed that the discharge values from both of the rating curves agree very well (see Figure 3-3).

The average of discharge obtained from Rating Curve 1 and Rating Curve 2 is taken as standard for this project (see Figure 3-4).

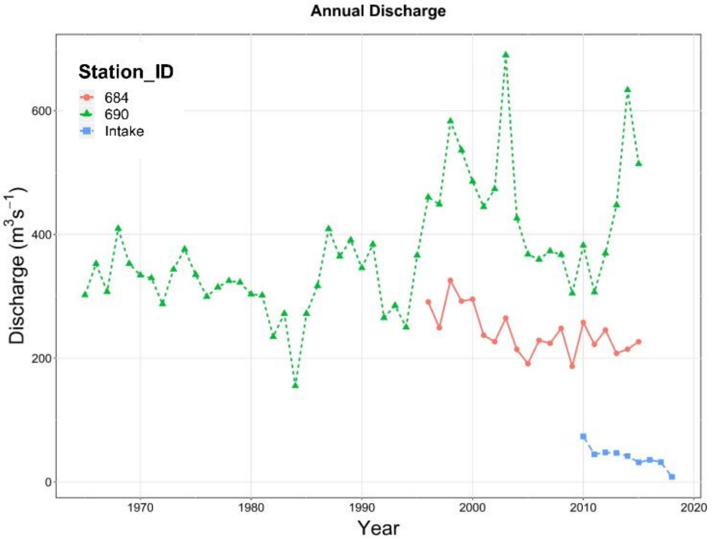


Figure 3-4 Annual Discharge Observations

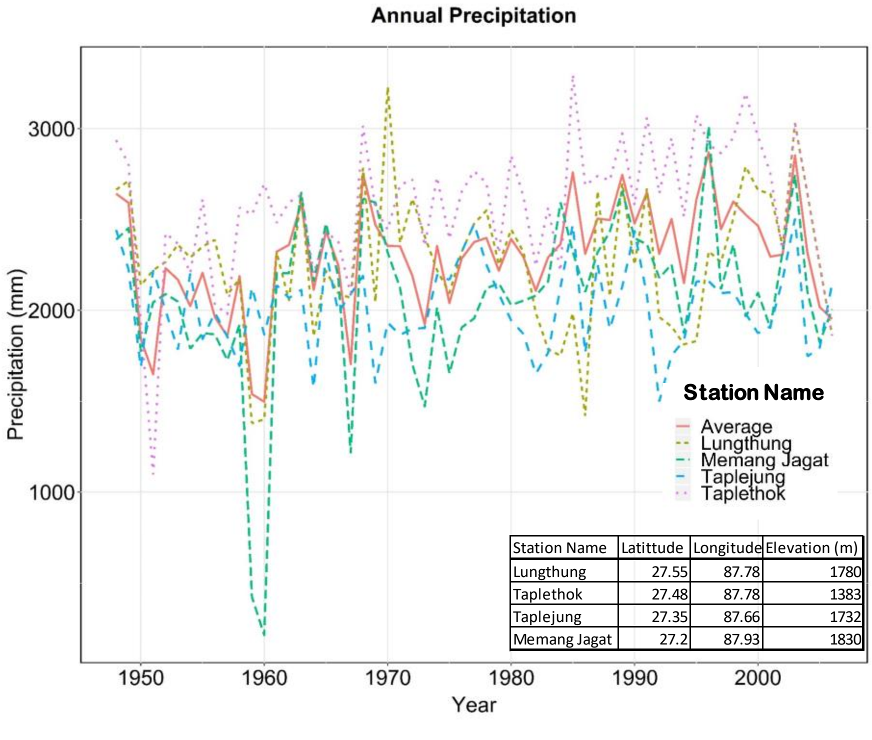
Trend analysis was carried out in the annual discharge data with the Mann-Kendall (MK) test and Sen’s slope estimator. The discharge at Station 684 was decreasing at the rate of 3.57 m^3s^{-1} per year for years 1996-2015 at 5% significance level. There could be a number of reasons for observation of such decreasing trend over time including data quality.

One study, for example, relates a sudden decrease in streamflow due to stronger El Niño influence compared to La Niña in Nepal (Shrestha and Kostaschuk, 2005). For Station 690 there was an increase in discharge at the rate of 1 m^3s^{-1} per year for year 1965-2015. However, the increase was not significant. A decreasing trend with a rate of 4.99 m^3s^{-1} per year was observed at the intake point. However, it is difficult to draw conclusion based on 8 years of data (2010-2018). A more detailed analysis on the peak flows is carried out in the flood analysis section.

3.1.2 Meteorological Data

3.1.2.1 Station Data

There are no meteorological stations within the KAHEP Catchment. DHM maintains a record of precipitation in the vicinity of the catchment. These stations are situated in similar elevation and are representative of the climate of the catchment.



Station Name	Latittude	Longitude	Elevation (m)
Lungthung	27.55	87.78	1780
Taplethok	27.48	87.78	1383
Taplejung	27.35	87.66	1732
Memang Jagat	27.2	87.93	1830

Figure 3-5 Comparison of ground station data and the average precipitation in the basin by Thiessen polygon

The average precipitation in the catchment was calculated using Thiessen polygons. The Sen's Slope was calculated for the average precipitation in the annual time series. A non-parametric Mann-Kendall test was used to test the significance of the trend. Before trend analysis, the time series was pre-whitened to remove the effect, of serial-correlation as the lag-1 autocorrelation was found to be significant.[1] The results of trend analysis of the precipitation time series show that the precipitation is increasing, however it is significant only in two of the ground stations. The average precipitation in the basin is increasing with an average rate of 0.41695 mm/year at 5% significance level from 1950-2008. Kabeli Basin is a part of the bigger Koshi Basin in Nepal which is observed to be getting wetter in general with shorter and more intense spells of rainfall (Shrestha et al., 2017). Changes in precipitation are further explored in the general circulation models as well in the flood analysis phase.

3.1.2.2 *Gridded Datasets*

Besides, ground station, there are a number of gridded climatological datasets available for South Asia, including the catchment. They are listed in Table 3-1 below. The list is not exhaustive.

Table 3-1 Partial List of Gridded Climatological dataset available for Kabeli Catchment

Datasets	Resolution (degrees)	Time Step	Region	Coverage	Variables	Citations
APHRODITE	.25 x.25	Daily	Asia	1951-2007	P	(Kamiguchi et al., 2010; Yasutomi et al., 2011; Yatagai et al., 2012)
CRU TS	.5x.5	Monthly	Global	1901/01-2015/12	P, Tmax, Tmin, Tavg, PET	(Harris et al., 2014)
GPCC	.5x.5	Monthly	Global	1901-2018	P	(Schneider et al., 2014)
TRMM	.25x.25	Daily	Tropics	1998-2018	P	
U Delaware	.5x.5	Monthly	Global	1900-2014	P, Tair	(Willmott, 2000)
Princeton	.25x.25	Daily	Global	1948-2010	P, T	(Sheffield et al., 2006; Yuan et al., 2014)

3.1.2.3 Comparison of the Data

The different sources of gridded datasets were plotted together to compare the datasets (Figure 3-6). The gridded datasets had different spatial and temporal coverage. The datasets were superimposed upon the basin (see Figure 3-7) and the average value were calculated for the basin for each gridded dataset based on the area of basin covered by each grid of the basin.

---

[1] *The Prewhitening procedure was followed* (Storch and Navarra 1995)

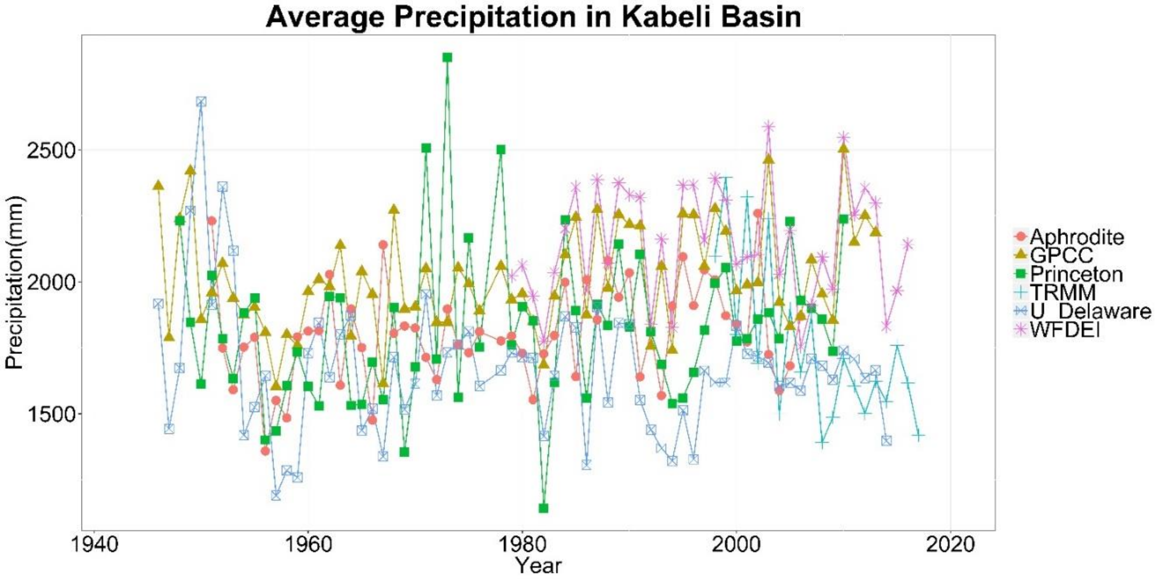


Figure 3-6 Average Precipitation from different data gridded dataset in Kabeli Basin

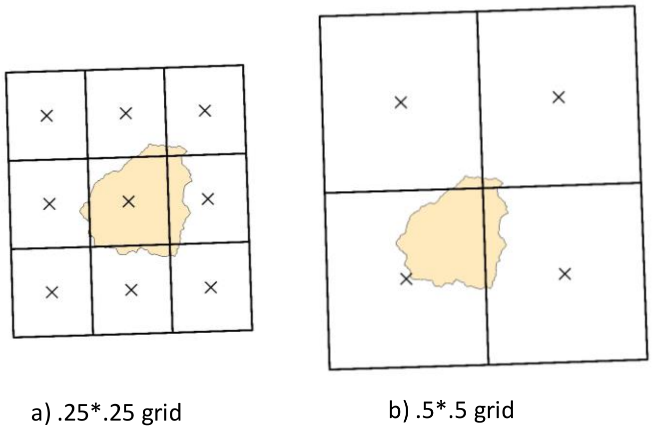


Figure 3-7 Resolution of gridded Datasets

During data analysis it was found that the TRMM dataset underestimates the contribution of precipitation due to snowfall (Andermann et al,, 2011; Palazziet al., 2013). Therefore, other available datasets were explored for the project area. WFDEI meteorological forcing data set is the WATCH Forcing Data methodology applied to ERA-Interim reanalysis data (Weedon et al., 2014)[2]. The data have eight meteorological variables available (3-hourly and daily values) from (1979 – 2016). The WFDEI data used in this project are 'Rainf_WFDEI_GPCC' and 'Snowf_WFDEI_GPCC'. These are daily-accumulated rainfall and snowfall, bias corrected with GPCCv5 data (v6 for 2010) and gauge "catch corrected" (average over previous 3 hours). These datasets are compared in Figure 3-8 and Figure 3-9. The observed data shows higher precipitation compared to other dataset. However, after 2000, there are many missing values in the observed ground station data.

---

[2] *Weblink: http://www.eu-watch.org/data_availability.*

A suitable precipitation dataset for the Kabeli Basin was chosen based on a monthly mass balance check as shown in Figure 3-8. The monthly accumulated precipitation in the basin was plotted together with the discharge at the intake of the basin. The discharge (in mm) was calculated by dividing the discharge at the intake by the area of the basin (859 km^2). It is clear that the TRMM dataset underestimates the precipitation. All further analysis in this report is continued using WFDEI dataset.

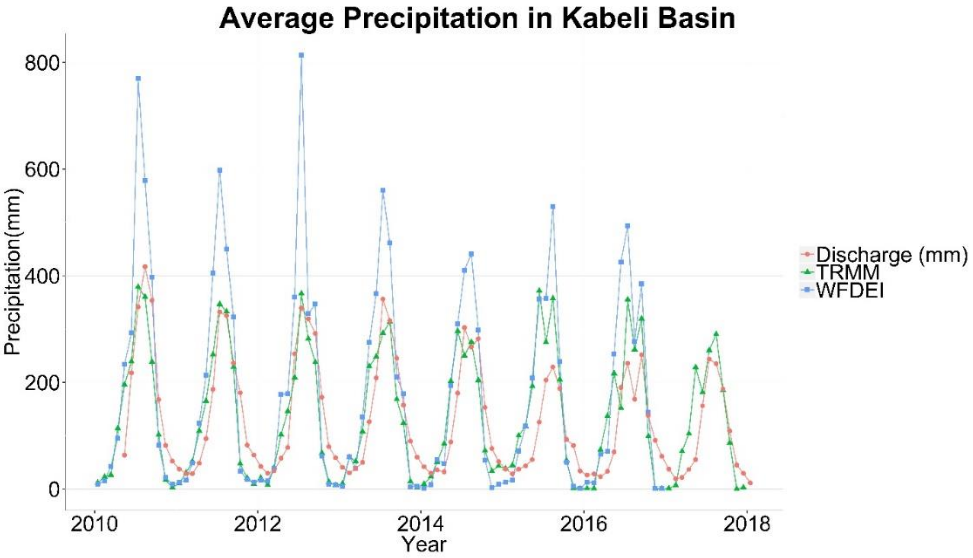


Figure 3-8 Monthly precipitation in Kabeli Basin

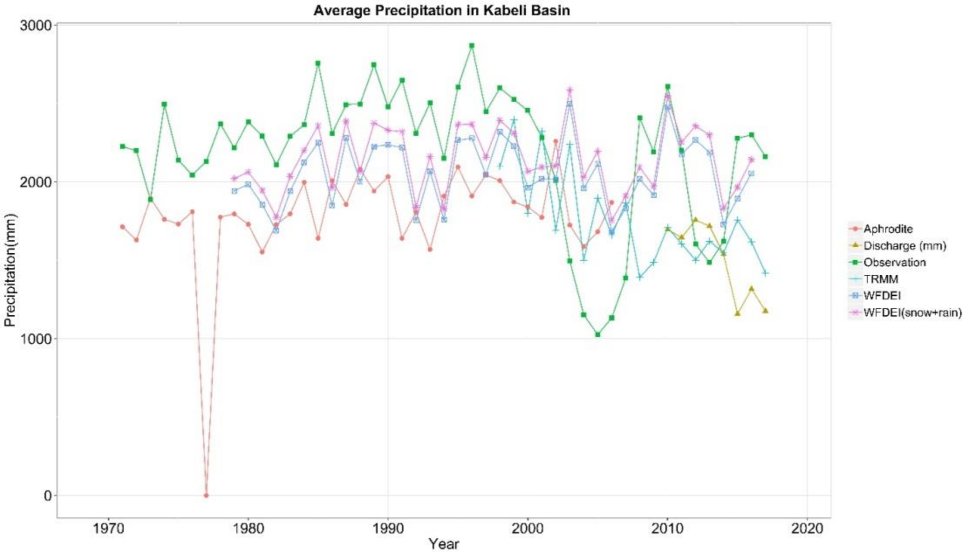


Figure 3-9 Basin Average Precipitation from different sources

The temperature data for the hydrologic model will also be used from the WFDEI dataset. A correlation plot of WFDEI temperature with ground observation is presented in Figure 3-10.

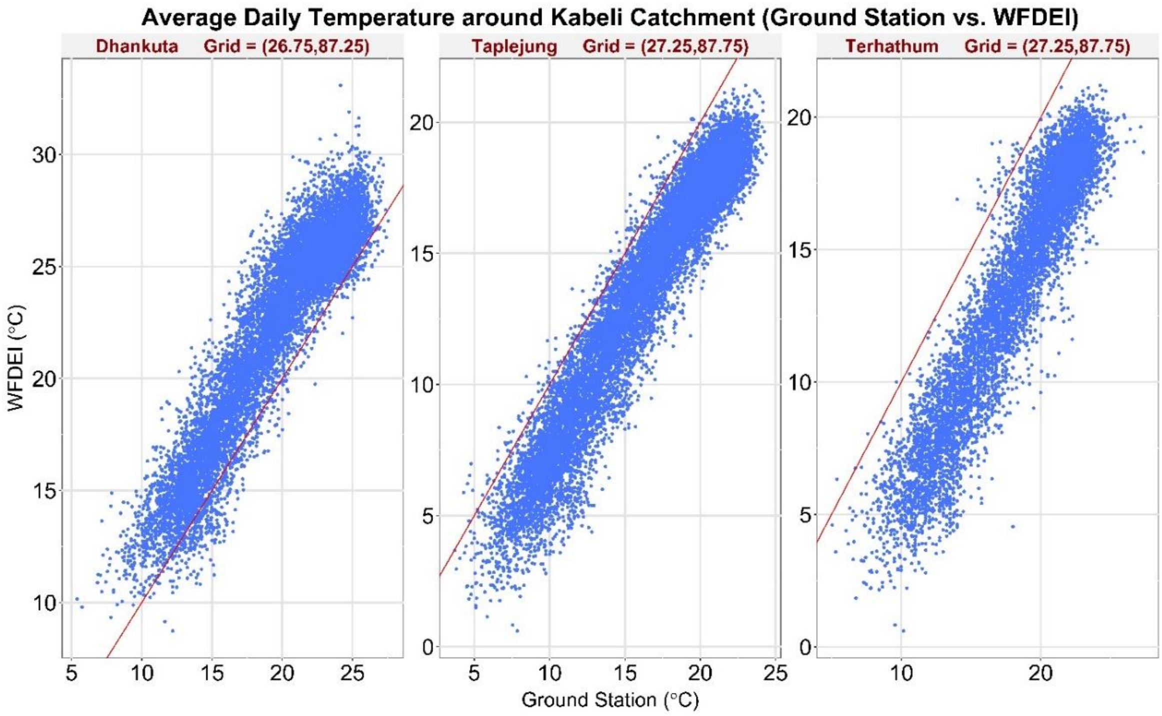


Figure 3-10 Correlation plot for average daily temperature of Kabeli Catchment (WFDEI dataset vs Ground Station). Three stations are shown within the same WFDEI grid cell.

The resolution of the WFDEI data is 0.5x0.5 degrees. The experts at Future Water have used this data before for their analysis. The data is resampled to a smaller grid size using interpolation techniques for precipitation. The temperature data is corrected by applying the lapse rate based on the elevation information from DEM file and resampled to finer resolution for Kabeli Basin.

The streamflow observation is available at the intake of the hydropower from 2010-5-15 to 2018-1-14. Thus, the hydrologic model is to be built using WFDEI data, and local streamflow gauge data. The limiting factor on the front end is the stream gauge (begins 2010-5-15) and the limiting factor on the back end is the WFDEI data (ends 2016-12-31). **We therefore have calibrated the hydrologic model from 2010-5-15 to 2013-12-31, and validated it from 2014-1-1 to 2016-12-31** using the HBV model.

3.1.3 Projections of Future Climate

In order to assess the possible future impacts of the climate change on climatic variables in Kabeli Basin, in this section, the changes in annual and monthly precipitation and temperature are projected for the upcoming years using the CMIP5 model.

Figure 3-11 and Figure 3-12 present boxplots of monthly precipitation/temperature change from the ensemble of CMIP5 GCM projections for Kabeli Basin (change in average annual precipitation/temperature in 2036-2065 relative to 1950-2000).

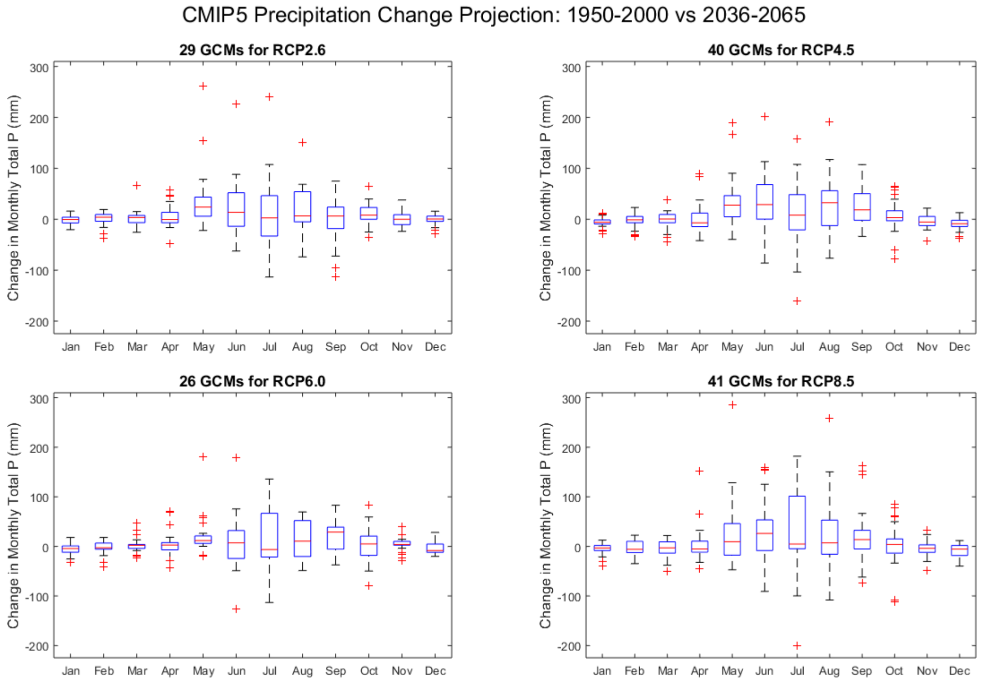


Figure 3-11 Boxplots of monthly precipitation change from Ensemble of CMIP5 GCM projections for Kabeli Basin (change in average annual precipitation in 2036-2065 relative to 1950-2000).

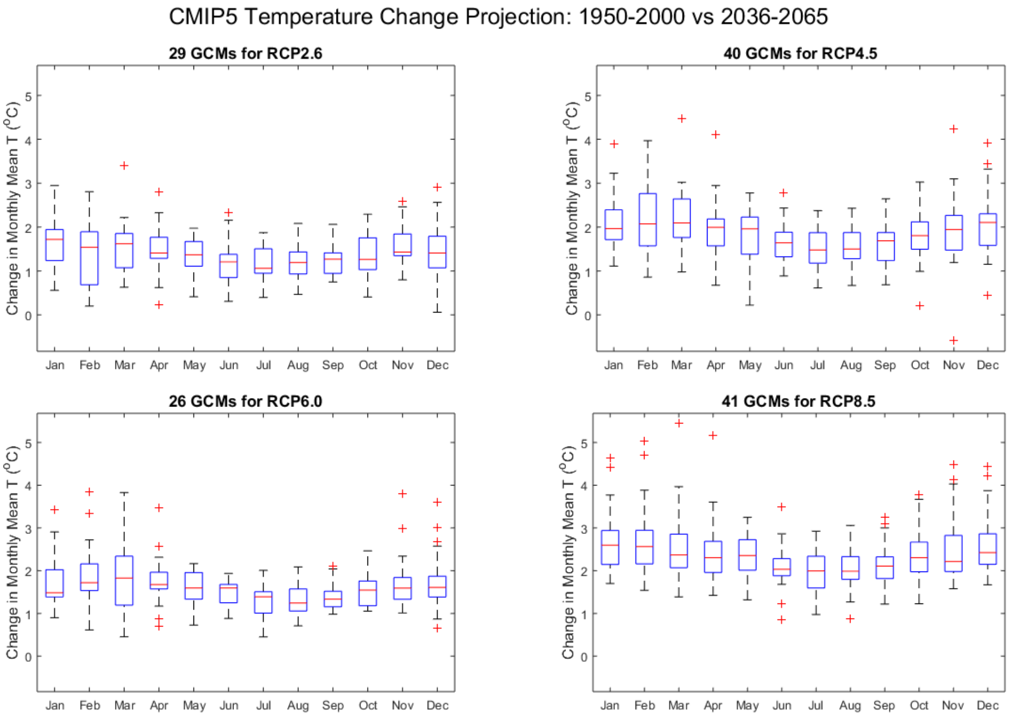


Figure 3-12 Boxplots of monthly temperature change from Ensemble of CMIP5 GCM projections for Kabeli Basin (change in average annual temperature in 2036-2065 relative to 1950-2000).

From Figure 3-13 it is seen that the GCMs agree that the future is likely to be warmer with a general agreement that the mean precipitation in the basin is likely to be within +/-20% of the current observation

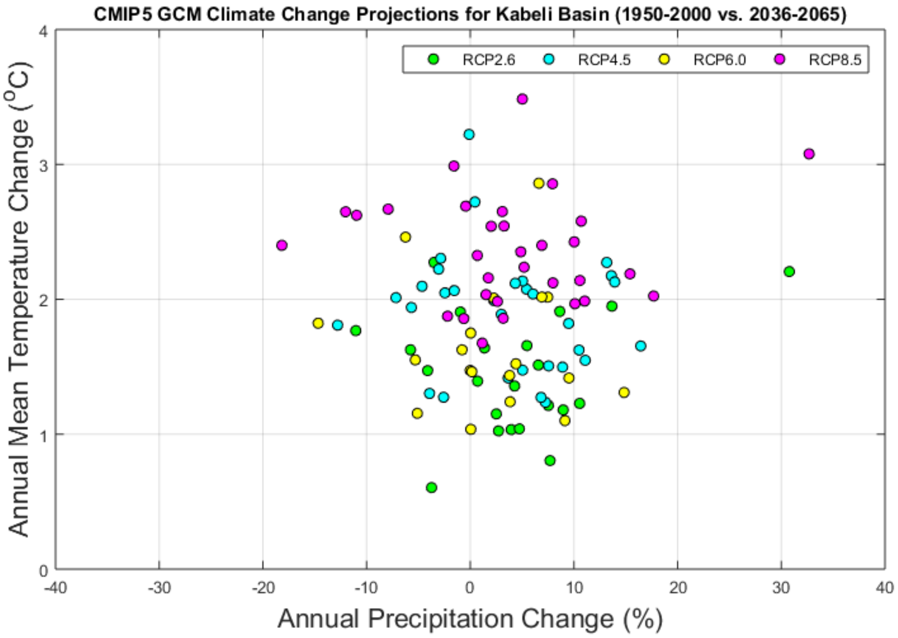


Figure 3-13 Ensemble of CMIP5 GCM projections for Kabeli Basin (change in average annual precipitation and temperature in 2036-2065 relative to 1950-2000)

3.1.4 Sediment Data

Sediment can cause a reduction in the efficiency of hydropower production due to abrasion of turbine components and capacity loss of storage/intake ponds due to accumulation over time (Wild et al., 2015). The issues during operation are largely due to suspended sediments, especially in Himalayan River like Kabeli which is associated with high incidence of landslides in the catchment. Studies from other parts of the Tamor Basin and the bigger Koshi Basin in Nepal have identified sediment to be one of the main issues in Hydropower Operation.

The amount of sediment carried by the river is termed “sediment yield”, and is generally expressed in tons of sediment per year. Although the sediment carried by the river consists of wash load, suspended load and bed load, the sediment yield estimate is used as a measure of the amount of suspended sediment, mostly because of the difficulty in measuring the bed load. The wash load consists of very fine particles like clay and silt carried in suspension in the river, and the bed load consists of coarser sediment particles that move either by rolling, sliding or hopping along the river bed. The bed load is taken to be between 5-25 percent of the suspended sediment load (Annandale et al. 2016). In a RoR project, the bed load is flushed and the suspended sediment is the one that interferes with the operation of the hydropower project. The suspended sediment concentration is associated with turbine abrasion (Bajracharya et al. 2008), reduction in unit efficiency and production loss (Padhy and Saini 2008). In this report, we only consider the suspended sediment.

Despite being a small Hydroelectric Project, KEL has put a great effort for sediment studies in the river for the project. Suspended sediment was measured in the river in 2011 for one year, and a physical hydraulic model was constructed in 2012 in order to verify that the headworks (intake, weir, flushing system, and related components) are sized correctly, and oriented properly to channel sediment downstream. The design of the KEL facility was responsive to the findings of the physical modeling exercise.

In parallel, a numerical model was developed by Mool et al. (2017), who coupled the Delft3D morphological model with hydrodynamic gate operation in order to evaluate the potential benefit of real-time control over river sediment during peaking hours.

KEL conducted additional sediment sampling to measure the suspended sediment in the Kabeli River years 2010-2016, and have made their findings available. The sampling location is situated 150 meters downstream of the gauging station at the left bank of the river. Sediment concentration, particle size distribution (PSD, Figure 3-14), mineral content, calculated suspended sediment load and organic content were estimated for the data collected. During the sampling period, maximum concentration of the suspended sediment was observed to be 7,767 parts per million (ppm) during high flow. It was observed that 72% of the samples contained sediment concentration below 100 ppm, which are difficult to settle in the settling basin. The total suspended sediment load passing through the sampling location during this period was computed to be 0.34 million tons. It was observed that 67 percent of suspended sediment consisted of hard minerals like Quartz, Feldspar, Tourmaline, Horneblende, Garnet and Kyanite (based on observations during the sampling period). These are above five in Moh's hardness scale (as hard as or harder than steel), and are responsible for reduction of the efficiency and the expected life of turbines as well as hydraulic structures of power plant.

In this report, loss of revenue due to unscheduled down-time, and cost of repair-maintenance can be a financial risk to the investor. The impact on system performance was evaluated across a range of scenarios of sediment concentration and characteristics. The scenarios account for possible future variations in sediment load, concentration and quartz percentage, as well as to account for possible risks due to landslide or sudden, unexpected sediment load. This evaluation is included in plans for the multidimensional stress test, Task 4.

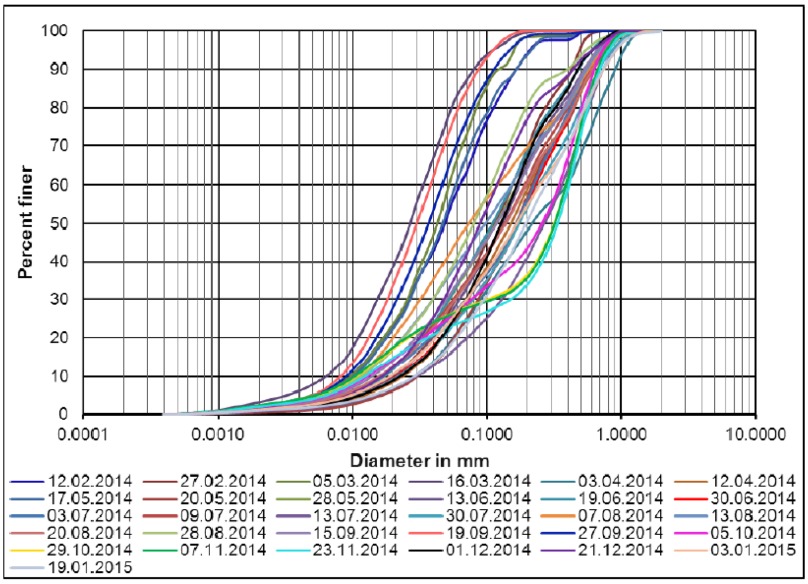


Figure 3-14 Compiled particle size distribution curves of suspended sediment samples collected from February 11, 2014 - January 31, 2015 (From the sediment report provided by KEL)

3.1.5 Groundwater Data

Unfortunately, there is no monitoring of the groundwater in the project basin.

The groundwater contribution in the area for base flow shall be analysed using a combination of literature review, expert elicitation, and hydrologic modeling (streamflow partitioning) throughout subsequent project phases.

3.2 Socioeconomic Data

The Kabeli Catchment lies partly in Panchthar District and partly in Taplejung District. The population of Taplejung district is 127,461 and the literacy rate[3] is 71 percent. For Panchthar district, the population is 191,817 with a literacy rate of 72 percent. Agriculture is the main occupation of people in both the districts. Reports on Cummulative Impact Assessment, Social Assessment, Environmental Impact Assessment, Social Action Plan, Ecological Flow, Design Documents have been provided to the Consultant that sets up the background of the project and supplements the first-hand information collected by the Consultant. The following paragraphs in this report are extracted from study of the reports mentioned above.

Although there are several touristic places in the basin, it is visited by only a fraction of the tourists that visit Nepal due to lack of adequate infrastructure. The majority of area has no industry. There are only limited manufacturing industries that are based on agriculture and forestry in the Basin confined to the urban centers. The Agriculture Perspective Plan (1995) has identified the Hills and Mountain region like the Kabeli catchment as ecological belts for potential horticultural development. Thus, with development of roads and other infrastructures in future, there is a possibility of promotion of ecotourism in Kabeli basin in the future.

Diversion of the Kabeli River (see Figure 2-1) is expected to have effects on riverine fish resources of the Kabeli for nearly 5.6 kilometers downstream of the intake from November through June (dry season). Fishing market is not well developed in this region and people living with primary occupation as fishing have not been identified in the basin. Communities living close to the river usually go for recreational fishing when they are free from the agricultural works. There is no threat to fish resources during the wet season. The reduction of river flow during the dry season might have some impact on the fish life, however the impact is expected to be small.

There are three cremation sites (Kholakharka cremation site, Kabeli cremation site and Sirupa cremation site) located at the dewater stretch. Out of these three, the Kabeli cremation site is one of the most common sites in the dewater stretch located about 2.5 km downstream at Kabeli Bazzar. People from surrounding VDCs also bring dead bodies to cremate at this site. Thus, the altered low river flow will affect the cremation site affecting the cultural practices of the people of the downstream villages. Since the cremation ceremony might need to be performed at any time of the year (even during the low flow period), this might be a serious issue.

3.3 Other Relevant Data

3.3.1 Electricity Prices

The agreed electricity-selling rate is the same throughout the year at the rate of $0.062985/KWhr. A 3% simple escalation per annum for 8 years as commonly used for Power Purchase Agreement (PPA) for Run-of-River (ROR) projects authorized by Nepal Electricity Authority (NEA).

---

[3] *A person above five years of age who can both read and write in any language is defined as a 'literate' according National Population and Housing Census 2011 issued by Central Bureau of Statistics in Nepal.*

3.4 Water Consumption Data

Data on the actual amount of water used by people from the river has not so far been available for this analysis. It is known that it is mandatory that 10% of the minimum monthly flow (each year) in the river should be left out for environmental flow, and that a minimum depth be maintained downstream of the project site for ceremonial purposes during funeral activities. Based on the review of the Environmental Impact Assessment report, 10% of minimum monthly flow (each year) was recommended to the project to fulfil the downstream water requirement for flora and fauna. The recommendation has been further validated by Ecological Flow Report that confirmed that the proposed 10% minimum release is appropriate considering fish diversity, composition and size of the captured fish.

4 Phase 2 of Decision Tree Framework

In this phase of the decision tree framework, an initial analysis was carried out to build a first-order approximate model for the system. For this, a correlation plot was developed between the total precipitation and average streamflow at a monthly time step (see Figure 4-1). The figure shows a fairly linear relatioship between precipitation and streamflow. It is to be noted that this linear relationship is taken only to explain the positive correlation between precipitation and streamflow and it should not be considered as a representation of the hydrologic model.

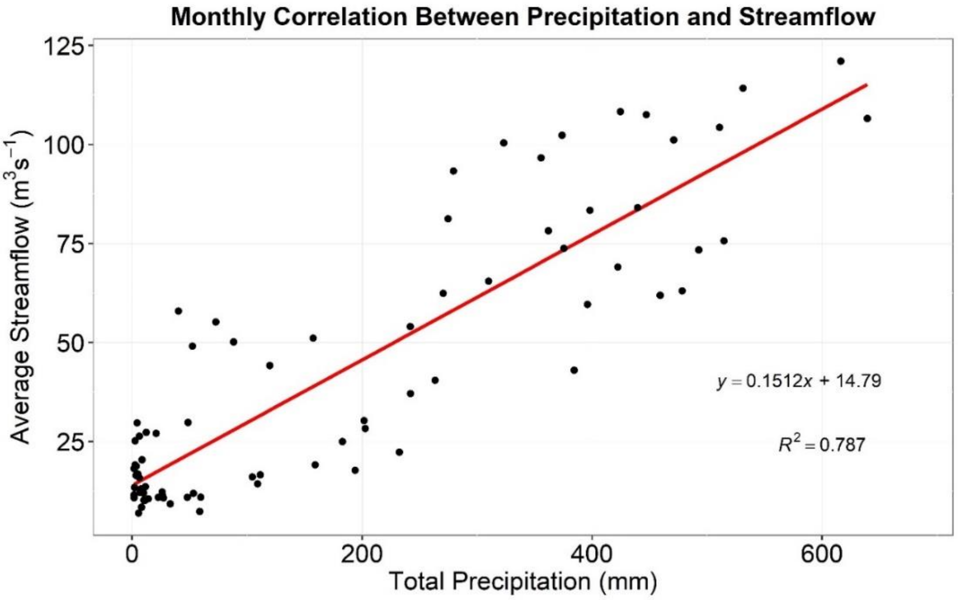


Figure 4-1 Correlation plot between total monthly precipitation and mean monthly streamflow in Kabeli River

It was identified in Phase 1 of the project that there was no glacier in the project area but the project location would receive some snow fall during winter months. Snow melt contributes to the streamflow in the Kabeli River, and is identified as being sensitive to changes in temperature.

The Kabeli Hydroelectric Project is designed with Q_{40} as design discharge. The streamflow exceedance probability for the gaging station established near the intake of the Hydroelectric project is presented in Figure 4-2. To generate the plot, average daily streamflow observations were ranked in ascending order (y-axis) and assigned an empirical rank-order probability with Weibull Plotting position (x-axis). From the plot, Q_{40} was calcuated to be 37.62 $m^3 s^{-1}$, which was very close to the design discharge of 37.73 $m^3 s^{-1}$ in the design documents.

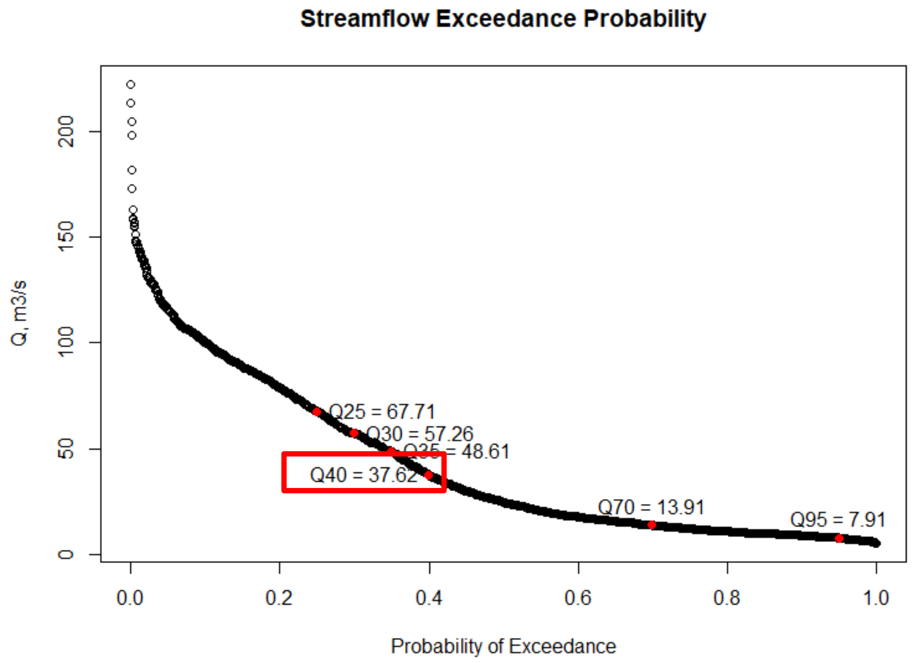


Figure 4-2 Streamflow Exceedance Probability Plot for gauging station at intake of Kabeli River (May 2010 – Jan 2018)

The energy production from the streamflow was calculated using the equation:

$$Power\ Generation\ \frac{GWhr}{day} = 0.002725 * \eta * Q\ \left[\frac{MCM}{day}\right].H[m]$$

Equation 4-1

Where:
0.002725 = unit conversion factor
Q = discharge in MCM/day
H = head in meters (112.6 m net rated head)
η = efficiency of the powerplant (90%)

Equation 4-1 represents the potential energy of a mass of water falling freely under gravitational force. Details on the derivation of the formula can be found in (Loucks et al., 2005). The equation represents the uncapped potential energy generation, which would subsequently be limted by the capacity of the hydroelectric power plant under existing design. The GWhr production per day calculated from Equation 4-1 is presented in Figure 4-3. The horizontal red-line represents the maximum GWhr production per day under the existing Hydroelectric Project design of 37.6 MW. The area under both the black curve and the red line represents the total energy generated limited by the upper boundary on the maximum energy generation per day.

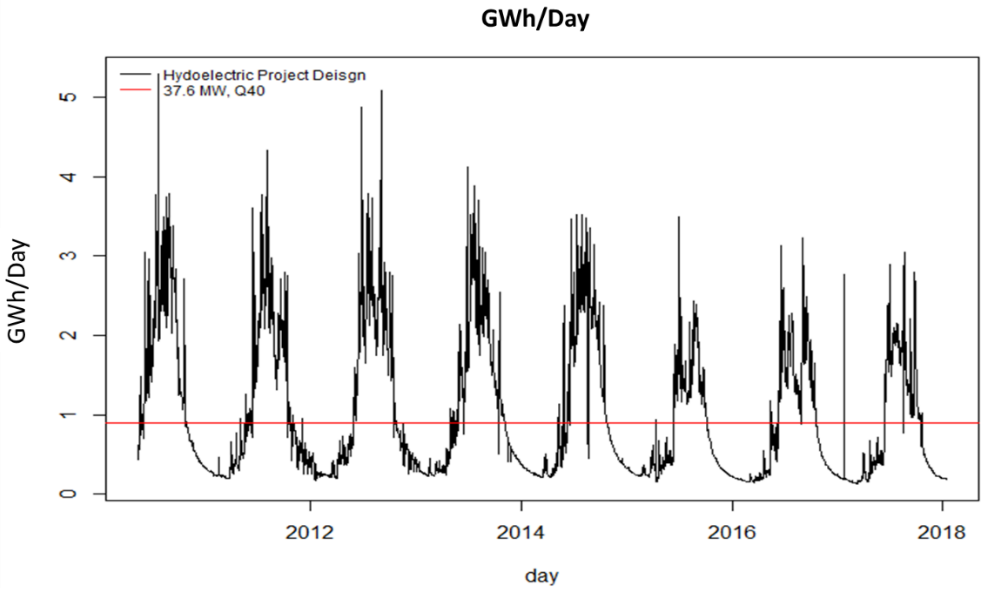


Figure 4-3 KAHEP, 37.6 MW RoR with a design discharge of Q_{40}, daily time series of GWh/day generation; the red-line represents the maximum GWh/day limited by the project design

The maximum GWhr production per day was taken into account while calculating the total annual power production from the hydropower. The calculated annual energy was found to be 210 GWh, which was within 3% of the 205.2 GWh identified in design documents.

Next, the sensitivity of annual power generation to changes in annual streamflow was analyzed and the result is presented in Figure 4-4. It is observed that the power production is highly sensitive to changes in streamflow. The correlation between percentage change in energy production and percentage change in streamflow is very strong, especially for the decrease in streamflow. It is observed that the sensitivity of the power generation decreases beyond an increase in streamflow by 20% which is probably because of the limit on the maximum GWhr production per day under the existing Hydroelectric Project design of 37.6 MW.

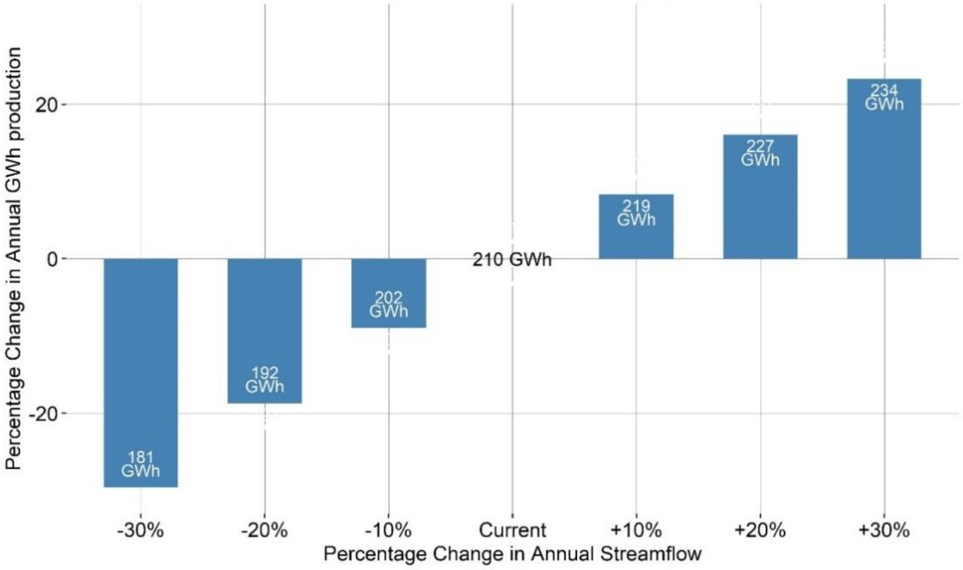


Figure 4-4 Sensitivity of Annual GWh Production with changes in annual streamflow in Kabeli Hydroelectric Project

Having identified a strong sensitivity of the hydropower production to streamflow and thus to climate, we now proceed to the next phase of the decision tree.

The Phase 2 procedure detailed in the International Hydropower Association's Climate Resilience Guide does not account for any non-climate risks. However, previous applications of the World Bank's Decision Tree Framework to hydropower projects in Nepal have accounted for non-climate risks in Phase 2. We therefore provide here a rapid review of potential impacts of uncertainty in non-climate factors.

1 Sediment Risks: Turbine abrasion due to suspended load was identified as one of the biggest concerns to KEL during the Inception meeting. KEL has collected and analysed 5 years of sediment samples. The analysis presented in Phase 3 of this report explores the sensitivity of the project performance to sediment changes in response to climate condition, and presents the associated loss in NPV.

2 Upstream or downstream changes to socio-economic conditions manifested in competetion for limited water resources: The basin is located in the eastern hills of Nepal. Based on the Socio-Economic Report and the Social Action Plan Report, no immediate growth of population or economy in the region is expected. Current uses of the Kabeli River for drinking water, religious ceremony, and recreational fishing are modeled in this work as constant. Risks of increases in those activities are not considered.

3 Electricity costs: The base rate of electricity-selling rate is the same throughout the year at $0.062985/KWhr for the project, though there is uncertainty regarding prices in the future. In this analysis, the sensitivity of the NPV to changes in the selling rate within a range of 0.5 to 2 times the baseline rate is analysed.

4 Capital costs: The initial cost of the project is reported as 70.84 Million US$ in the Environmental Impact Assessment Study, 2013, and US$102.6 million in the Sustainabiltiy Assessment Report, 2014.

5 During the Inception workshop, it was decided to evaluate the risk that the captial costs might increase by up to 3 times the original estimate. The sensitivity of NPV to this change is assessed in this report.

6 For seismic risk, to the best of the knoweledge of the consultants, no hydropower facility built in Nepal in the last 50 years has yet been destroyed by a seismic event. However, earthquakes and landslides have damaged (and temporarily taken off-line) hydropower facilities in Nepal (see for example Sun Koshi). The eastern Nepali Himalayan region is sesimically active with risk of catastrophic earthquake during the lifetime of the planned project (Bollinger et al., 2014). We therefore consider the possibility that the Kabeli A project could fail due to earthquake within the next 30 years, but model that failure as a low-probability event.

5 Phase 3 of Decision Tree Framework

Based upon the results of the Phase 2 analysis (see Figure 4-4), Phase 3 is entered. Given the reasonably high quality of data available, and the interest of the stakeholders in a thorough stress test, a comprehensive version of the CRG Phase 3 stress test is developed here. The performance metrics of concern to KEL are: 1) low (insufficient in the long term) flow (resulting in low financial performance); 2) high (flood) flow (resulting in damage to the structure, and potentially putting at risk the safety of those downstream); 3) sediment load greater than that for which the project was designed.

This section follows Figure 2-4, and is organized as follows: 1) development of the stochastic weather generator; 2) calibration of the hydrologic model; 3) description of the stress test for low flow (and financial) concerns, in which the stochastic climate traces are run through the calibrated hydrologic model; 4) flood risk assessment, in which historical trends on peak streamflow are evaluated and compared to projected changes to peak precipitation in order to develop expectations of change; 5) sediment load assessment, in which sediment loads are increased in proportion to long term average streamflow changes from step 3; 6) a multidimensional stress test (parallel coordinates plot) is presented.

5.1 Stochastic Weather Generator

Weather generators represent not only statistical properties of the local daily climate observations, but also the longer term (inter annual) cyclic behaviour of precipitation, as influenced by the El Niño Southern Oscillation (ENSO) or other relevant large-scale climate drivers.

To identify the existence of these cycles, their period and length, a wavelet decomposition can help. A wavelet decomposition was carried out on the vector of historical annual basin-total precipitation time series to see if there are any significant inter-annual periodicities in the climate data. No such signal was detected (refer Figure 5-1) in the climate data – the black line does not cross the dashed red 90% confidence level line on the right-hand figure. A stochastic weather generator was used to generate a daily time series of climate data (precipitation, maximum temperature, minimum temperature and mean temperature) with similar characteristics as the original time series. The WFDEI climate Data (1950-2016) was reshuffled by preserving the intra-annual and inter-annual variability to generate 50 years of synthetic data. A combination of ARMA model with KNN resampling on daily and annual values was used to generate the synthetic data. The details of the procedure followed can be found in Steinschneider and Brown (2013).

The only modification to the process presented in Steinschneider and Brown (2013) was that the lower bound for the dry state of precipitation was taken as the value corresponding to the 10th percentile rather than 0.3 mm, which was deemed to be too restrictive in the Kabeli case. Thirty traces of such synthetic data were generated and the statistical properties of the generated data was compared to the original data.

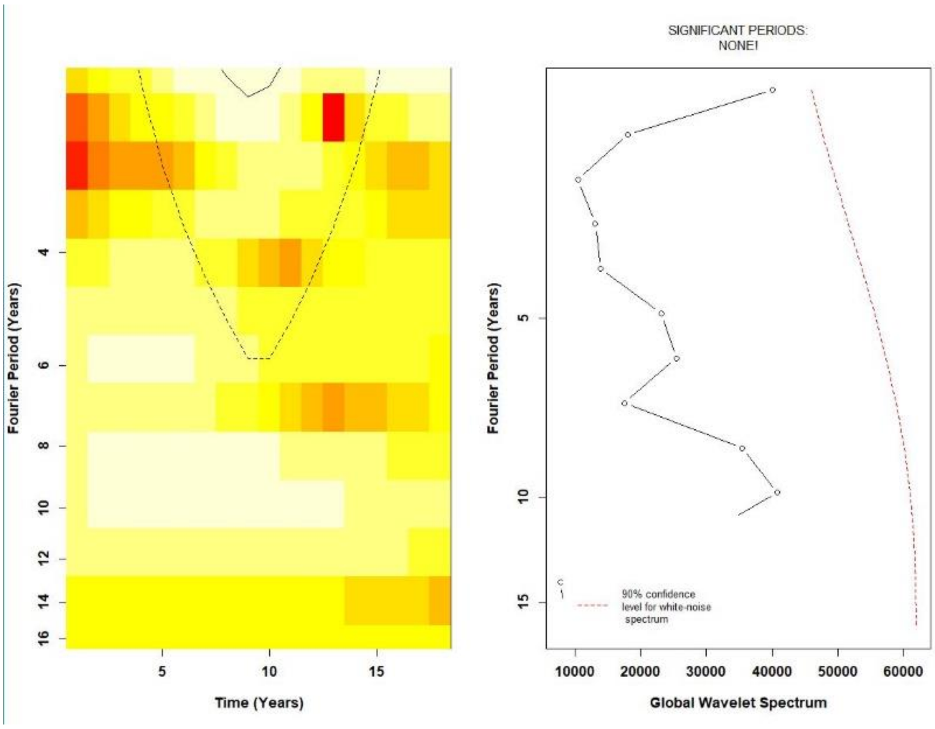


Figure 5-1 Spectrum Analysis of the Climate Variables in the Kabeli Hydroelectric Project

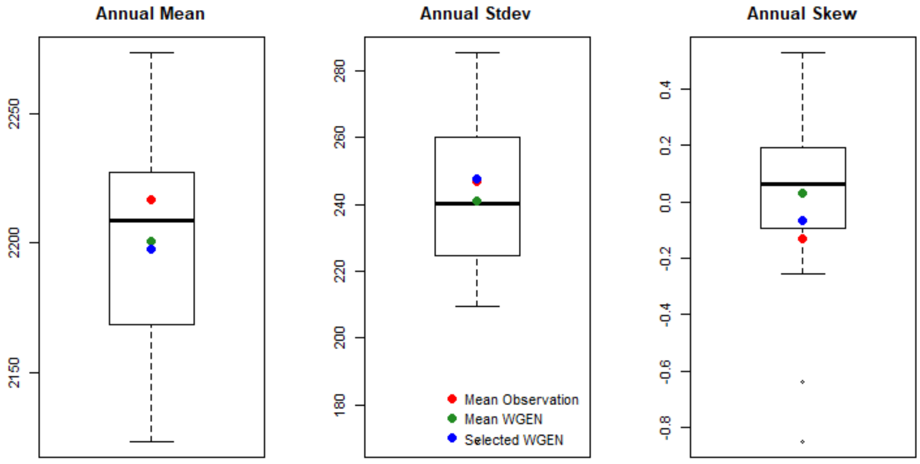


Figure 5-2 Statistical properties (mean, standard deviation and skew) of average annual precipitation values. The red and the green represents the average of observed precipitation, Weather Generator Stochastic trace respectively. The blue dot represents an example trace used in the analysis.

The mean, standard deviation and the skew of the outputs of the stochastic weather generator for precipitation are presented in the boxplots in Figure 5-2 (n = 30).

The red dot represents the annual average of basin-averaged observed precipitation. The green dot represents the annual basin-averaged precipitation averaged over all the traces.

The blue dot on the figure indicates an example, “representative”, climate trace. The stress test was not conducted using only the “representative” trace, but rather all 30 traces, with results presented on climate response surfaces for the average of the 30 results.

5.2 Hydrologic Model Calibration

Originally, the SPHY model was used as the hydrologic model for this analysis. The description of the model can be found in Task 2 – Development of a glacio-hydrologic distributed model and water resources system model earlier in the report. However, the SPHY model was limited in a number of ways that created problems during the stress test analysis. Model calibration was difficult because it does not include a module for parameter optimization to improve model performance. Secondly, and most importantly, the computation time and resources required of the raster-based model was prohibitively large. We therefore switched to the HBV model, Hydrologiska Byråns Vattenbalansavdelning. The model is run at a daily time step in the basin with the WFDEI dataset for the basin. The model was chosen because of its flexibility, low computational cost, and successful application under different climatic and physiographic conditions (e.g., Beck et al. 2017; Plesca et al., 2012; Te Linde et al. 2008).

The HBV model consists of 23 parameters from all the sub-routines of snow melt, evaporation, runoff estimation, soil moisture accounting and routing. For model calibration of the Kabeli basin, the parameters are simultaneously optimized using a genetic algorithm in the MATLAB programming environment. The genetic algorithm (GA) introduced by Wang (1991) is used as an optimization method for model parameter calibration. The optimization algorithm is used to maximize the Nash–Sutcliffe Efficiency (NSE) (Nash and Sutcliff, 1970) of the model. The NSE is by far the most utilized performance metric in hydrological model applications (Biondi et al., 2012). A lumped HBV model was used to model the basin. The NSE value of the calibration period was 0.8, and that of the validation period was 0.72. The NSE values above 0.7 are generally considered to indicate a well performing hydrologic model.

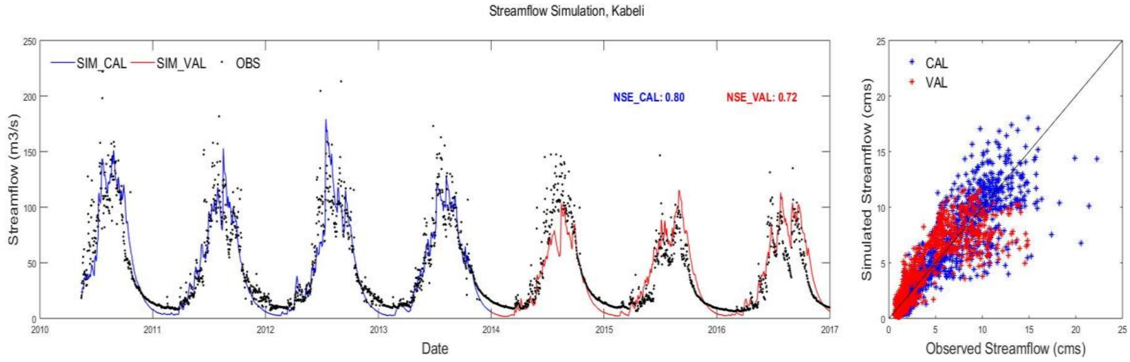


Figure 5-3 Calibration and Validation of HBV model

The parameters and their optimized value for the calibration of the HBV model are presented in Table 5-1. The parameter values were numerically optimized within the parameter bounds set to represent a Himalayan basin with similar topography, land use pattern, soil type and other basin characteristics. These parameters of the hydrologic model help in calibrating the model to represent the topography and other basin characteristics.

Table 5-1 Calibration Parameters and Values for HBV Model

Module	**Parameter**	**Description**	**Value**	**Unit**
Snow 17	SCF	Precipitation adjustment factor		
	PXTEMP	Temperature for separation of snow and rainfall	1.01	^{0}C
	MFMAX	Maximum melt factor during non-rain period	4.08	
	MFMIN	Minimum melt factor during non-rain period	1.44	
	UADJ	Wind function during rain-on-snow period	0.12	
	MBASE	Base temperature for snowmelt computation during non-rain period	0.20	
	TIPM	Antecedent temperature index parameter	0.58	
	PLWHC	Percentage liquid holding capacity (maximum)	0.30	%
	NMF	Negative melt factor (maximum)	0.27	
	DAYGM	Daily melt rate at snow-soil interface	0.20	
	TTI	Temperature interval for mixture of snow and rain.	0.17	
Soil Moisture Accounting	FC	Maximum storage capacity of soil moisture accounting tank	880.40	
	Beta	Shape parameter for effective precipitation calculation	1.37	
	PWP	Permanent wilting point of soil	0.64	
	L	Water level in the upper reservoir for the fastest flow occurrence	30.03	
	Ks	Near surface flow storage coefficient	0.04	
	Ki	Interflow storage coefficient	0.06	
	Kb	Baseflow storage coefficient	0.03	
	Kperc	Percolation storage coefficient	0.28	
Routing Lohmann	N	Catchment's UH shape parameter (N)	15.72	
	K	Catchment's UH scale parameter (K)	0.85	
	Velo	Wave velocity in the linearized Saint-Venant's equation	3.15	m/s
	Diff	Diffusivity in the linearized Saint-Venant's equation	2605.48	m^2/s

Parameter estimation uncertainty
A lumped version of the conceptual HBV hydrologic model was chosen for the climate change risk assessment of KAHEP due to its: a) fast run speed, b) module compatibility for parameter optimization, which lets the user choose from a range of parameters the best combination for a better model performance.

The model consists of 4 distinct modules with interactions that capture the rainfall-runoff process; viz. a) snow module consisted of 11 parameters of the Snow 17 model which controls the snow melt temperature, daily melt factors, degree day factors etc.; b) the soil moisture accounting module consists of 8 parameters that represents the baseflow (interflow, near-surface, deep surface flow etc.) and infiltration of water into the groundwater storage; c) Lohman Routing module consists of 4 parameters for the linearity wave velocity and diffusion coefficients. These parameters are values selected from a range suitable for catchment with similar geographical and climatic characteristics. The inputs to the model include a 30 m DEM model, the meteorological data (precipitation, maximum temperature, minimum temperature, and average temperature) at a daily time step.The model is calibrated with a daily time series of streamflow at the outlet point, which collects water from the catchment.

The use of a number of parameters for calibration with a single time series raises the question of uncertainty in the model and the risk of model over-fitting. Not all of the parameters listed in Table 5-1, are equally certain. We have higher confidence in our estimates of the snow parameters such as snow-rainfall separation temperature, maximum and minimum melt factor during the non-rain period, wind function during rain-on-snow period and daily melt rate at snow-soil interface as similar parameter values was observed in the Himalayan hydrology based on the past experience of the consultant. However, we have lower confidence in our estimates of the soil moisture related parameters, as we do not have sufficient data to verify the parameter estimates.

While the use of HBV model with 23 parameters adds uncertainty in the modelling chain, so would the use of more parsimonious hydrologic models, as such models would likely require substantial distribution (e.g., small grid scales) in order to achieve calibration fits nearly as good as the NSE values obtained by the HBV model. The use of conceptual model limits in compared to a fully-distributed hydrologic model, for the catchment such as that of KAHEP where we only have a daily time series of the streamflow at the outlet to calibrate the model.

5.3 Stress Test on Long Term Average Hydropower System Performance

The next step was the application of perturbations (direct delta shifts) to all values of the precipitation and temperature time series. The extent of the perturbation is informed by the projected changes in the future climate by the GCMs. The GCMs are used only to inform the ranges of possible future climate, and not for the climate data itself (unlike the top-down approaches which downscale GCM output for direct use in the modelling chain). The future projections were summarized in Figure 3-13 in the Inception Report. A change of -40% to +40% with an increment of 10% each was applied to the daily precipitation time series. A change of warming by 0^oC to 6^oC with an increment of 1 ^oC was applied to the daily temperature time series.

Daily streamflow values were computed with the hydrologic model for each combination of perturbed precipitation and perturbed temperature. The hydrologic model was run for 50 years of simulated data for each combination as well. The average annual streamflow was calculated for each combination. The response of the streamflow to changes in the climate was analysed and the preliminary result is presented in Figure 5-4.

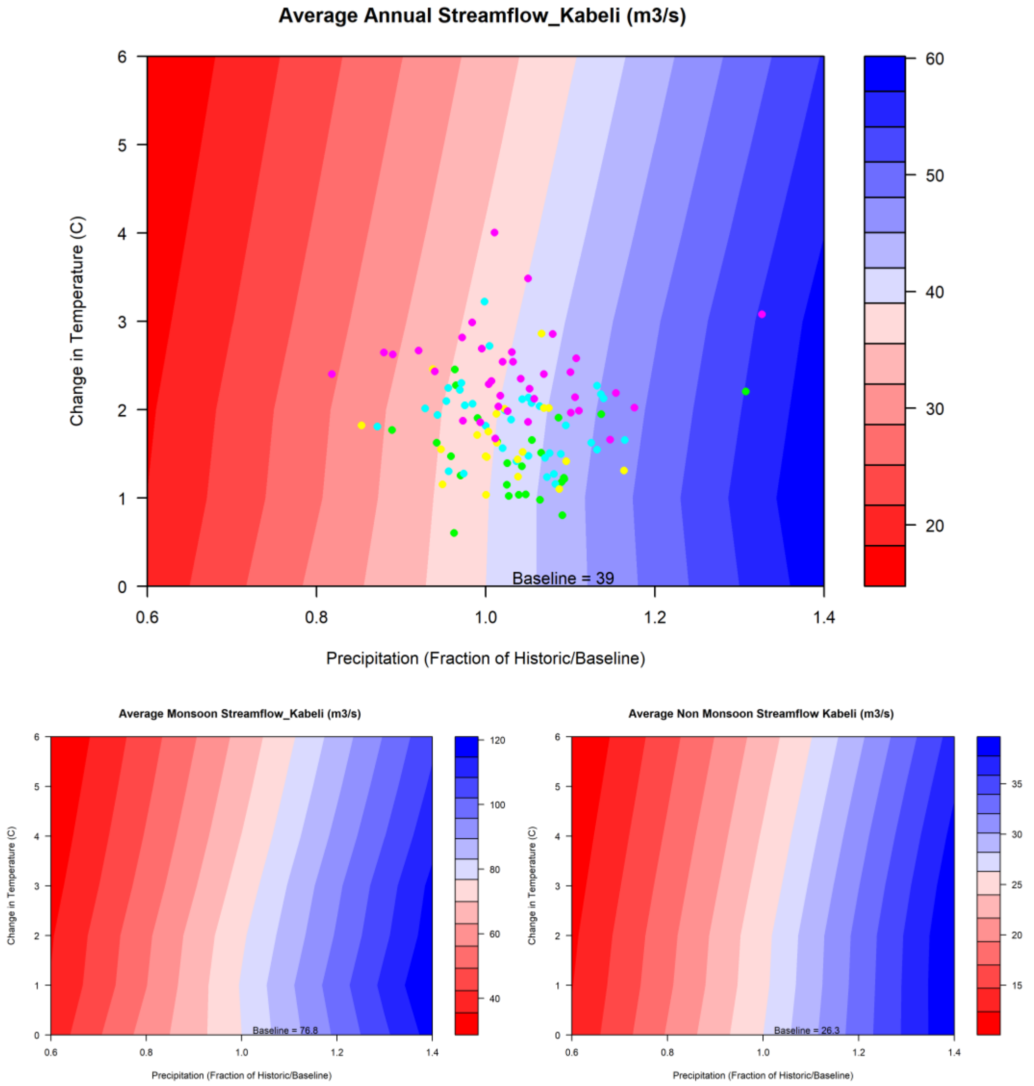


Figure 5-4 Streamflow Response Surface. The dots on the response surface represents the CMIP5 climate change projection (centered on year 2050). Green: RCP 2.6; Cyan: RCP 4.5; Yellow: RCP 6.0; Magenta: RCP 8.5.

It is noted that the monsoon season has been taken as June-August. Figure 5-5 shows the hydropower response surface for KAHEP. The figure shows changes in annual hydropower production on the range of +15% to -40% within the evaluated range of climate possibilities. Because of the nonlinear (capped) relationship between streamflow and hydropower production, reductions in streamflow in the monsoon season do not adversely affect hydropower production, but reductions in dry season streamflow do. Therefore, hydropower productivity is especially sensitive to changes in non-monsoon season flow. On an annual total basis, hydropower productivity is less sensitive to climate change than is total annual streamflow.

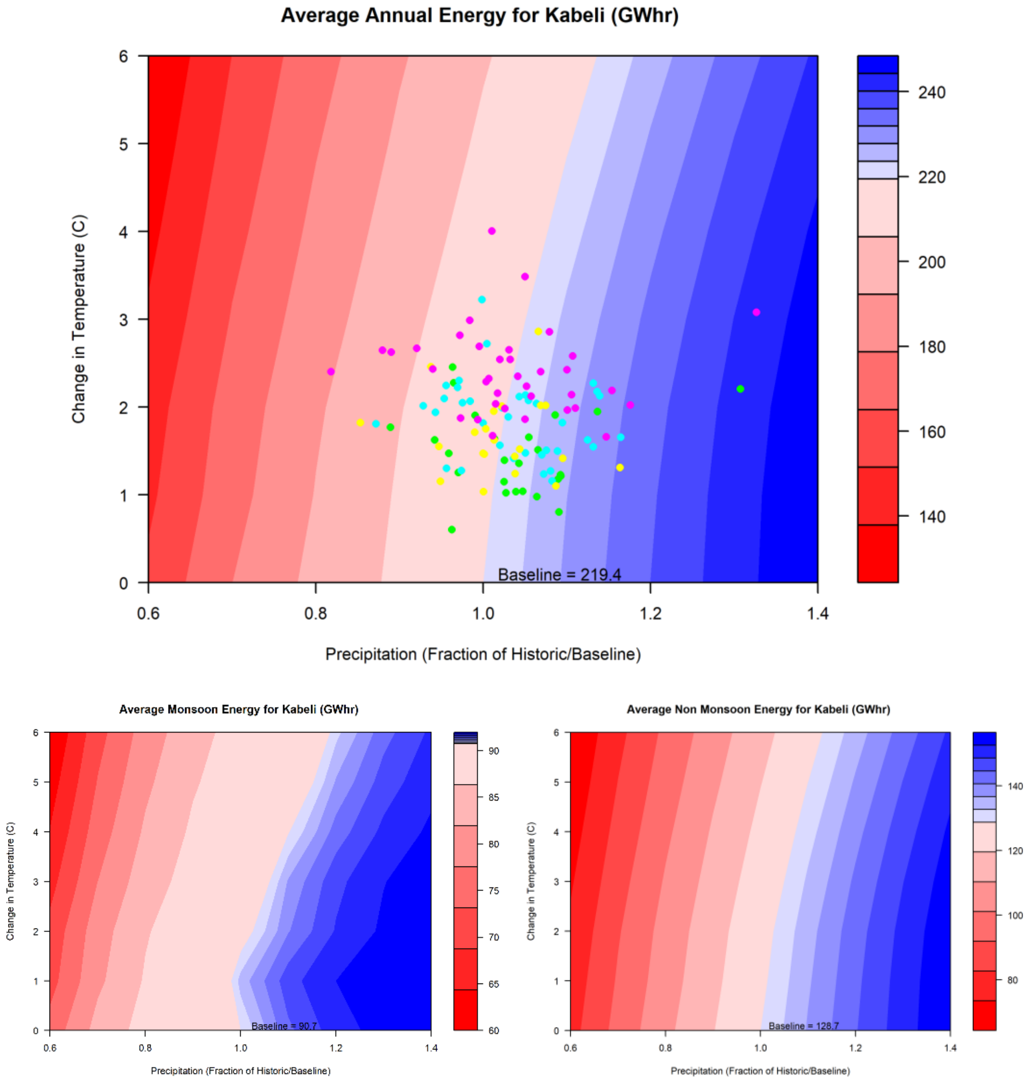


Figure 5-5 Hydropower response surface The dots on the response surface represents the CMIP5 climate change projection (centered on year 2050). Green: RCP 2.6; Cyan: RCP 4.5; Yellow: RCP 6.0; Magenta: RCP 8.5.

5.4 Financial Stress Test

The energy produced by the hydropower plant was translated to the financial terms with the evaluation of the Net Present Value of the project revenue. The NPV was calculated using equation at an annual time step.

$$Net\ Present\ Value\ (NPV) = \sum_{T=0}^{Project\ Life} Annual\ Cash\ Flow * \left(\frac{1}{1+Discount\ Rate}\right)^{T}$$

Equation 5-1

Where,

$$Annual\ Cash\ Flow = Energy\ Sold\ (KWhr) * \frac{0.062985\$}{KWhr} - Annual\ O\&M\ Costs$$

Equation 5-2

The NPV of the project estimated using equation 5-1 and equation 5-2 was found to be $18.1M. The NPV was calculated with the capital costs of $102.6M, the project life of 30 years, an annual discount rate of 10%, and the selling price of energy set at 0.062985 $/KWHr. The operation and maintenance cost was taken as $0.8M/year, which is about 3% of the capital cost per MW. The NPV reported by the design consultants (Hydropower Sustainability Assessment Report, 2014) was $22M. Thus, our estimates of the NPV of the project differ by about 18%. The discrepancy between the NPV reported by the design consultants and that calculated by the authors of this report was discussed with the KEL project team during the June 2019 2nd stakeholder workshop in Nepal. Upon discussion, KEL confirmed that the capital costs, discount rate, selling price, and, project lifetime were identical. The consultant was not provided with the exact OM costs used in the NPV estimation of the Hydropower Sustainability Assessment Report (2014), but KEL design team confirmed that the consultant's estimate was reasonable. We think that the following might be the reason for the underestimate of the NPV in our calculation:

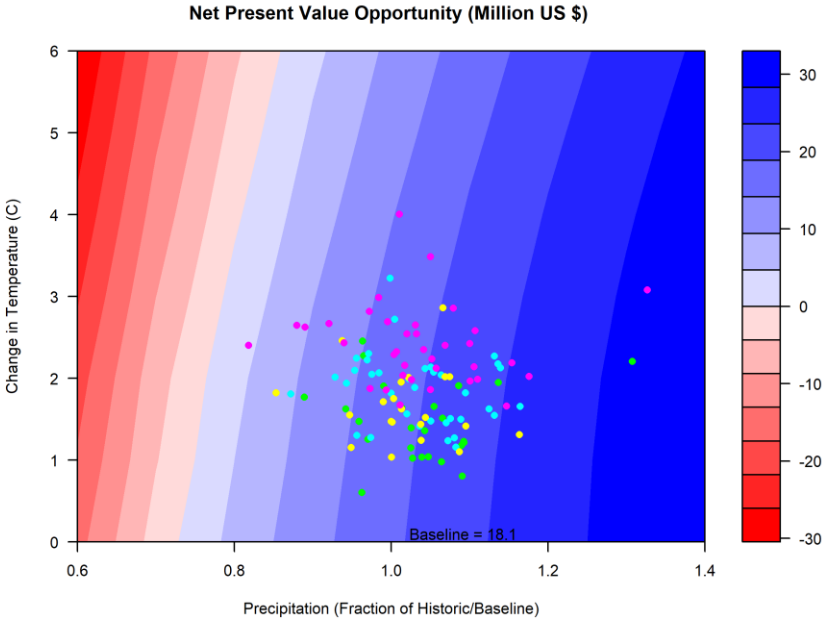
a. The possible difference in the operation and maintenance costs between the estimate adopted in this analysis and that used in the report (Hydropower Sustainability Assessment Report, 2014). The estimate adopted in the report was verified to be acceptable in the second mission to Nepal, although the same number might not have been used in the report. However, the overall contribution of OM costs to NPV is not very high, so this is not likely to be a significant cause of the discrepancy.
b. The operation of the power plant with 6-hour of peaking pond is not taken into account in this report. The peaking helps in energy generation during the dry season. The nuances of energy generation pattern within a 24-hour window should not make a very big difference in the daily cumulative energy. The overall impact of such pattern in annual energy generation and consequently the NPV is not substantial.
c. The significant source of discrepancy could arise from the streamflow simulations. The hydrologic model used in this report, underestimates the runoff during the dry season by as much as 18%. The difference (~20% less) in the NPV estimate in the report may be attributed to the hydrologic bias.

Separately, KEL recently (June 2019, during the 2nd mission to Nepal) provided us with a Power Purchase agreement with Nepal Electricity Authority (NEA), which sets a limit on the maximum energy that can be sold each month, with the total annual energy of 205.15 GWhr. The NEA does not buy the energy at peak performance of the powerplant, i.e., at full capacity for more than 6 hours each day. During the monsoon months, although the KAHEP can produce at full capacity 24 hours a day, KEL is only able to sell at full capacity, i.e., 37.22 MW power for six hours and less power, i.e., 35.24 MW during the rest of the day. This means that the production exceeds demand during the monsoon season. We further calculate that during some dry months, KAHEP cannot keep up with the demand of the Power Purchase Agreement. Our estimates show that, although KAHEP exceeds the annual energy demands of 205.15 GWhr, during monsoon there is excess unsold energy while in some dry months the PPA energy demand is unmet, limiting the saleable energy to about 190 GWhr per year. Thus, the opportunity NPV of 18 Million US$ (Figure 5-6 a), now drops to about 10.1 Million US$ (Figure 5-6 b). We acknowledge that the results are affected by the HBV model's underestimation of the dry season flow by the hydrologic model used. When we account for the bias in our hydrologic model, the estimate of $10.1M, can be expected to be about $12-13M US$.

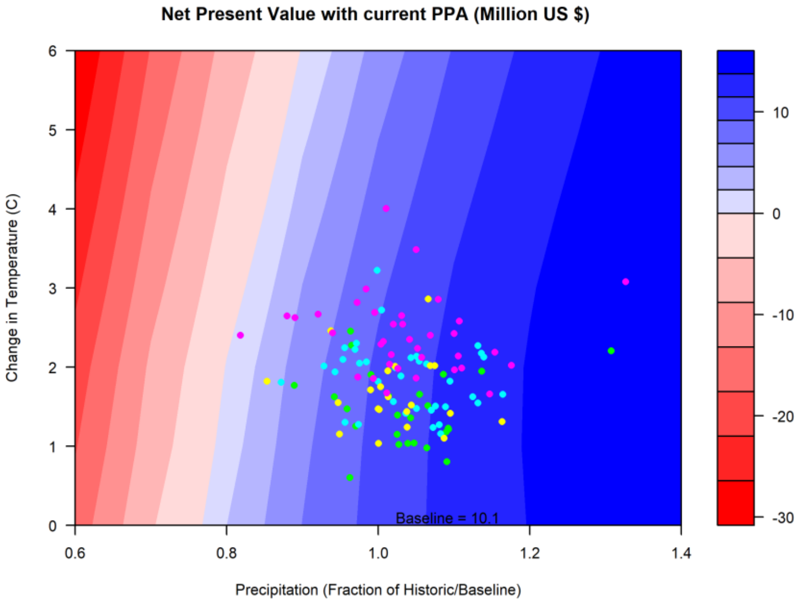
It is our understanding (though the Hydropower Sustainability Assessment Report (2014) report does not make this clear) that the KEL estimate of $22M NPV does not account for the limits on electricity sale imposed by the PPA. We therefore expect the $22M NPV to be substantially reduced, when the PPA is applied. Further discussion on the PPA and the contractual energy each month is continued in the following section

Impact of climate change on the NPV

The impact of climate change on the Net Present Value of the project is presented in Figure 5-6 a and b. Figure 5-6 a presents the opportunity NPV KEL could earn if they could sell all the energy they produce. Figure 5-6 b represents the NPV limited by the PPA. From Figure 5-6 b, the NPV of the evaluated climate scenarios ranged from approximately -$30M to $15M. Within the range encapsulated by the GCM projections, however, the NPV consistently exceeded $10M. The climate change associated with negative NPV is extreme, and based solely on shifts in average annual precipitation and temperature indicated by the CMIP5 ensemble of GCM runs, it is unlikely.



a)



b)

Figure 5-6 Net Present Value response surface. a) NPV for the saleable energy per year, b) NPV for the energy sold each year due to the maximum limit on the saleable energy per month with power purchase agreement. The dots on the response surface represents the CMIP5 climate change projection (centered on year 2050). Green: RCP 2.6; Cyan: RCP 4.5; Yellow: RCP 6.0; Magenta: RCP 8.5.

Conclusion to Financial Risk Assessment: It was observed that with the PPA, there can be a maximum limit on the annual saleable energy, which will reduce the NPV estimate of the project. The project is expected to be financially profitable (yield a positive Net Present Value) for all wetter future scenarios (approximately half of the uncertainty space), as well as drier futures, as long as the precipitation drop is less than approximately 20% and the temperature rise is not more than 3 ºC. Neither condition (precipitation drop greater than 20% or temperature increase greater than 3 ºC is likely within the next 30 years. A few GCMs under RCP 8.5 project potential futures for the project in which conditions skirt unfavorability, but generally the risk of flows insufficient to generate adequate financial returns appears low. It should be made clear that this analysis accounts only for shifts in average annual conditions. Shifts in extremes are evaluate in the flood risk section, but are not correlated to financial losses. Shifts in seasonality (or seasonal-specific results) were not closely evaluated, as the GCM outputs supporting the likelihood aspects of such evaluations are not of high confidence.

5.5 Flood Risk

Flood risk to the Kabeli Hydroelectric Project was analysed with respect to historical and GCM projections. Since the intake station at Kabeli Hydroelectric Project does not have a good record, the Tamor Mulghat station (690) further downstream of the intake is analysed. The analyses conducted in order to identify and quantify any non-stationarity in the flood record, and to inform recommendations for flood-related adaptation measures, include: a) a Mann-Kendall trend test on annual maximum streamflow; b) an extreme value analysis on annual maximum streamflow; c) trend analysis on the monthly maximum precipitation (monsoon precipitation); d) evaluation of range of GCM-projected precipitation from a subset of GCMs that most credibly reproduces the Indian Monsoon; e) reference to recent related work on downscaled daily precipitation and peak streamflow for the Trishuli basin nearby in Nepal.

Mann-Kendall trend test on annual maximum streamflow

Mann-Kendall trend test with Sen’s Slope on the annual maximum streamflow time series (1965-2017) indicates that the maximum flow is trending upward at 5% significance level with a slope of 15.06 m^3/s every year. (refer Figure 5-7)

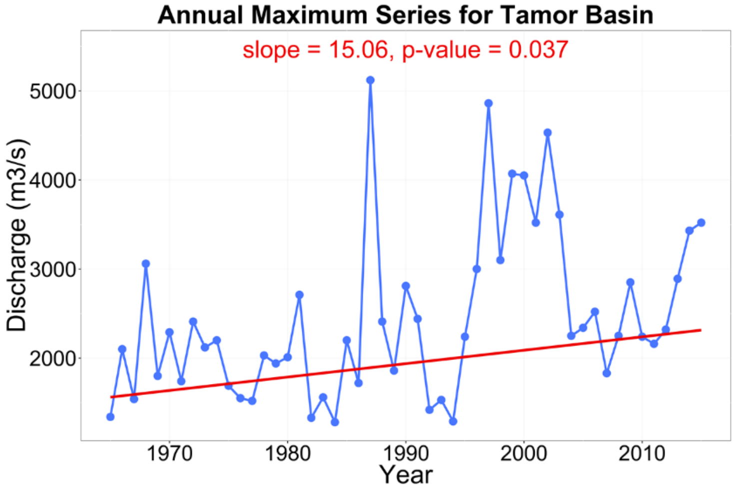


Figure 5-7 Annual Maximum Time Series for Station 690

Extreme value analysis on annual maximum streamflow

An extreme value analysis was carried out on the annual maximum series to evaluate the design flood of 1000-year return period. The annual maximum series was divided into two sections; 1965-1995 and 1985-2015 to analyse if there has been any change in the parameters of the Gumbel distribution - an indication of non-stationarity in the peak values. The results presented in Figure 5-8 demonstrate that both parameters of the distribution are changing with time. It was also found that the 1000-year return period flood in the recent past (1985-2015) has almost doubled its value from 1965-1995, which more clearly illustrated in Figure 5-9. It is to be noted that the 100-year flood (Q100) is taken as 5799 m^3/s, and the probable maximum flood or Q1000 (whichever is higher) is taken as 8259 m^3/s for Tamor River for tailrace design in the documents (referred from TOR).

Based on the historical record of the past 50 years, the annual maximum discharge in the Tamor is increasing at the rate of 15 m^3s^{-1} year. If this rate continues, we can expect an increase in the maximum streamflow by about 18% of the historical mean value of 2443 m^3s^{-1} today.

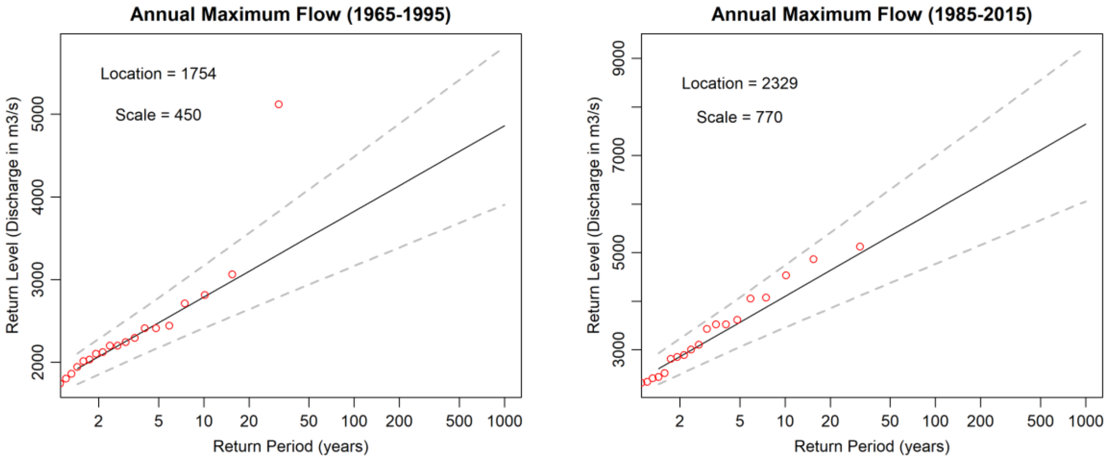


Figure 5-8 Gumbel Distribution fitted to the annual maximum streamflow time series for station 690.The time window chosen for the left is 1965-1995 and for the right is 1985-2015.

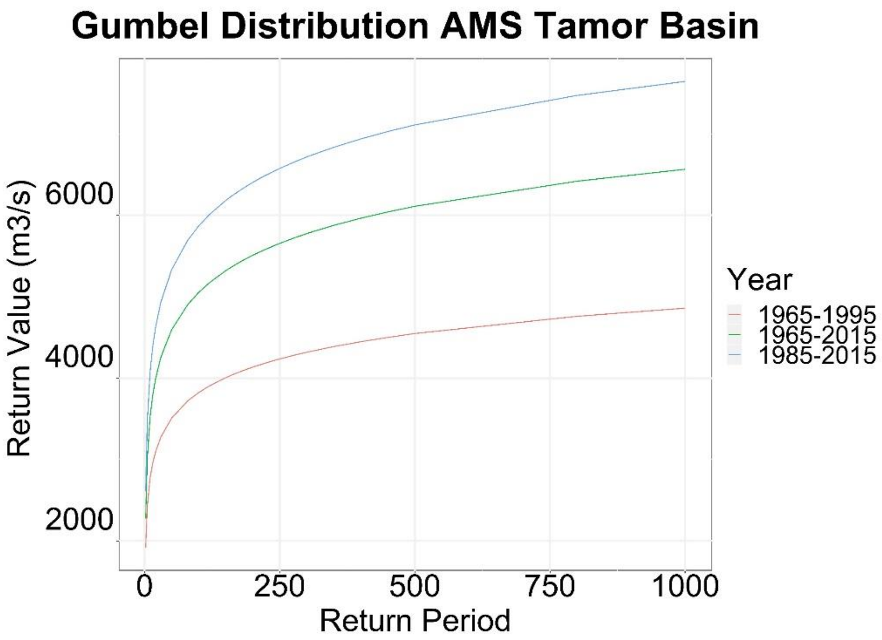


Figure 5-9 Comparative plots of Gumbel distribution fitted to the annual maximum streamflow time series for Tamor Basin. The red, green and blue are the analysis on 1965-1995, 1965-2015 and 1985-2015 respectively

Trend analysis on the monthly maximum precipitation (monsoon precipitation)

Presented in Figure 5-10 is the analysis of behaviour of precipitation time series. The data used is the WFDEI precipitation averaged over the Tamor Mulghat basin. From the bottom right graph we see that the monsoon precipitation is increasing over the years for the catchment.

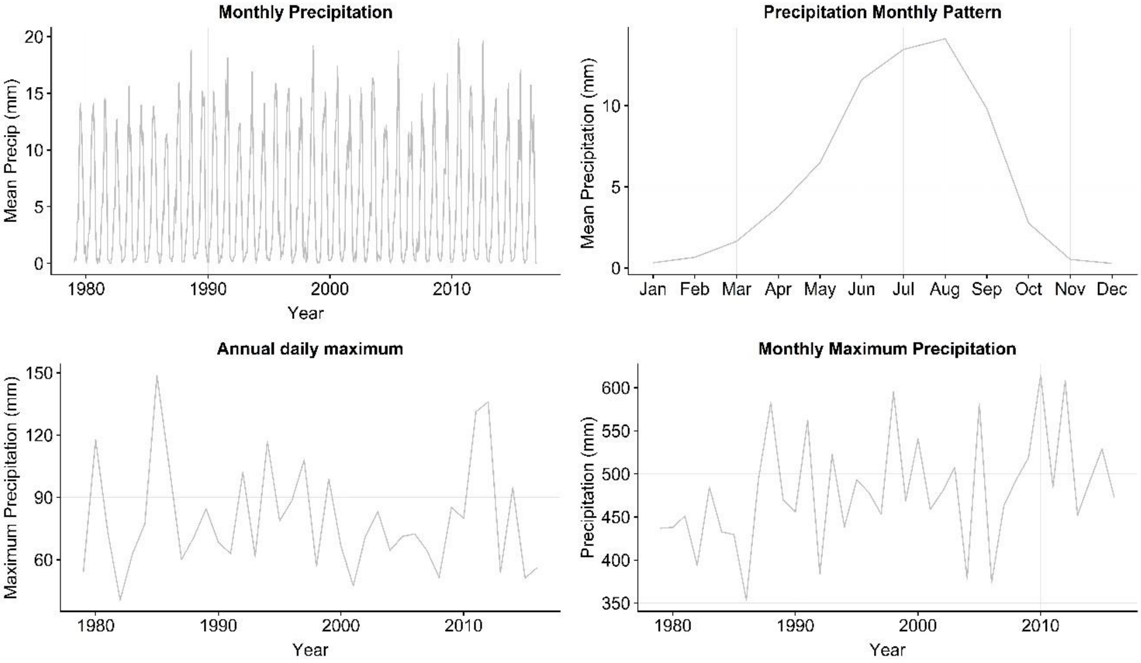


Figure 5-10 Analysis of the precipitation time series for Tamor Mulghat Basin. The data used is WFDEI precipitation

From the Figure 5-10d, we see an increasing trend in the historical maximum monthly precipitation. The MK test on the time series of the maximum monthly precipitation over the last 38 years (1979-2016) indicates a significant increase with a p-value of 0.027 and Sen's slope of 1.796 mm/year.

Evaluation of range of GCM-projected precipitation

The future prediction of GCM models in CMIP5 under different RCP scenarios for maximum monthly precipitation (indicative of monsoon) was explored for the project location. The results presented in Figure 5-11 indicate that the there is a general disagreement among the magnitude of direction of the summer monsoon precipitation in the basin in the future. The summer monsoon contributes to a major portion of precipitation in the basin and is responsible for major floods in the Kabeli River. In order to obtain meaningful information from the GCMs, further literature was explored to identify those models that captures the Indian summer monsoon processes well. Figure 5-12 presents the results from the models that skilfully capture South Asian summer monsoon under AR4 reports (Kripalani et al., 2007). Figure 5-13 is the results from the models that reproduce the Indian summer monsoon variability well in CMIP5 projections (Sharmila et al. 2015).

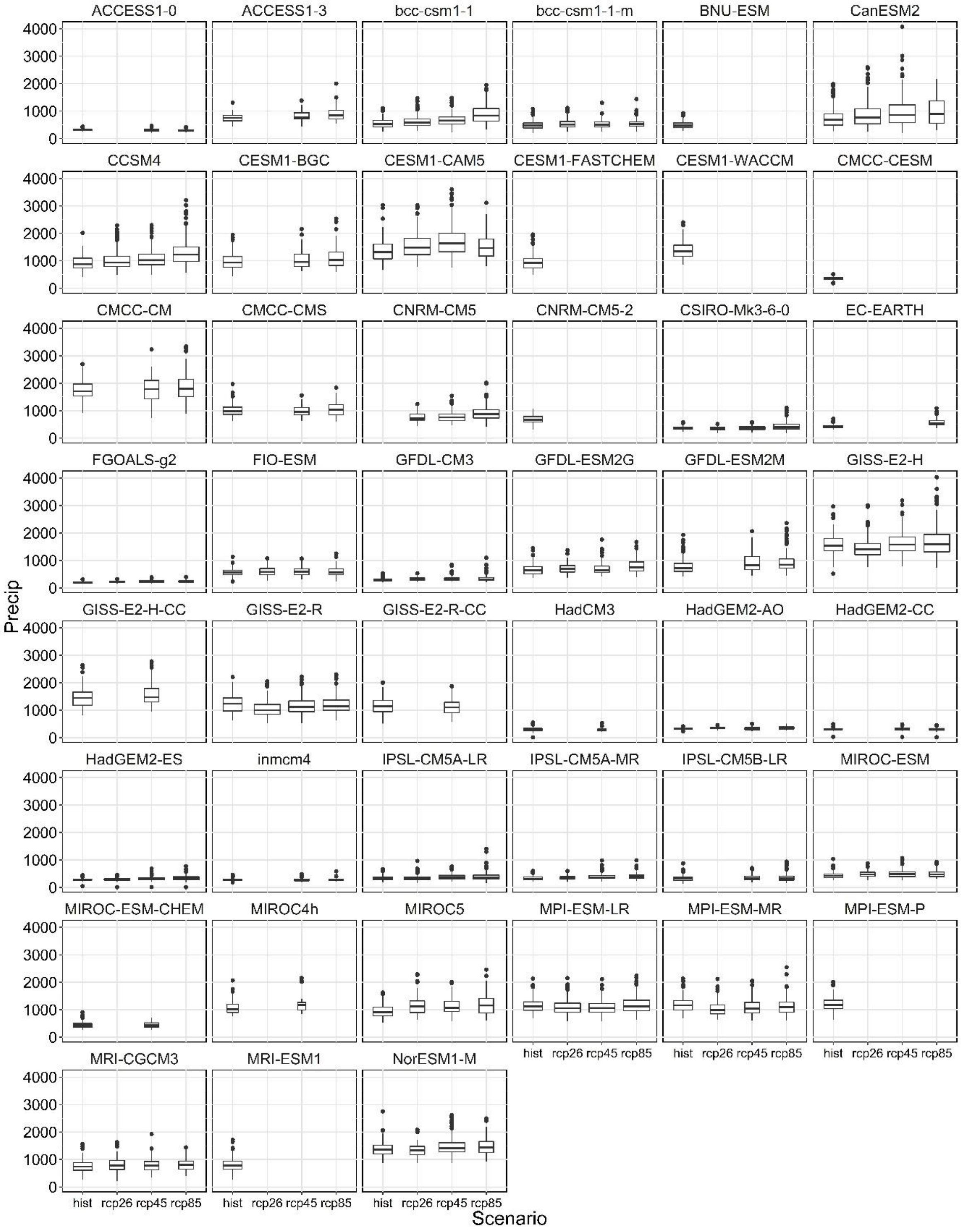


Figure 5-11 Maximum monthly precipitation analysis for the full ensemble of CMIP5 GCMs

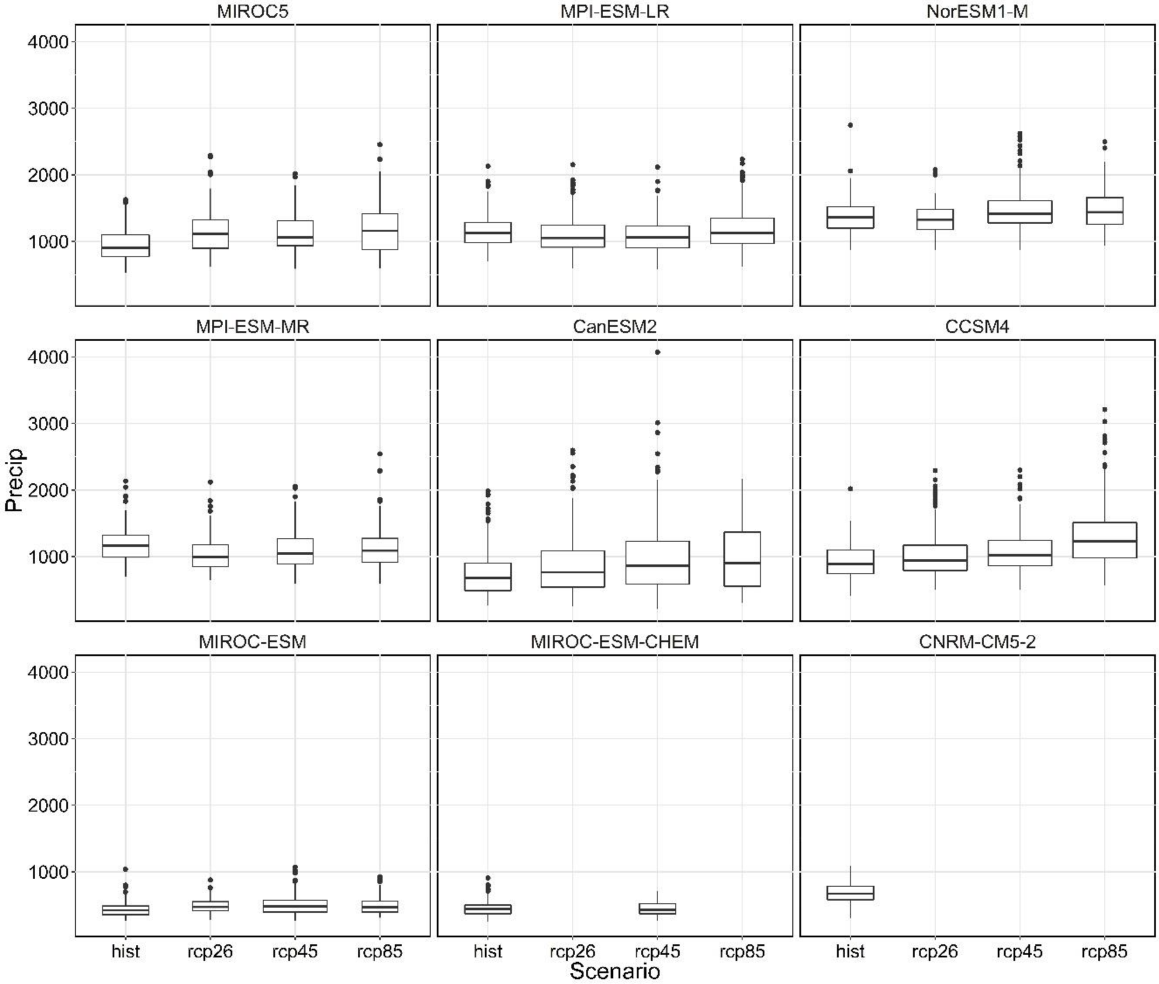


Figure 5-12 Maximum monthly precipitation for the project area abstracted from the GCMs identified by Kripalani et al. (2007) to capture the Asian monsoon processes well in AR4.

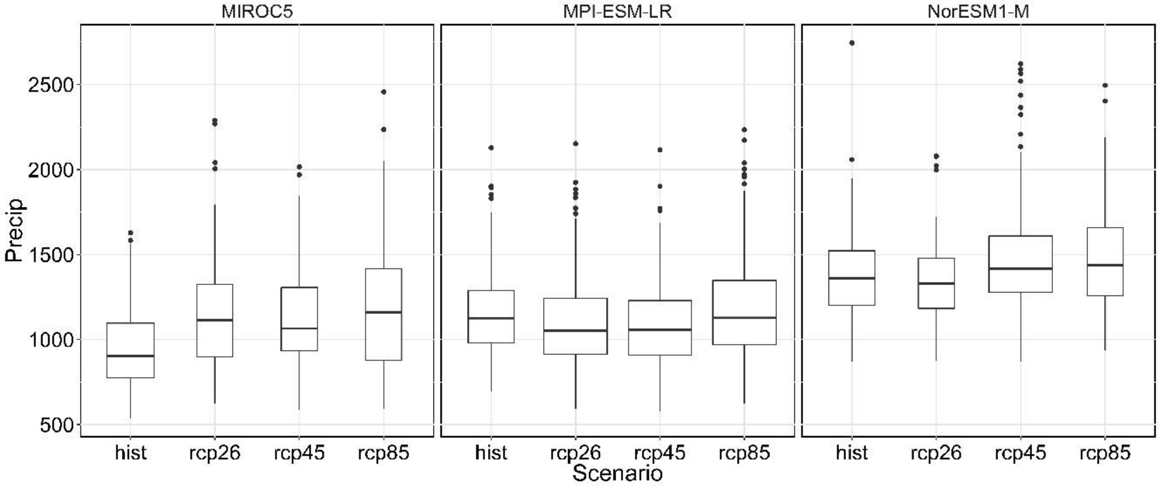


Figure 5-13 Maximum monthly precipitation for the project area abstracted from the GCMs identified by Sharmila et al. (2015) to capture the Asian monsoon processes well in CMIP5.

Reference to recent related work on downscaled daily precipitation and peak streamflow

The boxplot figures presented in Figure 5-12 and Figure 5-13 show that the models generally agree that maximum monthly precipitation in the basin is increasing, but disagree on magnitude. A more detailed analysis (including downscaling and hydrologic modelling) was conducted using GCMs for the Trishuli basin (Cloudwater, 2015), and is presented below.

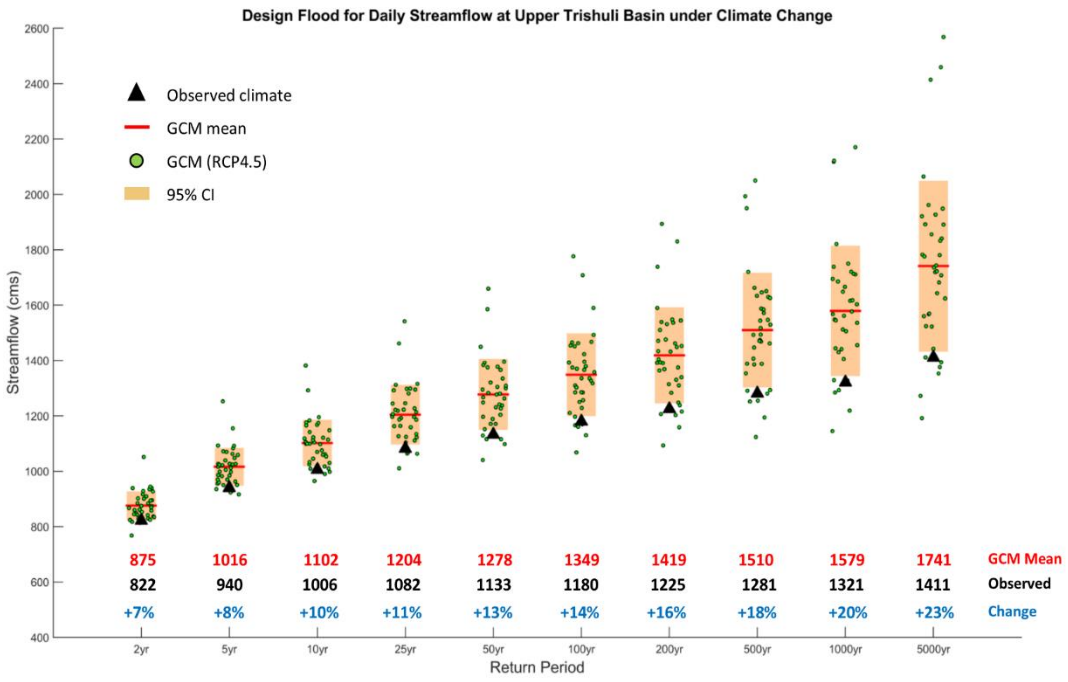


Figure 5-14 Example plot illustrating increasing intensity of peak streamflow events in the CMIP5 GCM ensemble (Cloudwater, 2015)

Conclusion to flood risk assessment

The design flood for the KAHEP facility is the 1000-year streamflow. Because we do not have available estimates of the consequences (either to the structure or to the downstream population) of exceedance of the 1000-year flood, we cannot evaluate all aspects (impact and likelihood) of flood risk to the KAHEP facility. However, this section shows that the magnitude peak annual streamflow, and the 1000-year flood, in particular, appears to be increasing throughout the period of historical record (since the middle of the past century), and is likely to further increase in the future. GCMs cannot be consulted directly for credible information on the future behaviour of extreme precipitation. However, when the local historical trends in extreme precipitation and streamflow are evaluated; and the information from the subset of GCM that capture the monsoon processes well are reconciled, we observe that the magnitude of flood peaks is increasing in the basin. The current design flood magnitude is likely to correspond to a much smaller return period, i.e., it may occur every 500 years in the hydro-climate of the next century instead of every 1000. When the structure was designed for what the designers understood to be a 1000-year return period flood, the designers anticipated a risk characterized by a chance of “not-failure” of the structure during the project life was $.999^{30}$, or about a 3% chance that a 1000-year flood would happen within the project lifetime.

Accounting for the historical climate trend, as well as somewhat qualitative information from the GCMs, we see that the magnitude of a 1000-year flood better corresponds to a 500-year return period flood. The probability that the flood magnitude would be exceeded during the project lifetime is now $1\text{-}0.998^{30}$, or about 6%.

5.6 Sediment Risk

The financial losses to KAHEP due to sediment concentration can be either due to a) the loss of energy generation opportunity with powerplant shutdown in the events of excessive sediment or b) the maintenance and replacement costs of turbine due to sediment erosion. In this section, we estimate the losses to the KAHEP due to sediment concentration in both of these cost aspects and potential impacts of climate change.

A) The loss of energy generation opportunity: During the second mission to Nepal upon discussion with the KEL team it was found that the operation rule for the powerplant is to shut down the plant to prevent excessive turbine damage when the sediment concentration exceeds 4000 ppm in the river at the intake (prior to settling basin).

B) Turbine maintenance and replacement costs: When the concentration is below 4000 ppm, the power plant operates and a certain portion of the sediment is trapped in the settling basin, while the remaining finer sediment passes to the turbine. The turbine is eroded with this sediment and is expected to be replaced every 5-10 years (Based on discussion in second mission to Nepal). The capital electromechanical cost of the project is US$9.44M ($250/kW x 37.76 MW x 1000 kW/MW). The cost for turbine replacement is estimated to be 15% of the total electromechanical cost of the project, i.e., US$1.42M. Under current design, with the average turbine replacement frequency of 7 years, it is estimated that the turbines will be replaced four times throughout the project lifetime. With an increase in the average sediment concentration, turbine erosion can be expected to increase in which case the turbines might have to be replaced more often.

Sediment and Climate Change

Several case studies have analyzed the impact of climate change on riverine sedimentation. However, the results are case specific and climate region specific, and not easily extrapolatable. For instance, an increase in the sediment load (Dao Nguyen Khoi and Suetsugi, 2014a), and rate of soil erosion (Dao Nguyen Khoi and Suetsugi, 2014b) in the wet season was reported in the Be River Catchment, Vietnam, where an increasing trend was observed in the annual precipitation. Similarly, an increase in the sediment yield was observed in watersheds in Jakarta, with an increase in rainfall intensity in the wet season under climate change (Poerbandono et al., 2014). A decrease in the total riverine sediment discharge in the Haunghe River (H. Wang et al., 2007) and the middle Yellow River (Shi and Wang, 2015) was observed where the annual precipitation was also observed to be decreasing. The changes in the sediment discharge in all of the above studies were attributed to the combined effect of anthropogenic changes and climate change, with the effect of the former being recognized as much stronger than the latter. Another study in the Wei River basin in China further strengthens the argument by suggesting that the human intervention is responsible for over 95% of the decrease in the sediment discharge, with less than 5% contribution due to decreased precipitation (Gao et al., 2013).

In the Kabeli basin, more than 70% of the area is covered with forest, and the remaining area constitutes of agricultural land and shrub-land.

Based on the Socio-Economic Report and the Social Action Plan Report, no immediate growth of population or economy in the region is expected. Some increase in the tourism industry is expected due to construction of hydorpower. However, there are no developmental plans in the catchment that could result in a substaintial change in the landuse type. In this report, we analyse the impact of changes in streamflow on the sediment concentration and load, assuming that the effect of human impact on sediment would remain the same.

The sediment studies available for KAHEP present suspended sediment recorded twice per day (regular sampling) and when the river is flooded (additional sampling) at a location immediately downstream of the intake gaging site with a Swedish hand sampler from 2010-2016. The samples are analysed for particle size distribution and the sediment load is calculated with the sediment concentration. The suspended sediment data available is summarized in Figure 5-15. The average concentration in the river every year was found to be 330 ppm.

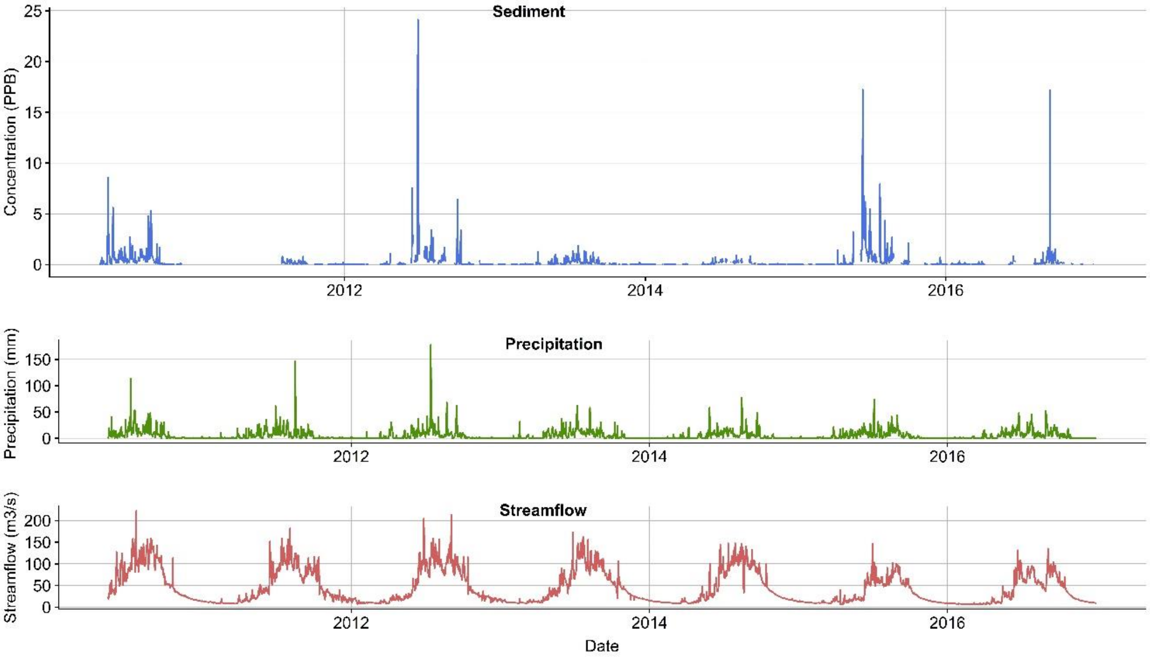


Figure 5-15 Suspended Sediment Sampling Data Available for Kabeli (Updated after second visit to Nepal)

Figure 5-15 represents the time series of precipitation, discharge and sediment taken for further analysis. The data has now been extended until the end of 2016 after the second mission to Nepal. The red series represent the time series of the daily average streamflow in the intake location; the green series represents the daily average basin precipitation in the basin from the WFDEI dataset; and the blue series represents the daily average sediment concentration at the sampling location recorded and maintained in the Kabeli basin.

Relationship between Sediment, Streamflow, and Precipitation for the Kabeli basin
We observe that there is correlation between the sediment, precipitation and streamflow time series from Figure 5-15. We are interested to explore the possible changes in the sediment concentration with changes in either discharge or precipitation in the future.

The relationship was explored by fitting a rating curve to the sediment concentration and discharge. The power function relationship was found to be the most suitable fit for the data after exploring linear, polynomial and exponential relationship between the variables. The discharge and sediment concentration were log transformed and plotted on a log-log scale (Figure 5-16), to derive the power function following the procedure described in Annandale et al. (2016). In the Kabeli River the monsoon flow (June, July, August) is much different than the rest of the year, thus a separate rating curve with the same log-log scale was established for monsoon (Figure 5-18) and non-monsoon months (Figure 5-17). The equations have been updated since the submission of the second interim report with the addition of more data.

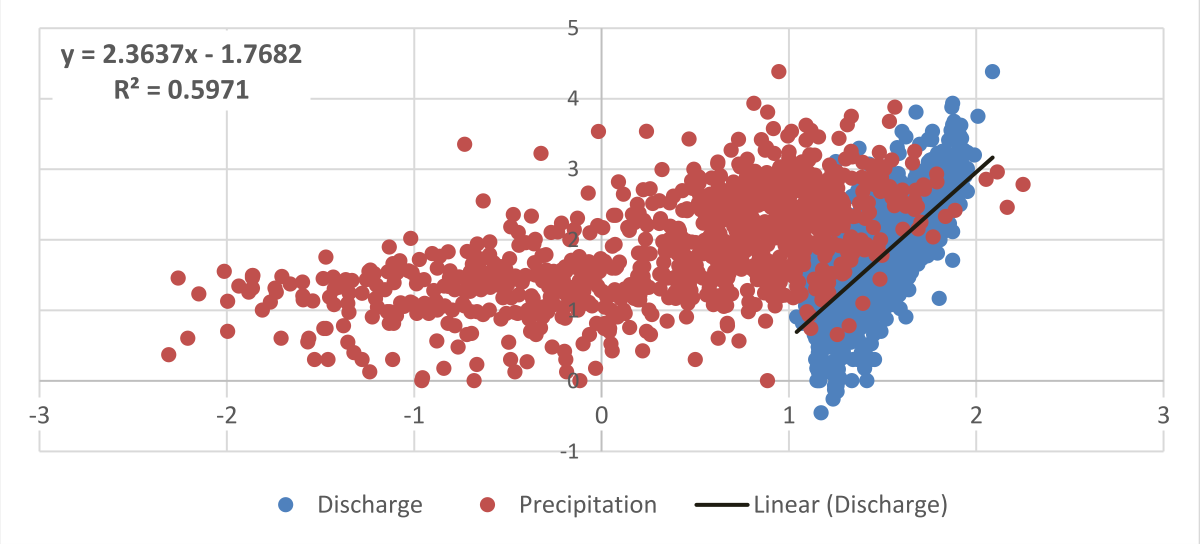


Figure 5-16 Sediment Discharge Relationship (Annual)

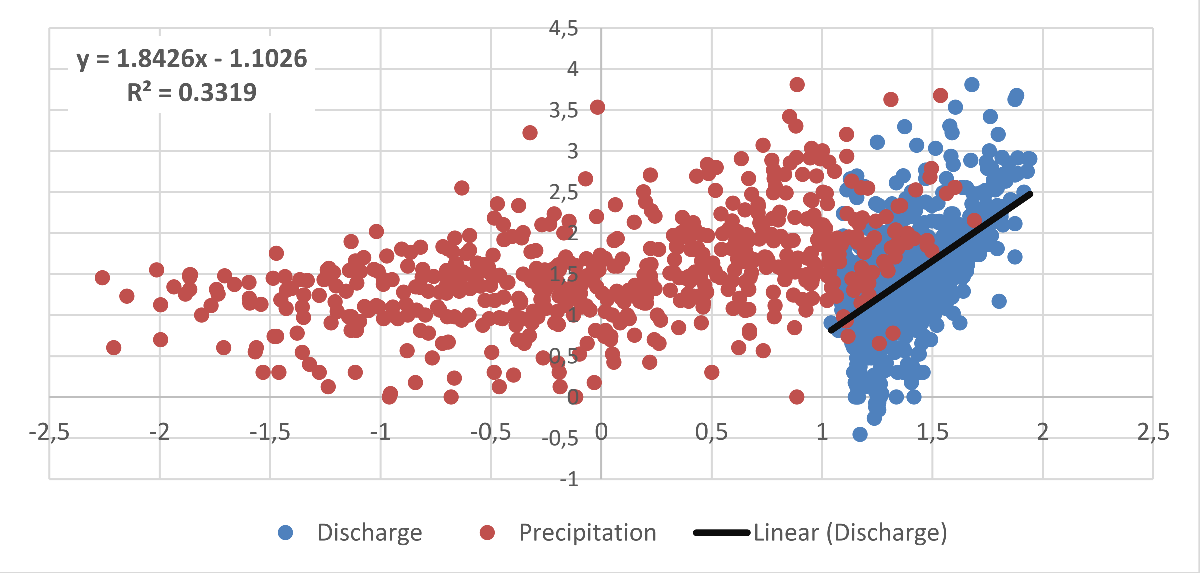


Figure 5-17 Sediment Discharge Relationship (Non - Monsoon)

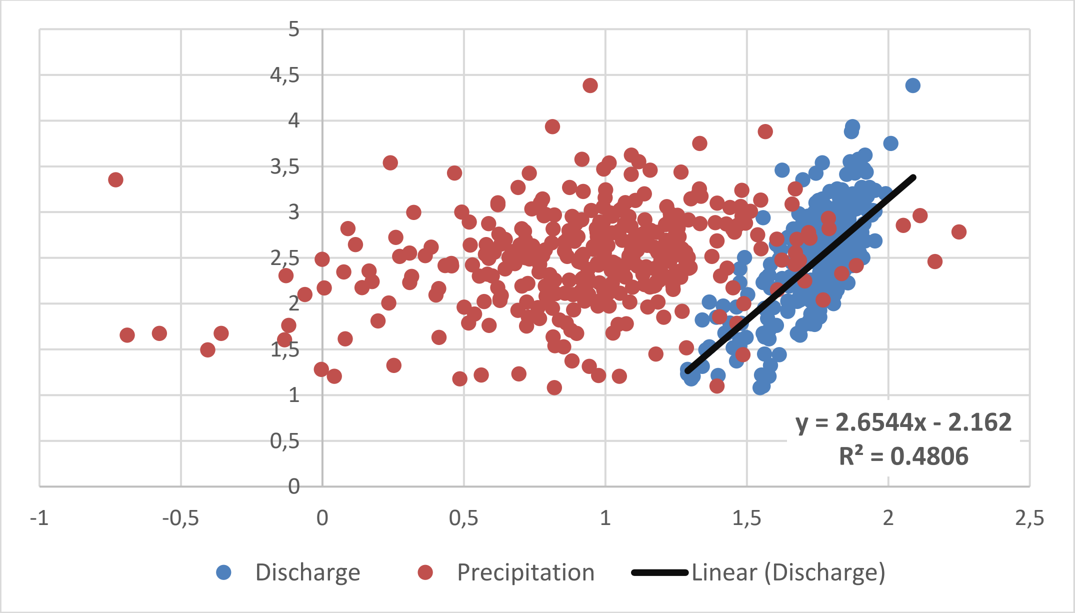


Figure 5-18 Sediment Discharge Relationship-Monsoon

Sediment rating curves are established separately for annual, monsoon and non-monsoon time periods and presented in the following equations. The curves only describe the suspended sediment load (and not rolling bed load).

Total Sediment:

$$C = 0.0171\, Q^{2.3637} \qquad \text{Equation 5-3}$$

(This relationship is used as it has greater correlation value)

Monsoon Sediment:

$$C = 0.0069\, Q^{2.6544} \qquad \text{Equation 5-4}$$

Non-Monsoon Sediment:

$$C = 0.079\, Q^{1.8426} \qquad \text{Equation 5-5}$$

Where
C = Sediment Concentration (PPM)
Q = Discharge (m^3s^{-1})

Note that the sediment discharge relationships established above do not account for a sudden increase in the sediment concentration in the river due to mass wasting or upstream construction activities. The relationships provide (preliminary) insight into changes in riverine sediment concentration that may be expected to occur due to climate change, all other factors remaining the same. It is further assumed that the sediment characteristics, composition, and size, etc., remain constant, with unchanged upstream land use characteristics during the project lifetime.

Calculation of turbine efficiency loss due to sediment concentration
Equation 5-1 gives the relationship between sediment concentration and discharge in the Kabeli River. The intake structure is used to extract the water from the river and trap the sediment particles in the settling basin. For KAHEP, the settling basin is designed to trap more than 90% of the particles greater than 0.2 mm in diameter.

Table 5-2 Summary of the sediment characteristics in the Kabeli River

Year	**Average Concentration (PPM)**	**Moh hardness >= 5 (%)**	**% finer than 0.2 mm**	**d_{50} (mm)**	**d_{50} (mm) (unsettled particles)**	**Quartz (%)**
2010	553	63	77	0.09	0.04	53
2011	152	62	80	0.105	0.08	49
2012	431	47	75	0.08	0.07	48
2013	287	61	70	0.09	0.04	53
2014	124	67	67	0.105	0.07	53
2015	537	68	72	0.1	0.06	52
2016	225	87	82	0.08	0.04	81
Average	**329.86**	**65 %**	**75 %**	**0.09**	**0.06**	**56 %**

Table 5-2 summarizes sediment characteristics in the Kabeli River. The particle-size distribution (PSD) analysis of the sediment samples for years 2010 - 2016 demonstrates that in the Kabeli River on average 75% of the particles are finer than 0.2 mm in size. The PSD analysis of year 2014 is presented in Figure 5-19 for reference.

Since more than 90% of particles with diameter greater than 0.2 mm (i.e. 25% of all particles in the river) are trapped in the settling basin, the remaining 75% of the sediment particles pass through the headrace tunnel into the turbine. Thus, 75% of the sediment concentration in the river is considered to pass through the turbine and affect the hydropower production.

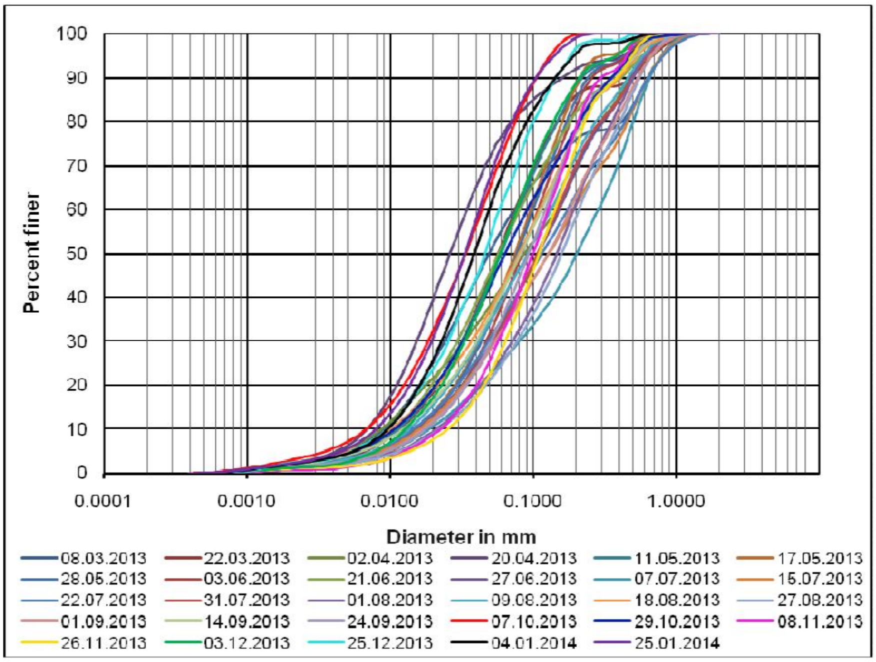


Figure 5-19 Compiled particle size distribution curves of suspended sediment samples collected from 1 March 2013 to 26 January 2014

Several studies have explored the relationship between sediment erosion and turbine efficiency loss in hydropower plants (e.g., Koirala et al., 2016; Noon and Kim, 2017; Thapa et al., 2012). The properties of sediment, the viscosity and velocity of the fluid (carrying the sediment), and the surface material govern the extent of damage due to sediment erosion (Bingley and Flynn, 2005). The erosion rate mainly depends on concentration, shape and the size of the sediment particles (Noon and Kim, 2017).

In this analysis, the sediment erosion model established by Thapa et al. (2015) for Francis turbines is used to calculate the loss in the efficiency of turbine due to sediment concentration. The relationship presented in Equation 5-6 is modification of the erosion model in the IEC-62364 (IEC) tailored for Francis turbine. The description of the parameters, their units and the values for KAHEP is tabulated in Table 5-3. The empirical constants in Table 5-3 is referred from Thapa et al. (2012).

$E_r = C . K_{hardness} . K_{shape} . K_m . K_f . a . (size)^b$ (mm/yr)

Where,

$\eta_r = c . (E_r)^d$ (%/yr)

Equation 5-6

Table 5-3 Parameters for estimation of loss in turbine efficiency

Description	***Symbol***	**Values**
Silt Concentration (kg/m3)	*C*	= 0.75* 330/1000 = 248
Empirical Constants	*a*	1199.8 (Quartz = 60%)
	b	1.8025 (Quartz = 60%)
	c	0.1522
	d	1.6946
Size (mm)	*d_{50}*	0.06 (d_{50} of particle size < 0.2 mm)

Fraction of particle harder than turbine material	$K_{hardness}$	0.65 (from Hydrolab report)
Factor that characterizes how abrasion relates to water flow around each component	K_m	2 (for carbon steel)
Shape factor of particle	K_{shape}	1
Factor that characterizes how the abrasion relates to the water flow around each component	K_f	2
Loss in efficiency (%/yr)	η_r	**2.2 %/yr**

We observe that based on the suspended sediment data collected in the basin for 7 years the loss in efficiency of the turbine solely due to sediment erosion is approximately **2.2% per year**. Thus, the project faces losses in power production as well as corresponding costs for repair and maintenance of the turbine to due to the loss in efficiency. Under the current design, the turbine replacement frequency for KAHEP is expected to be between 5-10 years, with an average lifetime of **7 years**.

Thus, under current design, the **maximum allowable efficiency loss** due to sediment erosion before turbine replacement can be calculated as Equation 5-7

$$Maximum\ allowable\ Loss\ in\ Efficiency\ (\boldsymbol{\eta_{max}}) = \frac{2.2\%}{year} * 7\ year = 15.5\%$$

Equation 5-7

Thus, the maximum allowable loss in efficiency before replacing the Francis turbines in KAHEP is calculated as **15.5%.** During the plant operation as the water laden with suspended sediment passes through the turbine for energy generation, it erodes the turbine and abrades other mechanical parts. The erosion of the turbine decreases the performance of the power plant and is calculated as an overall loss in efficiency of turbine per year. The loss in efficiency accumulates over the years, until it reaches a threshold of 15.5%. Once this maximum allowable loss is reached, the turbine is no longer functional and needs to be replaced. The loss in efficiency is dependent on the sediment concentration. However, it is to be noted that the calculation does not account for losses due to vibration, cavitation or other causes.

Response due to climate change

A) Loss of hydropower generation opportunity:

With changes in the streamflow and the corresponding changes to the sediment concentration in the river obtained using Equation 5-3, we observe that the sediment concentration in the river is influenced by climate change. The number of days in which the concentration exceeds the threshold of 4000 ppm is presented as a response surface in Figure 5-20. For each day of power plant shutdown due to excessive sediment (i.e. >4000ppm), the loss in energy production is 0.9 GWHr.

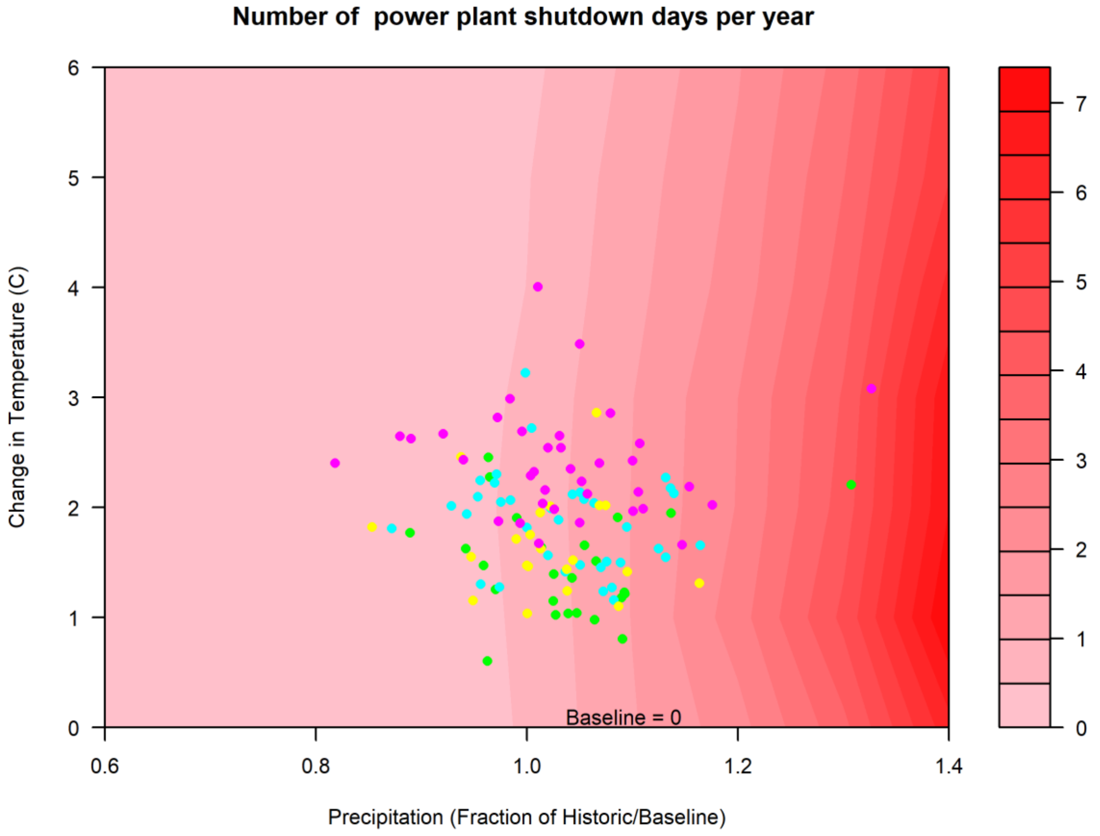


Figure 5-20 Response Surface number of power plant shutdown days due to excessive sediment in the river.

B) Turbine replacement.

Under the baseline design, the turbine is replaced every 7 years, allowing the loss in efficiency to drop upto 15.5% before replacement. Due to climate change as the sediment concentration increases, thus the loss in efficiency of turbine per year also increases following Equation 5-6. The increase in the sediment concentration, loss in turbine efficiency, turbine replacement frequency, and the corresponding cost associated with it is tabulated in Table 5-4. We estimate that the increase in sediment concentration by a 50% doubles the turbine replacement frequency and the replacement expenses during the project lifetime.

Table 5-4 Sediment Concentration and Costs

Sediment Concentration	**Loss in turbine efficiency per year**	**Number of times turbines to be replaced in project lifetime.**	**Cost in US $ M**
Baseline	2.2 %	4	5.66
20% increase	3.01%	6	8.50
30% increase	3.45%	7	9.91
50% increase	4.38%	9	12.74

The combined response of loss of opportunity cost and the turbine replacement cost subjected to changes in precipitation and temperature is presented in Figure 5-21. The figure on the left is the overall undiscounted cost associated with the sediment during the project lifetime. The figure on the right is the NPV of the costs discounted at a rate of 10% per annum.

We observe that the cost (undiscounted) associated with sediment under baseline design doubles with a 20% increase in the precipitation for the basin.

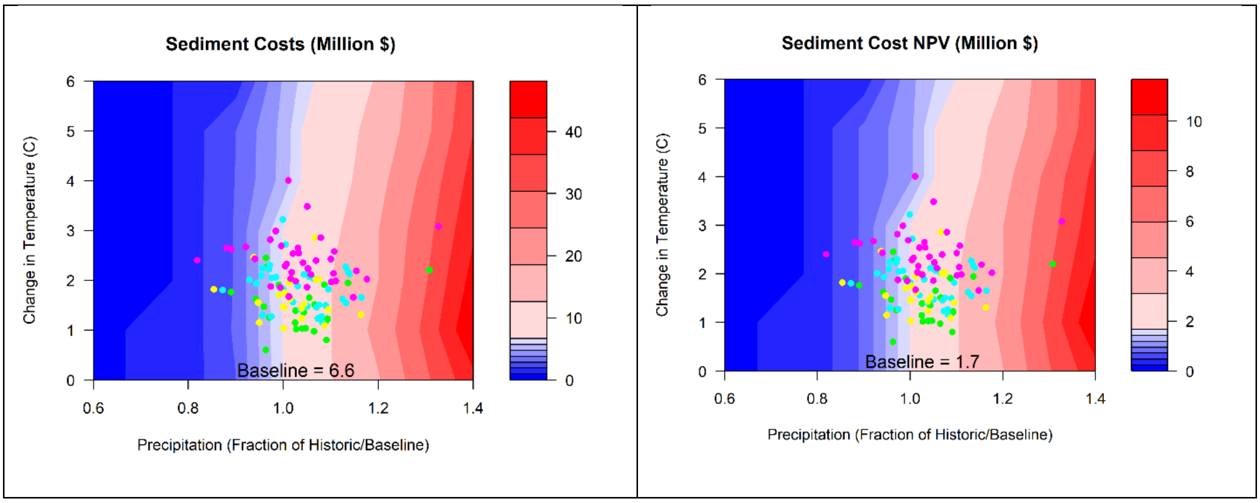


Figure 5-21 Response surface of total cost due to sediment concentration with decrease in turbine efficiency and power plant shutdown. The figure on the left denotes total expected losses. The figure on the right represents costs discounted at 10% per annum.

Conclusion to the sediment risk analysis: The sediment load impact on the annual energy production was analysed by calculating the number of days the power plant would be shut down due to excessive sediment in the river, using an empirical relationship between streamflow and suspended sediment, derived as part of this project. The analysis does not take into account rolling bed load. This section shows the response of project operating cost to climate-change-induced changes in sediment concentration. With an increase of precipitation by 20%, a reduction of 2.7 GWHr of annual energy production is predicted, which in terms of financial terms would be $170,100 per year.
Moreover, with an increase of precipitation by 20%, up to a 50% increase in the average annual sediment concentration is expected which could more than double the expected cost for turbine replacement in the project lifetime.

Reliability, Vulnerability and Resilience
KAHEP's performance metrics are calculated in this section terms of the deliveries of the monthly energy to NEA on the Power Purchase Agreement contract. Success is defined as full delivery of the contracted energy each month. Failure occurs when KEL is unable to produce the energy NEA is willing to buy.

All of the metrics are calculated over 30 traces of 30 years of simulated data on a monthly scale. Vulnerability is the largest shortfall in energy deliveries in any month over the entire project life. Reliability is calculated as the ratio of total success to the total number of months during the project life. Resilience is calculated as the ratio of total recoveries from failure to the total number of failures, and recovery time (in months) is defined as the inverse of resilience.

Using the historical streamflow observation in the intake of the project over six years of daily data (2011-2017), the vulnerability, reliability, resilience and the recovery time of the project are calculated to be 0.96 GWHr, 0.70, 0.38 and 2.67 months, respectively. Figure 5-22 shows the project performance in terms of Nepali Month.

The blue line graph on the top indicates the vulnerability of the project, i.e., the deficit in the energy that could have been sold to NEA in any given month. We can see that, even when the cumulative annual energy is met, the project might not be able to deliver to the monthly targets. The number on the bar graph represents the reliability to meet the energy demand each month. With the existing design and agreement, we observe that the reliability is low and the vulnerability is high during the dry season, particularly dry in the months Baishakh and Jestha (mid April – mid June).

The authors of the report noticed that in the power purchase agreement, the expected energy in the dry months, for instance Jestha (mid May-mid June) is higher than what is generally observed at the intake with 7 years of data. The reason for such difference could be the difference in the source of data used to prepare the power purchase agreement. In this report, the gaging station established at the intake is taken to be standard; while in the PPA, the streamflow input taken could possibly (though not explicitly reported anywhere) be a derived estimate from the streamflow data from the Tamor hydrologic station further downstream of the project site.

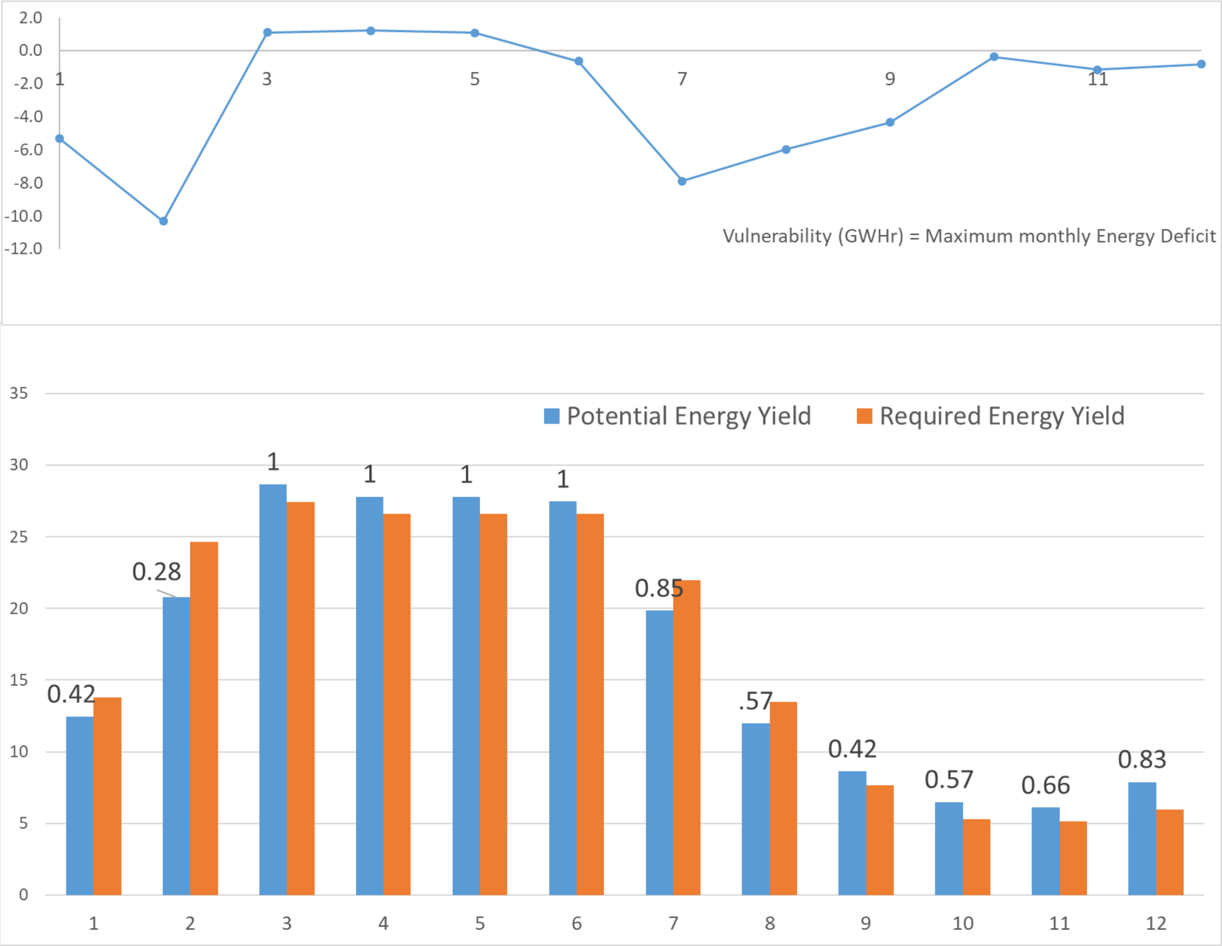
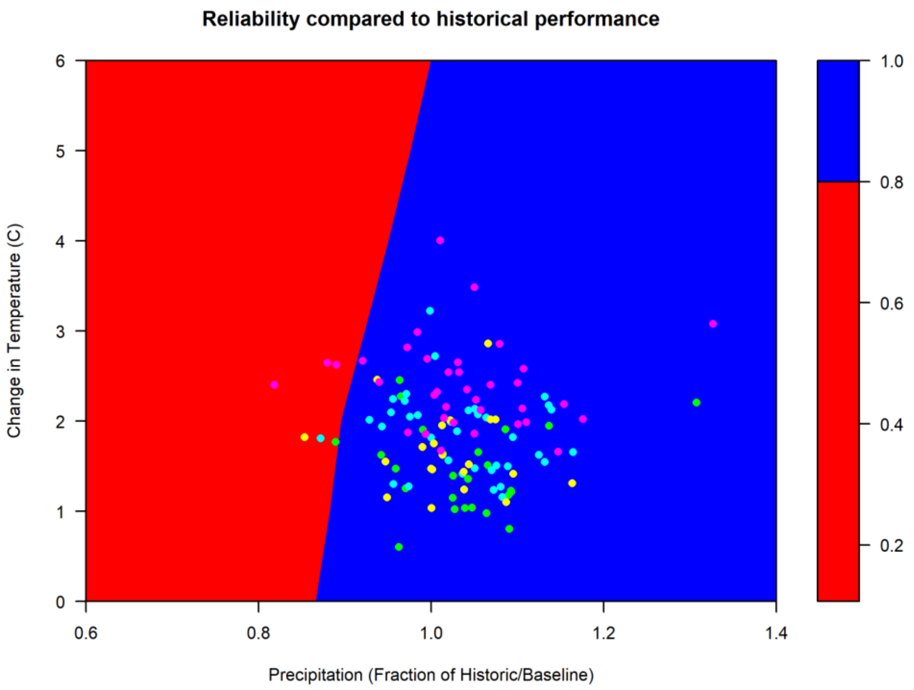


Figure 5-22 Illustration of the potential energy yield and the energy demand in the power purchase agreement with NEA. The x-axis is the Nepali month and y-axis is the energy in GWHr. The blue in the bar graph is the potential energy yield and the orange represents the maximum energy NEA is willing to purchase. The numbers on the bar graph represents the project reliability for each month. The blue line above the bar chart indicates the monthly vulnerability of the project.

The performance metrics of the project were then calculated with the streamflow generated using 30 traces of 30 years of synthetic data for the baseline condition of unchanged precipitation and temperature time series. The metrics for the vulnerability, reliability, resilience and the recovery time of the project are 0.99 GWHr, 0.57, 0.26 and 3.91 months respectively. The discrepancy between the observed and simulated, can be attributed to the low flow bias of the hydrologic model. The HBV hydrologic model in Figure 5-3 indicates that the model is satisfactorily calibrated with a reasonable NSE value, but it does not capture the low flows very well. Furthermore, we observe that on average the monsoon/wet season (June-September) reliability of the project is 0.98 while the dry season reliability is 0.38 (not shown in the report).

Next, we performed the stress test on these performance metrics to assess the project's sensitivity to climate change. We define the 'failure region' when the performance of the project drops below 80% of its baseline performance levels (indicated by the red colour in the response surface of the project).

a) Reliability (expressed as a ratio to the baseline; 80% taken as trigger)



b) Vulnerability = Maximum deficit in monthly energy

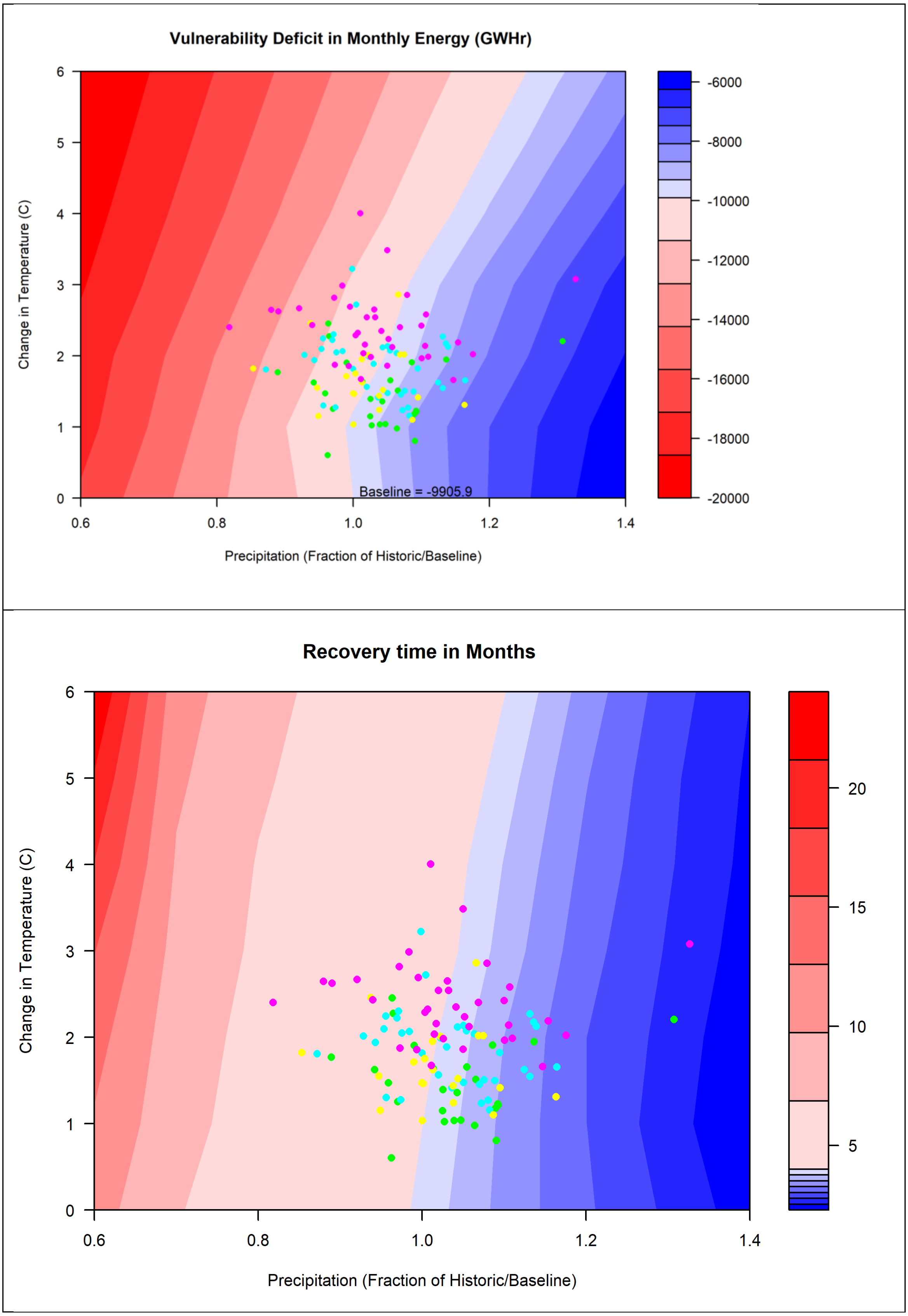


Figure 5-23 Performance Metrics. a) Relative Reliability, b) Vulnerability of the project, c) Recovery time in Months

Figure 5-23 a, b and c represent the relative reliability, vulnerability and the recovery time in months of the project after a failure has occurred. The relative reliability is expressed as a ratio of the project reliability with a perturbed climate to the baseline and the success is defined with a threshold of 80%. We observe in Figure 5-23 a, that the reliability of the project drops below 80% of its current value when the precipitation decreases by 15% and or the temperature increases by 3 degrees Celsius. From Figure 5-23 b, we see that the vulnerability or the maximum monthly energy deficit on the PPA increases when the future climate is drier or warmer above 1 degree Celsius. Figure 5-23 c, we see that the recovery time for the project to deliver the monthly targets on the PPA is about 5 months up to a 25% decrease in precipitation.

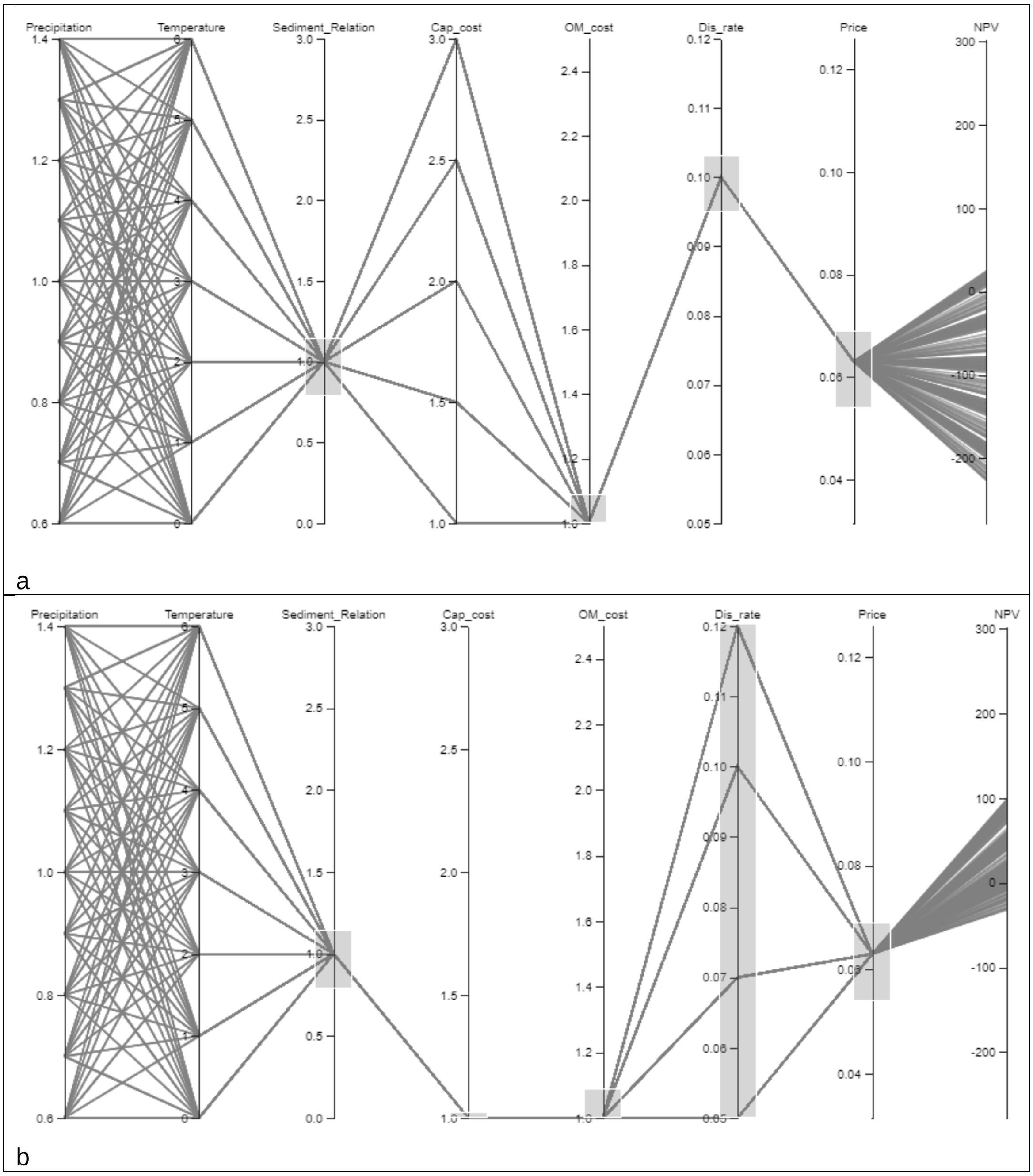
5.7 Multidimensional Stress Test

Table 5-5 summarizes the experimental design for the multidimensional stress test. It consists of both climatic and non-climatic factors. Ranges for non-climatic factors (capital costs, discount rate, operation and maintenance costs) were discussed with the stakeholders meeting during the June 2018 inception visit. The sensitivity to sediment concentration was analysed by calculating the NPV without any sediment consideration and using the three sediment-discharge relationships presented in equations 5-1 through 5-3.

Table 5-5 Strategy for Multidimensional Risk Assessment

Risks	Variables	Lower Limit	Upper Limit
Climate Variability (30 traces)	Daily Precipitation	Stochastic	Stochastic
	Daily Temperature	Stochastic	Stochastic
Climate Change (Perturbation to traces)	Delta P	-40%	40%
	Delta T	+ 0C	+ 6C
Sediment	Discharge-Sediment Relationships: No relationship, 1, 2 & 3		
Financial	Capital Cost	Base Cost	Base Cost * 3
	O & M Cost	Base Cost	Base Cost *3
	Selling Price	0.062985$/KWHr *.5	0.062985$/KWHr *2
	Discount Rate	5% - 12%	

The total number of cases considered in this exercise are 7*9*5*4*4*4*4 = 80640 cases for each trial. The ranges in the columns of Figure 5-24 presents the results of the multidimensional stress test in the form of a parallel coordinates plot. A web version of the plot is available at http://rpubs.com/dfd/KAHEP.


Precipitation
Temperature
Sediment_Relation
Cap_cost
OM_cost
Dis_rate
Price
NPV
a
b

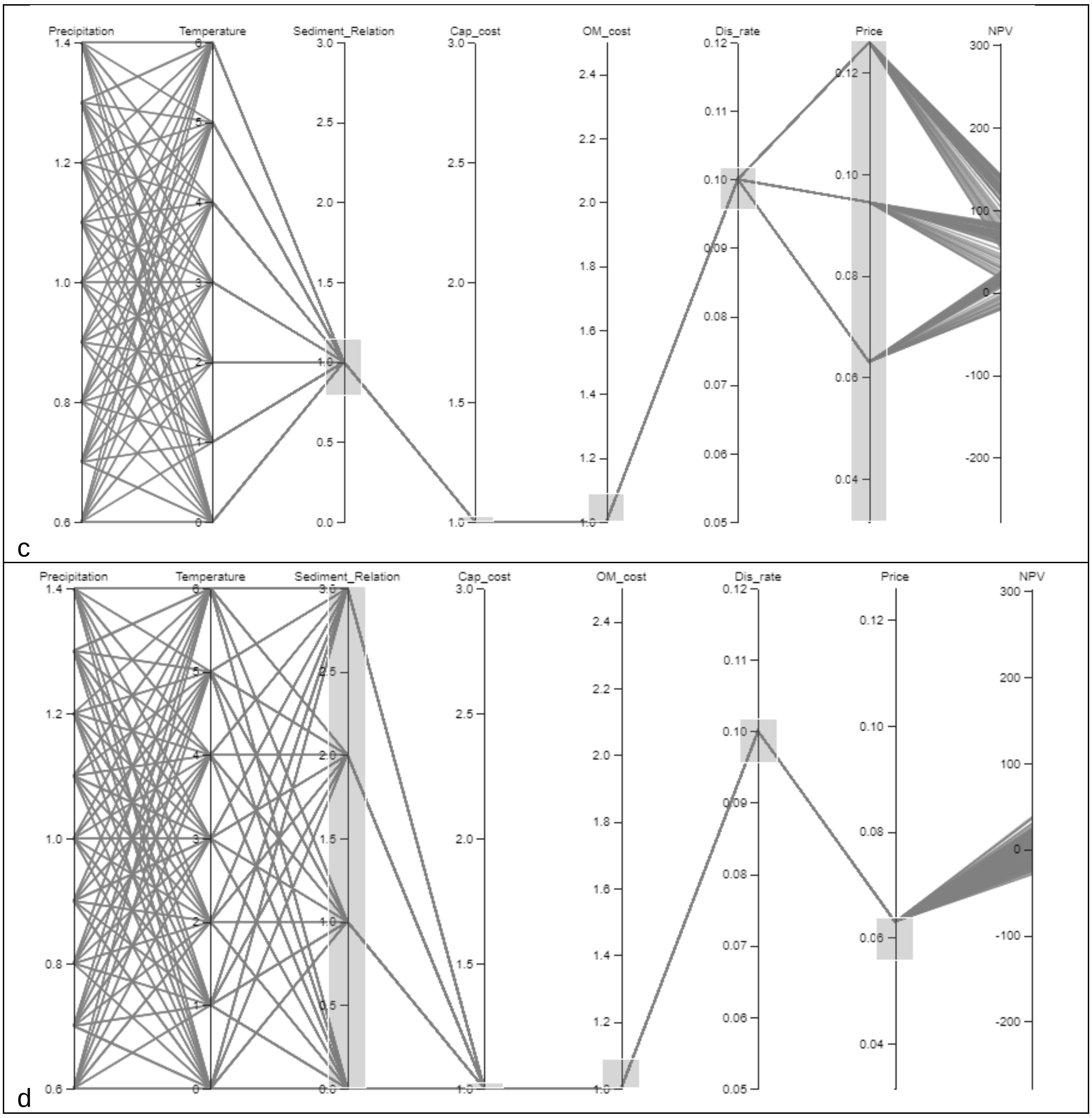


Figure 5-24 Parallel coordinate plot for multidimensional stress test of KAHEP. The highlighted columns are a) Capital costs, b) Discount rate, c) Energy selling price and, d) Discharge-Sediment relationship respectively.

Presented in Figure 5-24 is the parallel coordinate plot that illustrates the multidimensional risk assessment on the NPV presented in Table 5-5. The parallel coordinate plot consists of eight columns, each of which represents an uncertain parameter potentially affecting the Net Present Value of the project. The range of net present value calculated with a combination of these factor ranges from a loss of US$300 M to a gain of US$300 M. The ranges of the NPV solely due to climate change is a loss of US$30M to a gain of US$15M, which indicates that the project is more sensitive to a higher degree to other factor besides changes in precipitation and temperature.

The project is seen to be most sensitive to changes in capital costs and energy selling prices. Four separate figures are presented to discuss the effect of individual factor on the net present value of the project. Hereafter the figures are represented with letters ‘a’, ‘b’, ‘c’ and ‘d’ in the order they are presented.

Figure 5-24a represents the project sensitivity to changes in capital costs, other factors remaining the same. We see that the NPV of the project ranges from US$25M to -US$250M with if the project costs changes between 1 times to 3 times its present cost.

Figure 5-24b represents the project sensitivity to changes in the discount rate, with other factors held constant at baseline. We see that the NPV of the project ranges from –US$35M to US$100M with changes in the discount rate between 5% to 12% around the baseline of 10% per annum. We observe that if the discount rate were to drop to 5%, the NPV of the project could rise up to US$150M with not a very significant drop with increased discount rate up to 12% from the base value of 10%.

Figure 5-24c represents the project sensitivity to changes in the selling price of energy. We observe that the NPV of the project is highly sensitive to changes in prices and swings between -US$12M to over US$140M with changes in the selling price between 1 times to 2 times the baseline price 0.0689$/kwhr. The NPV of the project could be as high as US$200M, presenting a great opportunity. However, it is a big concern that if the selling price of the electricity were to be halved the project would face a loss between US$30M to US$70M.

Figure 5-24d represents the project sensitivity to sediment-discharge relationship used in the analysis. The NPV ranges between -US$30M to US$40M. Although the sediment concentrations from the three equations are very different, we do not observe much difference in the NPV of the project. The operation and maintenance costs associated with sediment and the loss in power production reduces heavily with the discount rate. Thus, we observe that in terms of the NPV, the project is not very sensitive to changes in the sediment concentration.

In summary, the multidimensional risk assessment of Kabeli A Hydroelectric Project demonstrated that the project is more highly sensitive to changes in the capital costs and the energy selling prices than to shifts in temperature and precipitation. An increase in the capital cost by 50% would result in a large loss to the project.

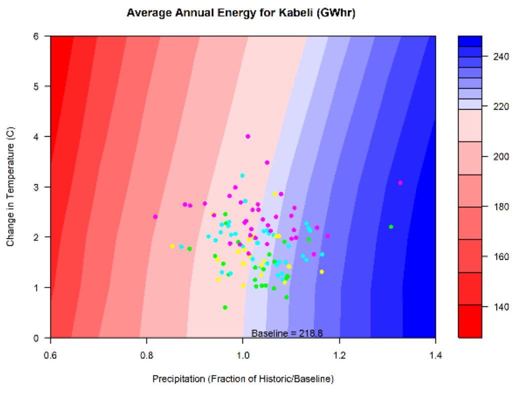
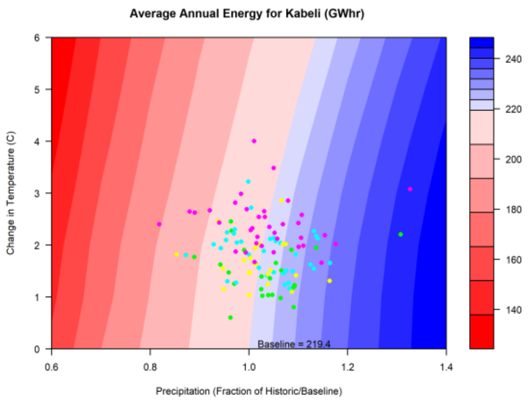
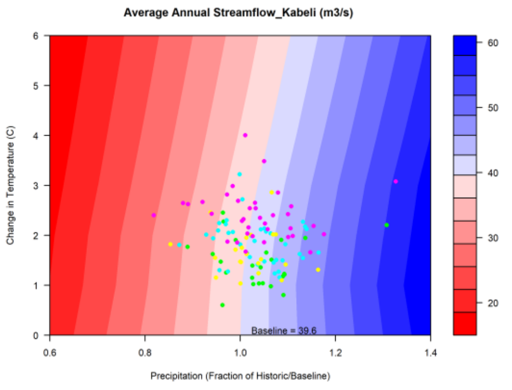
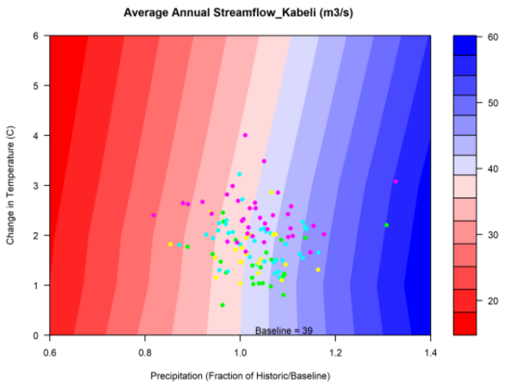
Given the limitations in available information regarding the probabilities of the future outcome of each non-climate factor, it was not possible to assign a posterior probability function to the NPV in this case. It is left to stakeholders and project planners to determine the relative likelihood of each non-climate factor, and the resultant risk to project NPV.

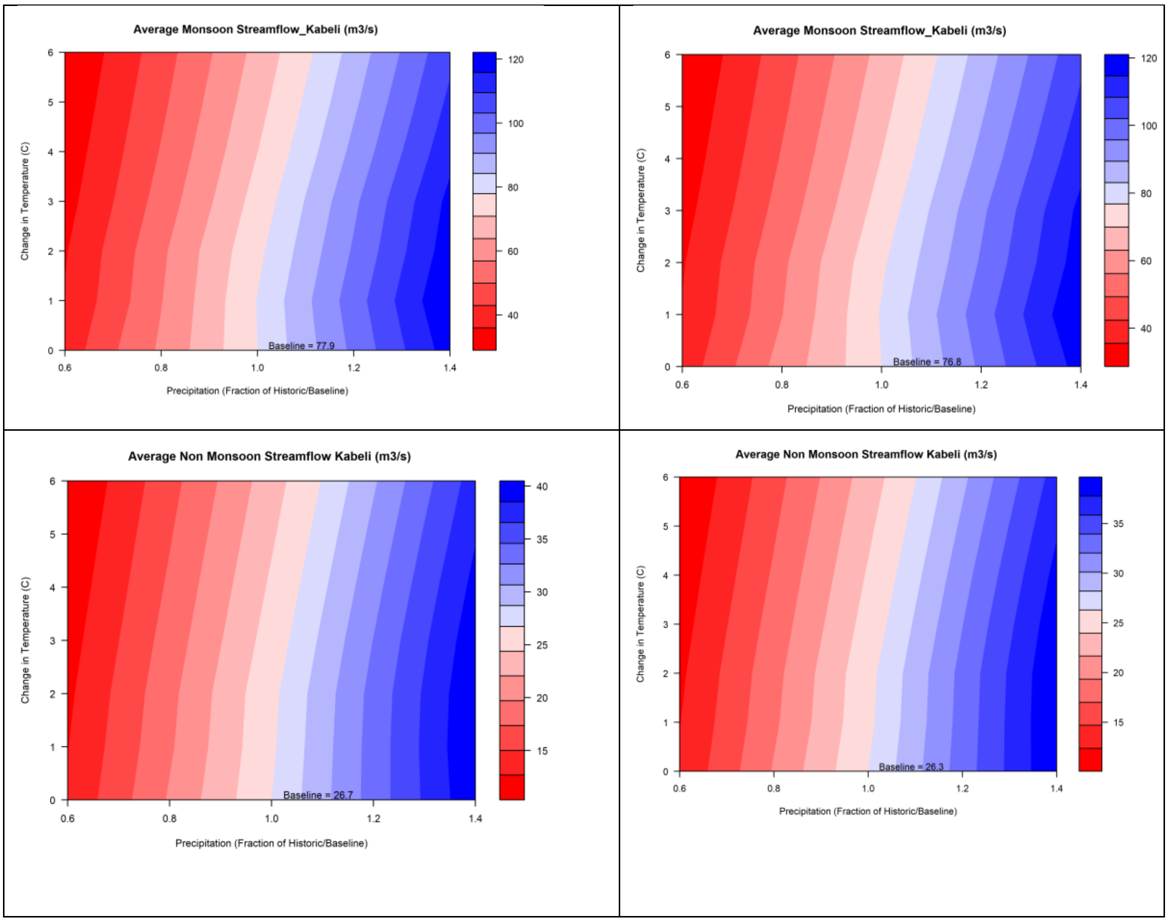
5.8 Stress test analysis with and without the weather generator

A stated aim of the World Bank in development of the Decision Tree Framework is adoptability by engineering consulting firms worldwide, which are engaged in civil and environmental engineering designs potentially impacted by climate change. Many of the target design firms lack the capacity to develop their own stochastic weather generators for the case of each project for which they are responsible.

This section demonstrates the results of a climate stress test using an alternative, simplified resampling approach. Comparison of response surface with and without weather generator is presented in Table 5-6. By using only on the historical record, as it occurred (directly perturbing the historical precipitation and temperature trace within the defined range), the analyst would be able to approximately generate the climate response surfaces produced by averaging 30 stochastic traces generated using a weather generator, for: average annual streamflow (monsoon, non-monsoon, total), energy production, and NPV. This is because the climate response surfaces selected for presentation here illustrate long term average performance governed by mean streamflow (which is, in turn, governed largely by mean precipitation, the very thing controlled for in the weather generator resampling algorithm). However, the analyst using only the historical trace (without developing a weather generator) would not be able to address questions of streamflow extremes (flood and drought) that are likely to exceed the range of the limited historical observations, as the hydrologic cycle accelerates with warming temperatures.

Table 5-6 Comparison of response surface with and without weather generator. The dots on the response surface represents the CMIP5 climate change projection (centred on year 2050). Green: RCP 2.6; Cyan: RCP 4.5; Yellow: RCP 6.0; Magenta: RCP 8.5.

Response Surface without WGEN	Response Surface with WGEN (30 trials with 50 years of data, averaged)
	
	


Average Monsoon Streamflow_Kabeli (m3/s)
Change in Temperature (C)
0
1
2
3
4
5
6
0.6
0.8
1.0
1.2
1.4
Precipitation (Fraction of Historic/Baseline)
Baseline = 77.9
40
60
80
100
120
Average Monsoon Streamflow_Kabeli (m3/s)
Change in Temperature (C)
Precipitation (Fraction of Historic/Baseline)
Baseline = 76.8
40
60
80
100
120
Average Non Monsoon Streamflow Kabeli (m3/s)
Change in Temperature (C)
Precipitation (Fraction of Historic/Baseline)
Baseline = 26.7
15
20
25
30
35
40
Average Non Monsoon Streamflow Kabeli (m3/s)
Change in Temperature (C)
Precipitation (Fraction of Historic/Baseline)
Baseline = 26.3
15
20
25
30
35

6 Phase 4

The second mission to Nepal was conducted from 3-6 June 2019. The purpose of the visit was to receive feedback from project stakeholders on the work done to date, especially the risk assessment findings of Phase 3. Meeting minutes can be found in Annex I.

Based on the assessment so far conducted, no modifications to the design to account for low or flood flow were deemed necessary by project stakeholders. However, it is likely worthwhile to evaluate opportunities for increased sediment holding facilities (to allow time for settling), abrasion-resistant turbine propellers, and early warning systems.

6.1 Low Flow – Managing Financial Risks from Insufficient Hydroelectric Power Production

For the Kabeli A Hydroelectric Project, the future climate projections predict an increase in temperature but do not agree on the future changes in precipitation of the basin. However, the response surface of the project indicate that the net present value remains positive even under the worst-case climate scenarios predicted by the future climate projections. Thus, the project is robust to changes in the low flow condition and no adaptation is recommended to the project for low flow conditions.

6.2 High Flow – Managing Safety Risks (to Structure and Downstream Population) from Flood Flows

Historical observations indicate that both the annual maximum monthly precipitation and maximum daily streamflow in the basin are increasing. The 1000-year return period streamflow has been increasing over the past 30 years, and extrapolating from the current trend in ground observations, the 1000-year return period flood magnitude may double during the lifetime of the project. GCM projections likewise indicate the likelihood of an increase in the maximum monthly precipitation in the basin. Thus, it is reasonable to expect flood magnitudes to increase in the basin.

Recalling the results from section 5.5, the probability that the maximum flood magnitude during the lifetime of the project exceeds the design flood increases from 3% (base design) to up to 6% (with climate change).

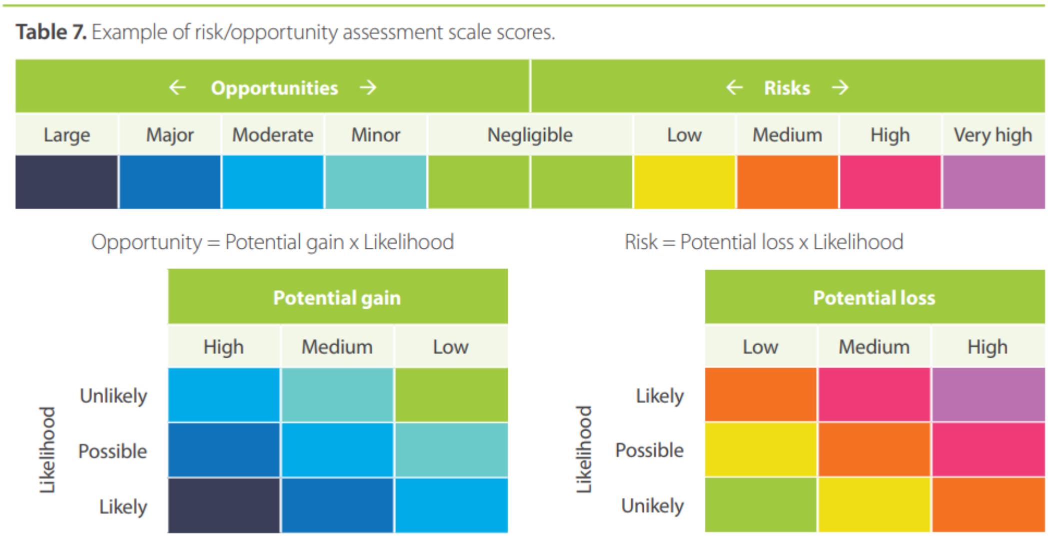


Table 7. Example of risk/opportunity assessment scale scores.

← Opportunities →					← Risks →			
Large	Major	Moderate	Minor	Negligible	Low	Medium	High	Very high
⬛	🟦	🔵	🔹	🟩	🟨	🟧	🟥	🟪

Opportunity = Potential gain x Likelihood

Likelihood	Potential gain: High	Medium	Low
Unlikely	🔵	🔹	🟩
Possible	🟦	🔵	🔹
Likely	⬛	🟦	🔵

Risk = Potential loss x Likelihood

Likelihood	Potential loss: Low	Medium	High
Likely	🟧	🟥	🟪
Possible	🟨	🟧	🟥
Unikely	🟩	🟨	🟧

Figure 6-1 Risk and opportunity assessment scale scores (IHA Climate Resilience Guide)

The likelihood of increase in flood magnitude is high, however the potential loss is low. There are two main reasons for it: a) the downstream locations of the weir and spillway do not have major population centres, or other properties prone to damage, b) the larger Tamor River a few kilometres downstream of the Kabeli River would help to dampen the floods in the Kabeli River. In accordance to Figure 6-1, an increase in flood magnitude is identified as an event with a possible likelihood and a low potential loss making it a low risk event to the project. Phase 4 adaptation measures for high flow concerns are thus not recommended.

6.3 Managing Sediment Abrasion and Accumulation Risks

With increased precipitation in the basin and increased discharge in the river, the sediment concentration is likely to increase in KAHEP.

In the Phase 4, we recommend to address the sediment risks to the project with two adaptation options. a) increase the dimension of the settling basin so that sediment concentrations greater than 4000 ppm can settle in the basin, eliminating the need to completely shut down the power plant above that threshold; or b) use coated runners in the Francis turbine that can withstand the turbine erosion due to higher sediment concentration. Here an alternative design by installing coated turbine runners and other electromechanical part is recommended as an adaption option for phase 4.

Recommended design modification:
Installation of coated turbine, which increases the initial investment by 40%, could help reduce the potential loss in the energy with power plant shutdown (Figure 6-2). In addition to reduction of shutdown days coated turbine also improves the reduction in efficiency with sediment erosion, though these improvements were not explicitly quantified in this analysis.

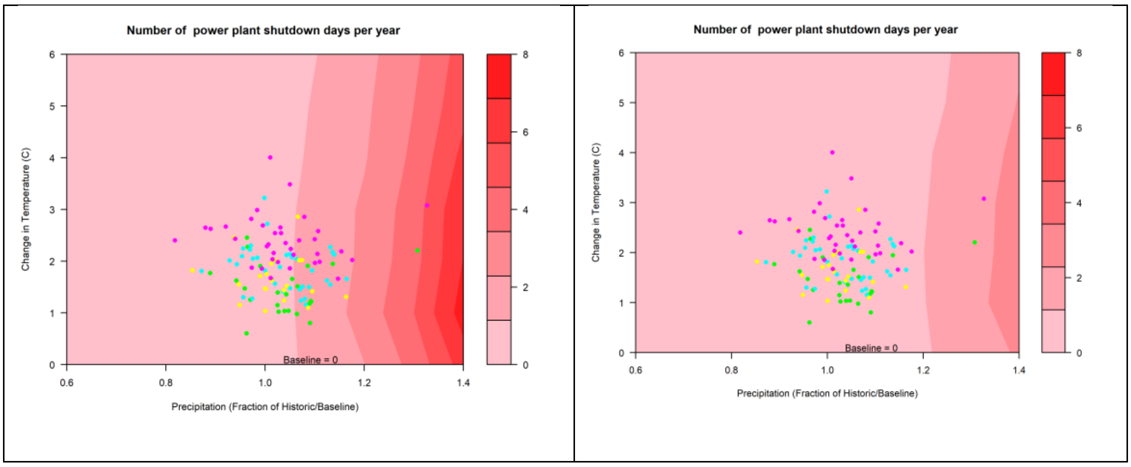


Figure 6-2 a) Response surface for number of days of powerplant shutdown due to sediment concentration exceeding 4000 ppm. b) Modified response surface if the shutdown occurs at a threshold of 6000 ppm (possibility with coated turbines).

Recommended operation rule:
Regular, tri-monthly inspection of the turbine components is recommended with special attention around the monsoon season. Regular repair and maintenance is recommended.

7 Recommendations for modification of hydropower guidelines

The IHA CRG was launched at the World Hydropower Congress on 12 May in Paris, France. The CRG builds on the World Bank's Decision Tree Framework, applying its hierarchical structure to hydropower projects, in particular. It provides four principal modifications to the Decision Tree Framework (which is re-conceptualizes as a decision "river" framework – see Figure 7-1), in order to better target it to the needs of the hydropower sector.

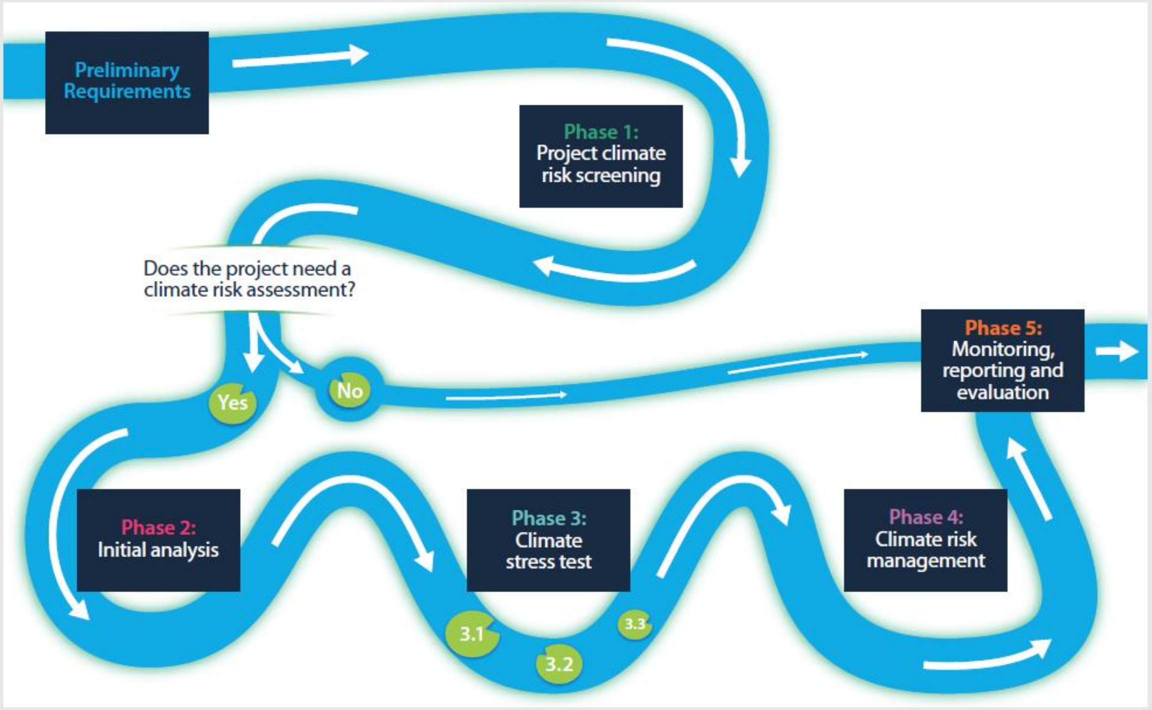


Figure 7-1 IHA CRG Decision "River"

The modifications are:

1. It adds a section on "preliminary requirements", which advises engineering design firms and infrastructure planning institutions on the technical capacity (human and other resources) needed to accomplish an effective climate change resilience exercise.
2. It adds a Phase 5 to the Decision Tree Framework to explicitly mandate monitoring, reporting and evaluation. This class of activities is alluded to in the Decision Tree Framework, but the IHA CRG makes the articulation of the monitoring and evaluation plan a required part of the risk management process.

3. It subdivides the Phase 3 climate stress test into three classes, as shown in Figure 7-2 and Figure 7-3:
    a. The Comprehensive Approach – essentially, full-rigor decision scaling. This approach is the default approach, and to be conducted in cases of medium to high potential detrimental impact of project failure (either lost lives as a result of structural failure or lost wellbeing as a result of insufficient access to electricity), and high quality hydroclimatic data (sufficient for the development of a distributed hydrologic model).
    b. The Semi-comprehensive Approach – decision scaling at reduced temporal and spatial resolution, with a semi-quantitative approach to the evaluation of streamflow extremes. This approach is to be used in cases of medium to high potential detrimental impact of project failure, and poor quality data or poor performing hydrologic models.
    c. The Limited Approach – empirical or heuristic rules of thumb (similar to rapid scoping/initial analysis) drawing from budyko-type models and historical climate analogues. This type of approach is to be used where the possible impacts of project failure are likely to be low, either because of remote location of facilities, small size, or relatively small contribution to the electricity grid.
4. It further subdivides the Phase 3 climate stress test into “safety concerns” and “performance concerns”. Safety concerns are evaluated as extreme flood events. Specific guidance is given in each subcategory of the stress test (comprehensive, semi-comprehensive and limited), for how best to estimate concerns that extreme flood events might be greater in the future than they have been in the observed past.

Two annexes in the CRG provide added value: Annex A: Examples of climate stressors on hydropower projects; and Annex C: Examples of structural and functional adaptation measures for new and existing hydropower projects.

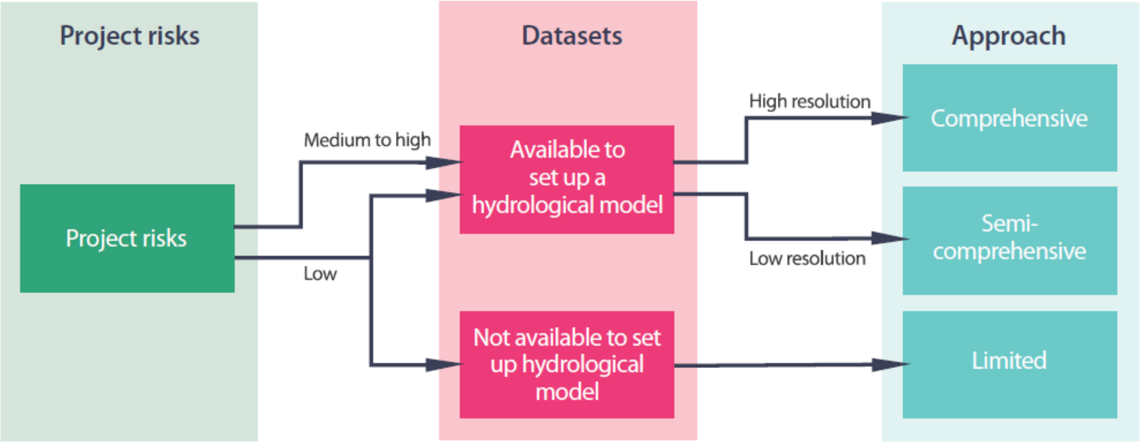
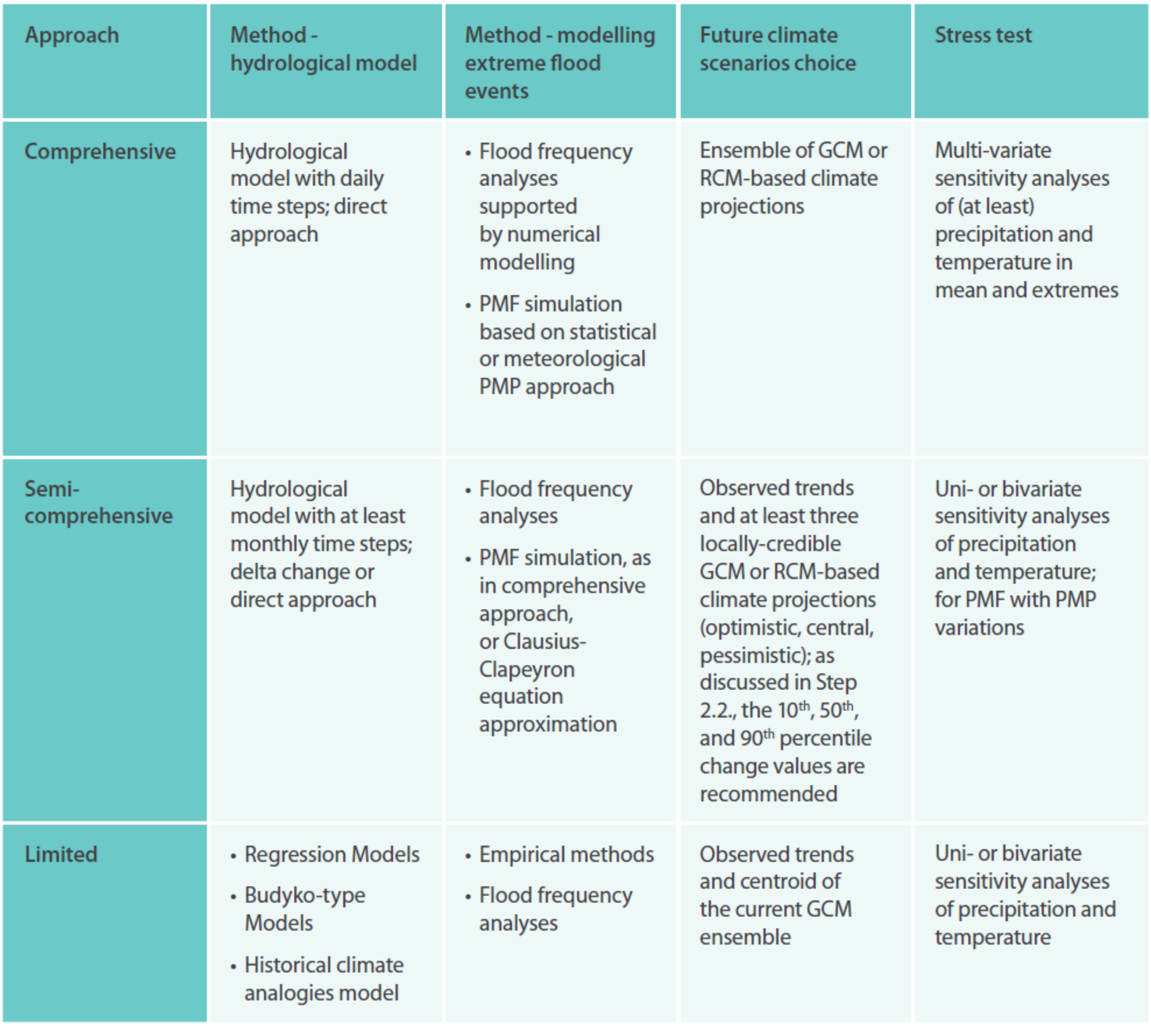


Figure 7-2 Process for identification of appropriate sub-category of Phase 3 Climate Stress Test in the IHA CRG



Approach	Method - hydrological model	Method - modelling extreme flood events	Future climate scenarios choice	Stress test
Comprehensive	Hydrological model with daily time steps; direct approach	• Flood frequency analyses supported by numerical modelling • PMF simulation based on statistical or meteorological PMP approach	Ensemble of GCM or RCM-based climate projections	Multi-variate sensitivity analyses of (at least) precipitation and temperature in mean and extremes
Semi-comprehensive	Hydrological model with at least monthly time steps; delta change or direct approach	• Flood frequency analyses • PMF simulation, as in comprehensive approach, or Clausius-Clapeyron equation approximation	Observed trends and at least three locally-credible GCM or RCM-based climate projections (optimistic, central, pessimistic); as discussed in Step 2.2., the 10th, 50th, and 90th percentile change values are recommended	Uni- or bivariate sensitivity analyses of precipitation and temperature; for PMF with PMP variations
Limited	• Regression Models • Budyko-type Models • Historical climate analogies model	• Empirical methods • Flood frequency analyses	Observed trends and centroid of the current GCM ensemble	Uni- or bivariate sensitivity analyses of precipitation and temperature

Figure 7-3 Analytical aspects each sub-category of Phase 3 Climate Stress Test in IHA CRG

For all its strengths, the IHA CRG is weak on safety concerns, reflecting a current state of the science that has not matured on design considerations for the risks of increased in peak precipitation from climate change. This Kabeli case study takes a comprehensive approach to the evaluation of historical trends and GCM projections of peak annual precipitation (and in the case of historical observations, trends also in streamflow). However, because of the lack of skill of GCMs in the reproduction of historical precipitation extremes, it is difficult to apply a decision-scaling-style impact/likelihood assessment to risks of increasing streamflow extremes. The recommendation of this report is that additional research of both the scientific community and the community of hydropower design engineers be applied to methods for the estimation of likelihood of increasing precipitation extremes. There are a few promising beginnings to this research which rely not on GCM skill in estimation of extreme precipitation, but rather on GCM skill in estimation of regional-scale pressure-based weather regimes. Examples include the work of Steinschneider et al. (2019) with the California Department of Water Resource and the US Army Corps of Engineers, and Schlef et al. (2019) with the Department of Defence in the Ohio River Valley.

One further recommendation for the IHA CRG based on this case study is to put an emphasis on selection of a simple and effective hydrologic model that can be run multiple times with minimal computational effort. The bottom up approach is based on the sensitivity analysis of the project performance under a number of climate and non-climate factors and thus quick and effective hydrologic model is a central part to the evaluation. In the experience of this research team (and as demonstrated using the HBV model in this analysis), it is not necessary to sacrifice quality (or spatial resolution) in hydrologic modelling in order to achieve speed and calibration efficiency.

8 Conclusion

The Kabeli-A Hydroelectric Project (KAHEP) is a proposed peaking run-of-river hydropower with an installed capacity of 37.6 MW, to be located primarily in Panchthar District in the Eastern Development region of Nepal on the Kabeli River, which is a tributary to Tamor River. It is at early stages of construction. KAHEP has a catchment area of 860 km^2 and a mean monthly flow of about 60 m^3s^{-1}. With a gross head of 118.80 m, KAHEP's average annual electrical output is expected to be approximately 205 GWh/year. It is expected to generate electricity to contribute to the national grid for two hours in the morning peak and four hours in the evening peak.

The Project Team (Deltares, University of Cincinnati, and FutureWater) was hired to evaluate the climate change risk to the performance of the KAHEP project, and to put those risks in context relative to risks of other kinds. The Project Team followed the methods laid out in the World Bank's Decision Tree Framework, and adopted by the International Hydropower Association (IHA) in its Hydropower Sector Climate Resilience Guide (CRG). The fundamental risks facing KAHEP and other similar run-of-river hydropower projects worldwide are: 1) drought; 2) flood; 3) increased sediment load. This project therefore evaluated each those three risks in detail, and summarized findings of the best understanding of the Project Team regarding the magnitude of each risk to the KAHEP investment.

Conclusion on Concerns Regarding Future Insufficiency of Flow: The project is expected to be financially profitable (yield a positive Net Present Value, NPV) for all wetter future scenarios (approximately half of the uncertainty space), as well as drier futures, as long as the precipitation drop is less than approximately 20% and the temperature rise is not more than 3 ^oC. Neither condition (precipitation drop greater than 20% or temperature increase greater than 3 ^oC is likely within the next 30 years. A few GCMs under RCP 8.5 project potential futures for the project in which conditions skirt unfavorability, but generally the project appears at low risk of poor financial return. It should be made clear that this analysis accounts only for shifts in average annual conditions. Shifts in extremes are evaluate in the flood risk section, but are not correlated to financial losses. Shifts in seasonality (or seasonal-specific results) were not closely evaluated, as the GCM outputs supporting the likelihood aspects of such evaluations are not of high confidence.

Conclusion on Concerns Regarding Increasing Flood Risk: The design flood for the KAHEP facility is the 1000-year streamflow. Because we do not have available estimates of the consequences (either to the structure or to the downstream population) of exceedance of the 1000-year flood, we cannot evaluate all aspects (impact and likelihood) of flood risk to the KAHEP facility. However, the magnitude peak annual streamflow, and the 1000-year flood, in particular, appears to be increasing throughout the period of historical record (since the middle of the past century), and is likely to further increase in the future. GCMs cannot be consulted directly for credible information on the future behaviour of extreme precipitation. However, when the local historical trends in extreme precipitation and streamflow are evaluated; and the information from the subset of GCM that capture the monsoon processes well are reconciled, we observe that the magnitude of flood peaks is increasing in the basin. The current design flood magnitude is likely to correspond to a much smaller return period, i.e., it may occur every 500 years in the hydro-climate of the next century instead of every 1000.

When the structure was designed for what the designers understood to be a 1000-year return period flood, the designers anticipated a risk characterized by a chance of “not-failure” of the structure during the project life of $.999^{30}$, or about a 3% chance that a 1000-year flood would happen within the project lifetime. Accounting for the historical climate trend, as well as somewhat qualitative information from the GCMs, we see that the magnitude of what was historically a 1000-year flood better corresponds to a 500-year return period flood in the project lifetime. The probability that the flood magnitude would be exceeded during the project life-time is now $1\text{-}0.998^{30}$, or about 6%.

Conclusion on Concerns Regarding High Sediment Load: The sediment load impact on the annual energy production was analysed by calculating the number of days the power plant would be shut down due to excessive sediment in the river. This was accomplished by using an empirical relationship between streamflow and suspended sediment derived as part of this project. The analysis does not take into account rolling bed load. With an increase of precipitation by 20%, a reduction of 2.7 GWHr of annual energy production is predicted, which in terms of financial terms would be $170,100 per year. Moreover, with an increase of precipitation by 20%, up to a 50% increase in the average annual sediment concentration is expected, which could more than double the expected cost for turbine replacement in the project lifetime.

Conclusion to Multidimensional Risk Assessment: When the impacts of uncertainty in sediment load, electricity selling price, capital and O&M costs, and discount rate are evaluated alongside uncertainty in future average annual precipitation and temperature, the project appears to be more sensitive to changes in the capital costs and the energy selling prices than to shifts in temperature and precipitation. An increase in the capital cost by 50% would result in a large loss to the project.

Recommendations for Climate Change Adaptation: No climate change adaptation measures are recommended to manage risks associated with low flows. For flood risk, though we cannot evaluate the trade-offs between flood risk management options in the absence of cost information regarding flood impacts, the Project Team recommends careful consideration by the design engineers of the costs of floods ranging from 100-year to 500-year occurrence intervals, which this analysis shows are much more likely in the next 50 years than they were in the past 50 years. In response to the risk of increased sediment load, this report proposes installation of coated turbines, which would increase the initial investment by 40%, but could help reduce the potential loss in the energy with power plant shutdown. In addition to reduction of shutdown days, coated turbines also reduce the efficiency loss associated with sediment erosion, though these improvements were not explicitly quantified in this analysis.

This report additionally has provided a summary of the IHA CRG – the modifications made to the Decision Tree Framework on which it was based, and an accounting of its strengths (analysis of risks of poor financial performance) and weaknesses (analysis of risks of increasing floods and sediment loads). It also makes recommendations regarding hydrologic (and other) models best fit for the type of stress test analysis adopted by the CRG.

Findings of this report regarding long-term average hydropower production are fairly confident. Findings related to precipitation and streamflow extremes are less so. The impact of increasing streamflow extremes on the weir are not well understood, but more importantly, are not of concern to KEL and other project stakeholders.

Therefore, though the likelihoods of changes in precipitation extremes are unsure, the conclusions regarding risk (with impacts derived directly from expert elicitation) are not. In the absence of data correlating streamflow extremes to weir damages, a quantitative modeling assessment of the statements of the stakeholders was not possible.

In order to address these weaknesses in the current analysis, we recommend: 1) detailed study of the impact on the structure and downstream population of floods exceeding the magnitude of the historical 1000-year return period event, with subsequent design modifications as warranted; 2) scientific exploration of the relationship between seasonality and peak floods in the Kabeli basin (and broader Himalayan range) and climate drivers likely to change with warming (esp., ENSO and the Indian Dipole); 3) further data collection, in Nepal and elsewhere, of data on suspended sediment and rolling bed load under a wide range of streamflow conditions. Points 1 and 2 would greatly strengthen the analysis of flood risk on this project (and other similar projects). Point 3 would strengthen the analysis of the risk of increased sediment load with hydrologic regime shift.

9 References

Andermann, C., Bonnet, S., and Gloaguen, R. (2011). "Evaluation of precipitation data sets along the Himalayan front." Geochemistry, Geophysics, Geosystems, 12(7)

Annandale GW, Morris GL, Karki P (2016) Extending the Life of Reservoirs. World Bank Publications, US

Bajracharya TR, Acharya B, Joshi CB, Saini RR, Dahhaug OG (2008) Sand erosion of Pelton turbine nozzles and buckets: A case study of Chilime Hydropower Plant 264:177-184. doi: 10.1016/j.wear.2007.02.021

Beck HE, van Dijk AI, de Roo A, Dutra E, Fink G, Orth R, Schellekens J (2017) Global evaluation of runoff from ten state-of-the-art hydrological models 21:2881-2903

Beyene T, Lettenmaier DP, Kabat P (2010) Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios. Clim Change 100:433-461. doi: 10.1007/s10584-009-9693-0

Bharati L, Gurung P, Jayakody P, Smakhtin V, Bhattarai U (2014) The projected impact of climate change on water availability and development in the Koshi Basin, Nepal 34:118-130

Bolch T, Kulkarni A, Kaab A, Huggel C, Paul F, Cogley JG, Frey H, Kargel JS, Fujita K, Scheel M, Bajracharya S, Stoffel M (2012) The State and Fate of Himalayan Glaciers 336:310-314. doi: 10.1126/science.1215828

Christensen NS, Wood AW, Voisin N, Lettenmaier DP, Palmer RN (2004) The effects of climate change on the hydrology and water resources of the Colorado River basin. Clim Change 62:337-363. doi: CLIM.0000013684.13621.1f

Cloudwater, L.L.C. (2015) Upper Trishuli-1 Hydropower Facility Climate Change Risk Assessment: Draft Final Report. Report submitted to the International Finance Corporation, 31 May 2015.

Dao Nguyen Khoi, Suetsugi T (2014a) Impact of climate and land-use changes on hydrological processes and sediment yield-a case study of the Be River catchment, Vietnam. Hydrol Sci J -J Sci Hydrol 59:1095-1108. doi: 10.1080/02626667.2013.819433

Dao Nguyen Khoi, Suetsugi T (2014b) The responses of hydrological processes and sediment yield to land-use and climate change in the Be River Catchment, Vietnam. Hydrol Process 28:640-652. doi: 10.1002/hyp.9620

Destouni G, Jaramillo F, Prieto C (2013) Hydroclimatic shifts driven by human water use for food and energy production 3:213

Finger D, Heinrich G, Gobiet A, Bauder A (2012) Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century. Water Resour Res 48

Gao P, Geissen V, Ritsema CJ, Mu X, Wang F (2013) Impact of climate change and anthropogenic activities on stream flow and sediment discharge in the Wei River basin, China. Hydrol Earth Syst Sci 17:961-972. doi: 10.5194/hess-17-961-2013

Giuliani M, Anghileri D, Castelletti A, Phuong Nam Vu, Soncini-Sessa R (2016) Large storage operations under climate change: expanding uncertainties and evolving tradeoffs 11:035009. doi: 10.1088/1748-9326/11/3/035009

Hamlet AF, Lee S, Mickelson KEB, Elsner MM (2010) Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. Clim Change 102:103-128. doi: 10.1007/s10584-010-9857-y

Hanshaw MN, Bookhagen B (2014) Glacial areas, lake areas, and snow lines from 1975 to 2012: status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru 8:359-376

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H. (2014). "Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset." Int.J.Climatol., 34(3), 623-642.

Ho JT, Thompson JR, Brierley C (2016) Projections of hydrology in the Tocantins-Araguaia Basin, Brazil: uncertainty assessment using the CMIP5 ensemble 61:551-567. doi: 10.1080/02626667.2015.1057513

IEC. Hydraulic machines—guide for dealing with abrasive erosion in water. IEC-62364 Ed 102009

Immerzeel, W.W., L.P.H. van Beek, M.F.P. Bierkens. 2010. Climate Change Will Affect the Asian Water Tower. Science 11 Jun 2010: Vol. 328, Issue 5984, pp. 1382-1385. DOI: 10.1126/science.1183188

Immerzeel, W.W., N. Wanders, A. Lutz, J.M. Shea, M.F.P. Bierkens. 2015. Reconciling high-altitude precipitation in the upper Indus basin with glacier mass balances and runoff. Hydrology and Earth System Sciences

Immerzeel, W. (2008). "Historical trends and future predictions of climate variability in the Brahmaputra basin." Int.J.Climatol., 28(2), 243-254.

Kamiguchi, K., Arakawa, O., Kitoh, A., Yatagai, A., Hamada, A., and Yasutomi, N. (2010). "Development of APHRO_JP, the first Japanese high-resolution daily precipitation product for more than 100 years." Hydrological Research Letters, 4 60-64.

Koirala R, Thapa B, Neopane HP, Zhu B, Chhetry B (2016) Sediment erosion in guide vanes of Francis turbine: A case study of Kaligandaki Hydropower Plant, Nepal 362:53-60. doi: 10.1016/j.wear.2016.05.013

Kraaijenbrink P.D.A, M.F.P. Bierkens, A.F. Lutz, W.W. Immerzeel. 2017. Impact of a 1.5 °C global temperature rise on Asia’s glaciers. Nature, 54, 257–260. doi: 10.1038/nature23878.

Kripalani, R. H., Oh, J. H., Kulkarni, A., Sabade, S. S., and Chaudhari, H. S. (2007). "South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4." *Theoretical and Applied Climatology,* 90(3-4), 133-159.

Laghari AN, Vanham D, Rauch W (2012) To what extent does climate change result in a shift in Alpine hydrology? A case study in the Austrian Alps 57:103-117

Lehner B, Czisch G, Vassolo S (2005) The impact of global change on the hydropower potential of Europe: a model-based analysis 33:839-855. doi: 10.1016/j.enpol.2003.10.018

Lindström G, Johansson B, Persson M, Gardelin M, Bergström S (1997) Development and test of the distributed HBV-96 hydrological model 201:272-288. doi: 10.1016/S0022-1694(97)00041-3

Lutz, A.F., W.W. Immerzeel, P.D.A. Kraaijenbrink, A.B. Shrestha, M.F.P. Bierkens. 2016. Climate Change Impacts on the Upper Indus Hydrology: Sources, Shifts and Extremes. PLOS ONE 11(11): e0165630. doi: 10.1371/journal.pone.0165630

Madani K, Lund JR (2010) Estimated impacts of climate warming on California's high-elevation hydropower. Clim Change 102:521-538

Majone B, Villa F, Deidda R, Bellin A (2016) Impact of climate change and water use policies on hydropower potential in the south-eastern Alpine region. Sci Total Environ 543:965-980. doi: 10.1016/j.scitotenv.2015.05.009

Markoff MS, Cullen AC (2008) Impact of climate change on Pacific Northwest hydropower. Clim Change 87:451-469. doi: 10.1007/s10584-007-9306-8

Maurer EP, Adam JC, Wood AW (2009) Climate model based consensus on the hydrologic impacts of climate change to the Rio Lempa basin of Central America 13:183-194. doi: 10.5194/hess-13-183-2009

Mehta VK, Rheinheimer DE, Yates D, Purkey DR, Viers JH, Young CA, Mount JF (2011) Potential impacts on hydrology and hydropower production under climate warming of the Sierra Nevada 2:29-43. doi: 10.2166/wcc.2011.054

Minville M, Brissette F, Krau S, Leconte R (2009) Adaptation to Climate Change in the Management of a Canadian Water-Resources System Exploited for Hydropower. Water Resour Manage 23:2965-2986. doi: 10.1007/s11269-009-9418-1

Mool, P., Popescu, I., Giri, S., Omer, A., Sloff, K., Kitamura, Y., and Solomatine, D. (2017). "Delft3D morphological modelling of sediment management in daily peaking run-of-the-river hydropower (PROR) reservoirs in Nepal."

M.S. Bingley ,D. J. O. Flynn, "Examination and comparison of various erosive wear models, Wear 258 (2005) 511–525.

Noon AA, Kim M (2017) Erosion wear on Francis turbine components due to sediment flow 378-379:126-135. doi: 10.1016/j.wear.2017.02.040

Padhy MK, Saini RP (2008) A review on silt erosion in hydro turbines 12:1974-1987. doi: 10.1016/j.rser.2007.01.025

Poerbandono, Julian MM, Ward PJ (2014) Assessment of the effects of climate and land cover changes on river discharge and sediment yield, and an adaptive spatial planning in the Jakarta region. Nat Hazards 73:507-530. doi: 10.1007/s11069-014-1083-x

Palazzi, E., Hardenberg, J., and Provenzale, A. (2013). "Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios." Journal of Geophysical Research: Atmospheres, 118(1), 85-100.
Plesca, I., Timbe, E., Exbrayat, J. F., Windhorst, D., Kraft, P., Crespo, P. V. K. B & Breuer, L. (2012). Model intercomparison to explore catchment functioning: Results from a remote montane tropical rainforest. Ecological Modelling, 239, 3-13.

Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space, Colorado, USA. Digital Media. DOI: https://doi.org/10.7265/N5-RGI-60

Ray, P. A., Bonzanigo, L., Wi, S., Yang, Y. E., Karki, P., Garcia, L. E., Rodriguez, D. J., and Brown, C. M. (2018). "Multidimensional stress test for hydropower investments facing climate, geophysical and financial uncertainty." Global Environ.Change, 48 168-181.

Ray, P., and Brown, C. (2015). “Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework." World Bank Group, Washington, D.C., doi: 10.1596/978-1-4648-0477-9. https: //openknowledge.worldbank.org/handle/10986/22544

Schaefli B, Hingray B, Musy A (2007) Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties 11:1191-1205. doi: 10.5194/hess-11-1191-2007

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., and Rudolf, B. (2014). "GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle." Theor Appl Climatol, 115(1), 15-40.

Sharma RH, Shakya NM (2006) Hydrological changes and its impact on water resources of Bagmati watershed, Nepal 327:315-322

Sharmila S, Joseph S, Sahai AK, Abhilash S, Chattopadhyay R (2015) Future projection of Indian summer monsoon variability under climate change scenario: An assessment from CMIP5 climate models 124:62-78. doi: 10.1016/j.gloplacha.2014.11.004

Sheffield, J., Goteti, G., and Wood, E. F. (2006). "Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling." J.Clim., 19(13), 3088-3111.

Shi H, Wang G (2015) Impacts of climate change and hydraulic structures on runoff and sediment discharge in the middle Yellow River. Hydrol Process 29:3236-3246. doi: 10.1002/hyp.10439

Shrestha, A., and Kostaschuk, R. (2005). "El Nino/Southern Oscillation (ENSO)-related variablity in mean-monthly streamflow in Nepal." J.Hydrol., 308(1-4), 33-49.

Shrestha, A. B., and Aryal, R. (2011). "Climate change in Nepal and its impact on Himalayan glaciers." Regional Environmental Change, 11(1), 65-77.

Shrestha, A. B., Bajracharya, S. R., Sharma, A. R., Duo, C., and Kulkarni, A. (2017). "Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin 1975–2010." Int.J.Climatol., 37(2), 1066-1083.

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., and Beniston, M. (2012). "Climate change impacts on glaciers and runoff in Tien Shan (Central Asia)." Nature Climate Change, 2(10), 725.

Steinschneider S, Brown C (2013) A semiparametric multivariate, multisite weather generator with low-frequency variability for use in climate risk assessments. Water Resour Res 49:7205-7220. doi: 10.1002/wrcr.20528

Storch, H. v., and Navarra, A. (1995). Analysis of climate variability: Applications of statistical techniques. Springer-Verlag, New York.

TANER, M.U., RAY, P. and BROWN, C., 2017. Robustness-based evaluation of hydropower infrastructure design under climate change. Climate Risk Management, 18, pp. 34-50.

te Linde AH, Aerts, J. C. J. H., Hurkmans, R. T. W. L., Eberle M (2008) Comparing model performance of two rainfall-runoff models in the Rhine basin using different atmospheric forcing data sets 12:943-957. doi: 10.5194/hess-12-943-2008

Terink, W., W.W. Immerzeel, A.F. Lutz, P. Droogers, S. Khanal, S. Nepal, A.B. Shrestha. 2017. Hydrological and Climate Change Assessment for Hydropower development in the Tamakoshi River Basin, Nepal. FutureWater Report 164.

Terink, W., A.F. Lutz, G.W.H. Simons, W.W. Immerzeel, P. Droogers. 2015. SPHY v2.0: Spatial Processes in HYdrology. Geoscientific Model Development 8: 2009-2034

Thapa BS, Dahlhaug OG, Thapa B (2015) Sediment erosion in hydro turbines and its effect on the flow around guide vanes of Francis turbine 49:1100-1113

Thapa BS, Thapa B, Dahlhaug OG (2012) Empirical modelling of sediment erosion in Francis turbines 41:386-391. doi: 10.1016/j.energy.2012.02.066

Wang H, Yang Z, Saito Y, Liu JP, Sun X, Wang Y (2007) Stepwise decreases of the Huanghe (Yellow River) sediment load (1950-2005): Impacts of climate change and human activities. Global Planet Change 57:331-354. doi: 10.1016/j.gloplacha.2007.01.003

Wang QJ (1991) The Genetic Algorithm and Its Application to Calibrating Conceptual Rainfall-Runoff Models 27:2467-2471. doi: 10.1029/91WR01305

Wi, S., Yang, Y. C. E., Steinschneider, S., Khalil, A., and Brown, C. M. (2015). "Calibration approaches for distributed hydrologic models in poorly gaged basins: implication for streamflow projections under climate change." Hydrology and Earth System Sciences, 19(2), 857-876.

Wild, T. B., Loucks, D. P., Annandale, G. W., and Kaini, P. (2015). "Maintaining sediment flows through hydropower dams in the Mekong River Basin." J.Water Resour.Plann.Manage., 142(1), 05015004

Willmott, C. J. (2000). "Terrestrial air temperature and precipitation: Monthly and annual time series (1950-1996)." WWW Url: Http://Climate.Geog.Udel.Edu/~ Climate/Html_pages/README.Ghcn_ts.Html, Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., and Wilkes, A. (2009). "The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods." Conserv.Biol., 23(3), 520-530.

YANG, Y.C.E., WI, S., RAY, P.A., BROWN, C.M. and KHALIL, A.F., 2016. The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories. Global Environmental Change-Human and Policy Dimensions, 37, pp. 16-30

Yasutomi, N., Hamada, A., and Yatagai, A. (2011). "Development of a long-term daily gridded temperature dataset and its application to rain/snow discrimination of daily precipitation." Global Environ.Res, 15(2), 165-172.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., and Kitoh, A. (2012). "APHRODITE Constructing a Long-Term Daily Gridded Precipitation Dataset for Asia Based on a Dense Network of Rain Gauges." Bull.Am.Meteorol.Soc., 93(9), 1401-1415.

Yuan, X., Wood, E. F., and Liang, M. (2014). "Integrating weather and climate prediction: Toward seamless hydrologic forecasting." Geophys.Res.Lett., 41(16), 5891-5896.
Von Storch, H.; Navarra, A. Analysis of Climate Variability - Applications of Statistical Techniques. Springer-Verlag, New York, USA., 1995

A Annex I: Minutes of Workshop Meetings in Nepal

1. Part I: First Visit (Inception Workshop)

The Consultant made a visit to Nepal (June 25, 2018 – June 29, 2018) to present and discuss work plan with stakeholders and compile additional information. We were in deep discussion with the Kabeli Energy Limited (KEL) team leaders, World Bank Energy Team, Social Team and Environmental Team. We also had meeting with the leaders of the Upper Arun Team who shared their feedback on the previous pilot project in similar Climate Resilience Guidelines in Nepal. We met with the Government representative of Department of Electricity Development (DoED) and Department of Hydrology and Meteorology (DHM). We also interacted with some young engineers at Hydro Lab who were presenting their ideas on Climate Impacts on the Himalayas.

There was a significant amount of information exchange and useful reports and data previously collected by the responsible teams were shared with us. It was identified that some non-climate risk factors like sediment, chances of increase in the capital cost by two to four times and significant delay in construction work was of major concern to the stakeholders. In addition, climate risk factors as flood, dry period, inter-annual climate variability particularly shifts in monsoon peak flow was of particular interest to the stakeholders. It was a consensus among the participants that the aspects of livelihood and social wellbeing of the society in such large-scale construction should be addressed better. The government representative, particularly those from DoED expressed that there is not enough interaction, collaboration and coordination amongst individual companies building hydropower within the same catchment. They voiced a necessity to have a basin-wide impact assessment and better coordination for overall development.

Another important question raised during the meetings with the stakeholders was a necessity of assessment of landslides and soil erosion trigged by rapid rainfall in the rugged terrain which could have two negative impacts. The immediate impact is on the intake or other component hydropower plant and the secondary impact is on the transmission lines carrying the electricity to the distribution grids. Besides, owing to the fact of a huge earthquake in Nepal in 2015 resulting is significant loss of life and property, the hydropower is also faced with a high seismic risk. Other things like flow for cremation sites, festivals, environmental flow.

Date	Meeting with	Venue	Key points
June 25, 2018, 2-4 PM	Kick off meeting KEL Team leader (Sher Singh Bhatt and Ravi Kumar Gautam) Deltares(Sanjay Giri) WB Energy Team (Barsha Pandey) WB Social Team (Caroline) WB Env Team Homero Paltan	Sagarmatha Conference Room, WB office	• KAHEP is studied a lot. Lots of pilot projected has been done there. • Caroline strongly expressed her opinion that road construction callused landslide in Upper Arun. She also raised some contractor issues in the KAHEP and some other issues on non-compliance of environmental and other guidelines by the project.
June 26, 2018 11 am	Upper Arun Team (Bishwa Dhoj Joshi) Homero Paltan	Upper Arun Office	• Currently in design docs phase – detailed design just started. • Highway being built to U Arun site, so far extending to Arun III (900 MW) road is very good. • Consultant now doing cost optimization on Upper Arun. 3 scenarios being evaluated: Q25 (1300 MW) up to Q80 (w/Q40 725 MW). Optimization based on energy market, not hydrology. Up to Q40, sell-able in domestic market. • Status of India agreement: almost entirely an import market now (and flat throughout year); but expectation is that the agreement will be revised to allow for export soon. • G2G versus private companies (Government to Government). Sell up to Q40 @ 4.8 and 8.4 rupees/kWh wet/dry, then sell the rest to India. Don't know the price we would sell at yet, but probably at the already agreed import rate of about 3.5 rupees/kWh. • 30 months to build road, 4-5 years to build after road gets built. Commissioned by about 2026. $1.4 Billion USD, developed through company. Already established Upper Arun Hydroelectric Company. • 30 MWIkhuwa Khola project in tributary to Arun River being developed by same company at same time. 600 m of head, Q40, 6.6 m^3/s.

			• The Q_{70} was 335 MW but new design is proposed with 500 MW. (lines up with the suggestion from the pilot study) • Butwal-Gorakhpur 400KV double Circuit Transmission Line is planned and is expected to be completed within next 3-4 years. Would create a market to sell excess energy during wet season to India. They estimated the selling/buying rate would be 3.55 IC/KW = 0.049$/KW. • Strong suggestion not to translate the benefit to money using discount rate and to have comparison based on energy production. • IPP – Independent Power Producer • CDMA – subsidiary company of NEA, more flexibility. NEA owns majority share: 68% of Upper Arun. 15% to public. 10% to local people. 5% to NEA staff. • Arun IV is under evaluation/study between Arun III and Upper Arun, and even another one upstream of Upper Arun, 2 km from boarder. • *do financial assessments using discount rates undermines these types of cc analyses – maybe skip financial analysis part.
June 26, 2018 2 pm	• Government Officers of DoED • Sandev Kumar Dev • Sunil Piya • Homero Paltan	• Department of Electricity Development	• Have not signed the contract yet, but hope to in the next 2-3 weeks. • ERM – Environmental Resources Management • Kabeli – detailed design already done, project now under construction • 4-5 projects throughout Kabeli basin • Project awarded in 2007, but very delayed • HIDC – Hydropower investment and development company funding bank • Possibility of large storage project on the Tamor River that would be very large and would inundate the Kabeli Project • If Kabeli only operates for 10-20 years, would that be fine? • Kabeli Company to operate project for 35 years

			• Nepal really needs storage. We continue to evaluate opportunities for large storage dams. • Energy banking agreements with India always in discussion (Nepal to India in wet season; India to Nepal in dry season) • Government goals: 10 years 5000 MW total; now, it's about 1000 MW. Next year will add 800 MW from Upper Tamar Koshi. Then each year after that an additional 400-500 MW/yr. • Budhi Gandaki 1200 MW, 100 km from Kathmandu. Displacing 50,000 people. Finished detailed design, so construction will start soon. Will take about 7 years to build. • The national electricity/hydropower plan was done in the 1980s. Needs to be updated. But load shedding was done for so long (about 10 years) that now they are desperate and just approving everything. When our stomachs are full… will reassess. Big interest in basin-wide plan, once no longer desperate. Take steps to ensure downstream peaking flow when approving upstream. Lower Arun to Arun III to Upper Arun, for example. • Need for Cumulative Impact Assessment in the basin. • Coordination is required among different hydropower companies • Cummulative Impact Assesment is being carried out for the first time for the entire Tamor Basin (Bigger basin including Kabeli) . Are willing to share data on the basin (No of hydropower/transmission lines existing/proposed in the catchment)
June 26, 2018 4 pm	• Hydrolab • Homero Paltan • Deltares(Sanjay Giri) • IHA (Maria) •	• Hydrolab	• Sustainability has a different meaning for the private investors than it has for the government. Maybe 20-30 years vs 100+ years. How do the hydropower resilience guidelines reconcile these conflicts? • Concern raised: The Nepali Hydropower Guidelines are poor and consultants just take money for approximately following rules. Don't know how to think about uncertain future performance • Climate Assessment intended to be accomplished at the same time as the ESIA.

			• It is difficult to measure sediment load. All they measure is suspended solids, but that is only part of the story. There is also rolling bed sediment movement. Standard practice is to use the few catchments in Nepal where there are sediment measurements and extrapolate to other catchments using regressions based on size and land use characteristics.
June 27, 2018 9 am	• Vishnu Pandey • • IFC (Ross Hamilton) • IHA (Maria) • Homero Paltan •	• IWMI Office	• IFC has performance standards, which include climate change risks. Ross says that IFC increasingly asks if climate concerns have been addressed. The response might be “well, we followed this”, so IFC cares that it is good and addresses their concerns. • Vishnu says IWMI has adopted a process of GCM/RCM to downscaling to hydrologic model to infrastructure model. Asks me about how we predict the future. How do we pick which GCMs/RCMs to use out of all the options? • Social Impact Assessments across the board are done very poorly. In the engineering community, we tend to focus on engineering solutions, hard solutions. IWMI has good experience in soft solutions, sorely lacking in the guidelines. • Until now, largest project is 144 MW. Now government unbundling NEA to make Hydropower Development Companies capable of developing larger hydropower projects – 1000 MW currently under development. • IWMI trying to understand discourse around hydropower. Ranging throughout country. • Climate vulnerability of various basins throughout Nepal w/social elements and human dimensions. Report on IWMI website: request this. • Vishnu: what he would want out of Hydro Guidelines: 1) put 0.5 ^{o}C change in financial terms – does it matter? 2) does it affect costs/revenues? 3) does it change human dimension / social or environmental factors? 4) clim change may matter globally, but does it matter locally? 5) where do clim change risks rank relative to other risks?

			• Offered Help and support. Doing similar works in other parts of Nepal • They are the local geographic experts. Need help form them in holistic ranking of the project. • Discussions on hard and soft solutions (if local people are causing hindrance to the construction or destructing equipment, give them share from the beginning of the project)
June 28, 2018 10am-1 pm	• IFC (Ross Hamilton) • IHA (Maria) • KEL Team leader • (Sher Singh Bhatt • and • Ravi Kumar Gautam) • • Deltares(Sanjay Giri) • Homero •	• World Bank Office	• Follow-up meetings • Peak-power contractual obligations – what are the risks that will fail to meet it? And maybe will meet it overall, but with shifting monthly distribution? • Trade-off disaster risk – power purchase agreement of hydrological risk: natural interannual variability versus long term trends. If discharge seasonality is shifting, you can make an amendment to the PPA Agreement, shifting delivery agreements. You can declare 1 month before that you won't be able to deliver next month, then you can be adjusted up to 10%. In deemed energy, you can declare planned outages (maybe 6%) as well. CONTINGENCIES • *Seasonality and Forecasts* - big opportunity here for innovation in the use of these mechanisms for improving projections of next month's production. What is the skill of seasonal forecasts for this region? Can we use these to improve expectations for how much will be delivered next month? Potentially a very cool idea. Are there Columbia Univ papers? Ganges? ENSO? • Kabeli project only has a 1000 year flood risk – small project, so smaller flood worry (dambreak) from damage to structure. • Environmental Issues: cremation flows, ecological temperature sensitivity, Kabeli A has been monitoring water temperatures, but the station damaged 1 year ago (theft?) – and crop sensitivity question • Sediment: KEL has sediment data since 2010, analyzed by Hydrolab. Peaking reservoir itself has desilting capacity. Debate with contractor about whether desilting additions are needed.

			Can just open 4 gates and pass 1000 year flood in wet season to flush. • Early warning system needed? Already have it. Have 20-25 minutes time to evacuate. • Social Action Plan: get access to that. Social panel of experts, environmental panel of experts. • Technical Engineer: Fichtner • 37.4 MW, so that's a lot of experts gathered for such a small project. • n-1 criteria: need to be able to pass the design flood even if one of the gates is out of order. • Kabeli: CCRA climate change risk assessment • Cost of road is not included in the cost of the project. Accessiblity is a prerequisite for consideration of the project. Cost of transmission line not included, either. That cost is taken by the off-taker. • 20-yr gap between data (1985-2006) and turning it on (in 2026). Hydrology might change in that time. • Sher Sing Bhat used to work at NEA and when contractors would complain about PPA and ask for amendment, he would say it's year 1 and you are generating 50% of what you designed for, so it's your mistake! This is not climate change. • Standard PPA form NEA in order to understand risks of not delivering on contract and what amendments are possible? • If you have a wet year then a dry year, can you bank the wet year Kw deliveries? • What about transmission lines and other ancillary issues? Not risk borne by KEL, exactly, but sort of. If power lines go down, KEL can't sell. Also, might take blame even if not fair. Court of public opinion. Landslide/GLOF risk. Transmission lines designed for max electron flow, just before lines melt. If +3 ^{o}C, lines melt faster so have to reduce electron flow? Interesting question…

			• Great interest in hydrological natural variability probabilistic modeling. Uncertainty and variability in planning model. Challenge the observed stream flow itself. Perhaps should assign 40% probability to “natural” flow based on climate change risk. • How much extra sediment might the river carry because of climate change? • So far so good on performance of power producers. They are all delivering on their contracts. Many over-delivering. NEA has option to buy, but can refuse. And if buy, then pay only 50% for extra energy. • ICIMOD: “we have not been consulted”. Will give nasty comments on our work. Swiss/Swedes/Dutch fund WB and ICIMOD. WB sends a study to donors saying “hey, look at our cool analysis.” They’ll send to ICIMOD and say “what do you think of this?” ICIMOD will say “they have no credibility”. So, need to included ICIMOD! • Discussion on Available data and reports. KEL was willing to share the reports and data they had collected in the basin. • Issue with contractor on the size of desander and number of flushing gates.
June 28, 2018 2pm	• Government Officer from DHM • • Deltares(Sanjay Giri) • Homero • Ross Hamilton	• Department of Hydrology and Meteorology	• Expressed an interest in the work we are doing.
June 29, 2018	• Ross Hamilton • ICIMOD Team • Bikash Sharma(Economist) • Neera Shrestha Pradhan • Kanchan Shrestha(Koshi Basin) • Santosh Nepal	• ICIMOD	• Willingness to help and support • Information and knowledge exchange

	• Arun Bhakta Shrestha (*The cryosphere guy; Physical Risks for Climate Change • *He has done a lot of good work has good papers.		

2. Part II : Second Visit to Nepal (Stakeholder Meeting and Feedback on Phase 3 Risk Assessment)

The Consultant made a visit to Nepal (June 3, 2019 – June 6, 2019) to present and to receive feedback on the stress test results of Phase 3 of the analysis from stakeholders and compile additional/missing information. We had a deep discussion with the Kabeli Energy Limited (KEL) team leaders on the results and its significance on the safety and economy of the project. We also had a meeting with World Bank Energy Team in Kathmandu and presented our findings. We met with the team at Hydrolab who shared their experience working with the sediment data in KAHEP and other catchments in Nepal, and provided insights on the problems induced with sediment concentration. We also interacted with some graduate students specializing in Water Resources Engineering and Climate Change at the Institute of Engineering, Pulchowk Campus and shared our ideas on Climate Impact assessment in the Himalayan Hydropower sector.

Venue	Time	Participants	Meeting Details
KEL Office, Kathmandu	June 3, 2:00 – 4:00 PM	Prabash Aacharya Sher Singh Bhat Bishnu Sharma Asphota Wasti Homero Paltan (remote access)	**Low flow** concerns are minimal. Likelihood of increase in **flood magnitude** is high, but the impact to the downstream population is low. Thus, the overall concern is low. KEL stakeholders are interested in the evaluation of **changes in the sediment** concentration and associated risks. Not very concerned about turbine abrasion or loss in efficiency. Interested in the evaluation of shutdown of the hydropower plant due to sediment overload. KEL also discussed about the power purchase agreement and were interested to understand how changing climate might affect the PPA.
Skype Meeting	June 3, 8:00 - 8:30 PM	Homero Paltan Asphota Wasti	Agreement with the stakeholders meeting and plans for Phase 4. Homero mentioned consultation with Hydrolab, local sediment expert for calculations and evaluations of sediment risks might be helpful for phase 4.

World Bank Office, Kathmandu	June 5, 1:30 – 2:00 PM	Subodh Adhikari Asphota Wasti Garima Mandavya	Discussion on the project progress and next steps for Phase 4 of the project.
Hydrolab, Lalitpur	June 6, 2:00 – 3:00 PM	Meg Bishwakarma Asphota Wasti Garima Mandavya	The loss in turbine efficiency and repair/maintenance cost of the turbine is a huge part of cost. However proper documentation or theory is not available. Suggested threshold for shutting down the project = 4000 ppm. Phone conversation with the operational engineers from Jhimruk Hydroelectric Project (> 3000 ppm) and Khimti Hydroelectric Project (> 6000 ppm). *“It is difficult to estimate the loss in turbine efficiency due to sediment concentration in a hydropower plant as it depends on the operation rule. It is a common practice in Nepali rivers to shut down the power production when the sediment concentration in the river exceeds a threshold. The threshold depends upon type of turbine, sediment concentration, sediment mineral content and is decided based on the operational experience”* based on conversation with Meg Bishwakarma, Hydrolab. Based on phone conversation with operational manager at a) Jhimruk Hydroelectric Project, the plant is shutdown when the sediment concentration exceeds 3000 PPM, b) for Khimti Hydroelectric Project, the operational suggestion was to shutdown the power plant when the sediment concentration exceeds 6000 PPM. With more than 20 years of operational experience, the regime has been changed and now the power plant is

			not shutdown regardless of sediment concentration. The runner of the Francis turbine is repaired every year alternating between two available runners extending the replacement cycle of turbines to 10-12 years. The threshold for power plant shutdown due to sediment is project-specific and determined based on operational experience. For this analysis of the Kabeli A Hydroelectric Project, the value is taken to be 4000 PPM.
Institute of Engineering, Pulchowk Campus, Lalitpur	June 6, 5:00 - 6:00 PM	Pawan Bhattarai Asphota Wasti Presentation on IHA Guide and Bottom Up approach to ~ 40 graduate students from IOE, Pulchowk Campus (MSc Climate Change, MSc Water Resources)	Students interested in doing climate study for water resource management and learn the skill for development of response surface. - Interested in the global gridded datasets and availability of those datasets. - Decision Tree Framework and Bottom up approach being included as a chapter in the course for MSc in Climate Change. - Huge possibility of further collaboration.

B ANNEX II: SPHY Model Description

A hydrological model commonly used for climate change impact assessments in the Himalayas is the Spatial Processes in Hydrology (SPHY) model (Terink et al., 2015). This model includes glacier and snow dynamics and has been used for high-impact peer-reviewed scientific papers (Kraaijenbrink et al 2017, Lutz et al 2016, Immerzeel et al 2015). The model is developed by consortium member FutureWater, in collaboration with the International Centre for Integrated Mountain Development (ICIMOD), Nepal, and available in the public domain.

The SPHY model is a fully distributed cryospheric-hydrological model that supports studies at a variety of spatial scales and is typically run with daily timesteps. The algorithm incorporates all major hydrological processes as well as cryospheric processes. It has been used in several studies to evaluate and predict river discharges and water availability in Nepal and surrounding countries.

In SPHY, the actual runoff which is calculated for each grid cell consists of four contributing factors. These are: runoff originating from rain, runoff originating from snow melt, runoff originating from glacial melt, and base flow. The model allows tracing the origin of the flow and thus gives for every point in the basin an assessment of how the flow can be potentially influenced by future changes in snow and glacier dynamics upstream (see example in the Figure 9-1 below). Since only limited data is available at the intake, multiple calibration and validation steps may be necessary (Wi, Yang, Steinschneider, Khalil, & Brown, 2015).

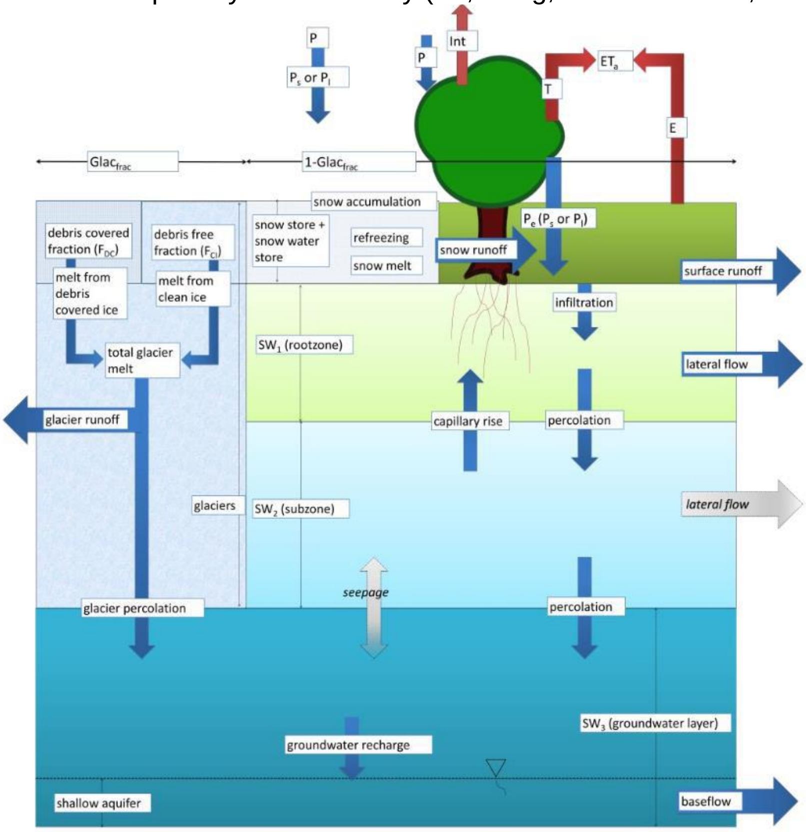


Figure 9-1 SPHY model concepts [Terink et al., 2015].

C ANNEX III: Discussion on Working Definitions for Metrics of Project Performance

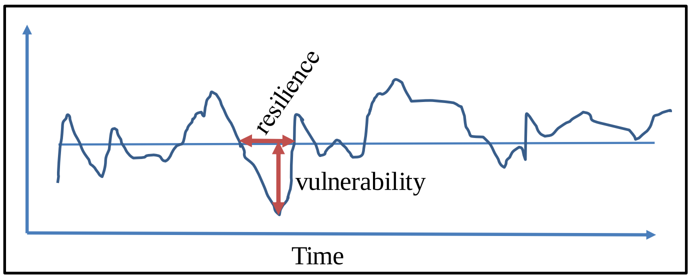
In the DTF applications we need to evaluate the performance of two development projects: a combined irrigation expansion/flood protection project in the Nzoia river in Kenya and a run-of-river hydropower project in the Kabeli river in Nepal.

It is good to notice in advance that the applicability of performance definitions depends on the delineation of the system, what is endogenous and exogenous e.g. should water demand and/or supply, energy supply and or/demand, flood protection, coping with floods, preparedness, response, recovery, with or without operating rules be included? Basically the question that needs to be answered is whether the system should be stretched beyond the engineering works included in the project and the services it has to deliver with certain reliability?

Resilience is often used as the central term in the climate and natural hazards community but how useful are the several definitions when it comes to 'measuring' it in actual project assessments? In addition metrics are needed to assess the performance of plans and projects over time and under uncertain future conditions, e.g. robustness and flexibility/adaptability are often mentioned in literature. The discussion below can be seen as a starting point, searching for the most appropriate metrics for both projects.

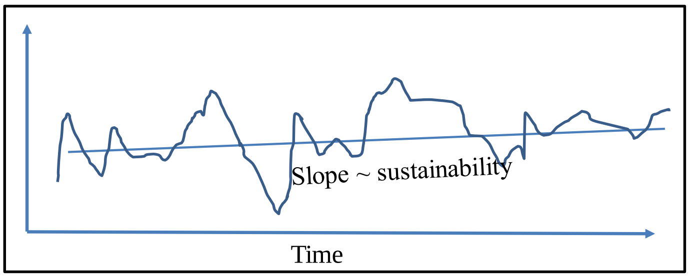
Conventional Engineering Approach

Resilience in engineering (Hashimoto et al. 1982) has a particular definition, which means, essentially, how quickly the system returns to acceptable performance when it fails. It is the inverse of long term average of the duration of failure events. When we say resilience that is approximately what we mean.



Resilience

Sustainability



Incorporation of Adaptability

However, in addition to the time-of-failure aspect, we are trying to combine the best of Decision Scaling robustness with Adaptation Pathways flexibility/adaptability. The robustness paradigm is, "over how many (and which) future states is the system acceptably resilient"?

The adaptability paradigm is, “can modifications to system operation be made easily in the future that prolong its acceptable resilience?”

Also, “are there some decisions we can make now (i.e., pathways on which we can embark) that make future necessary system transformations less ‘costly’”?

The Hashimoto et al. (1982) engineering definition includes no notion of adaptation. The baseline system can be described as having a certain resilience that makes no reference to budget or effort that will go into addressing the system vulnerabilities once the system fails. That notion of resilience appears as a kind of passive resilience. It is something like elasticity – it will stretch, and return mechanically, and automatically.
It is a characteristic of the system from inception (or in the civil engineering case, from construction and first establishment of operating rules). The reservoir empties, failing temporarily, and then the rain fills it back up again.

However, resilience from Matalas and Fiering (1977), maybe more fundamental to water resources engineering than the Hashimoto et al. (1982), is essentially the inverse of vulnerability. The resilience of a system was described as its ability to adjust (or be operated in a different way) so as to keep economic losses below some critical threshold.

According to the American Psychological Association, resilience is “the process of adapting well in the face of adversity, trauma, tragedy, threats or significant sources of stress.” It means “bouncing back” from difficult experiences, but it means it in a more active sense, with a kind of change (and effort) implied. In the civil engineering case, this could mean that the original reservoir stands, but it would not bounce back well unless we changed the operating rules, or raised the freeboard, for example. The resilient reservoir system in this case is resilient specifically because it can be operating flexibly (or accepts costless or otherwise fairly automatic alterations to its design characteristics). So enters the word “flexibility” or “adaptability” in our definition of resilience.

According to Pete Loucks (personal communication) a sustainable system is not an “unchanging” system. It is a system marked by long-term non-decreasing performance. The system likely needs to adapt along the way, in order to be sustainable.

Lessons from Ecology

The definition in ecology means something more like “resistance” or “stability”. It is the “persistence of a system near or close to an equilibrium state”, or “the amount of disturbance that a system can absorb without changing state”. This ecological definition of resilience may be closer to robustness. There is discussion in the ecological literature about global versus multiple equilibrium, however this conversation might not be very useful for civil engineering. In civil engineering cases it might be more suitable to define a long-term acceptable global condition, and if it departs from that condition, then it is not resilient for our intents and purposes. The wetland transforming to the grassland, as an example of a resilient system with two equilibria, is not useful for our built environment. Therefore, though the notion of “transformability” enters the ecological discussion of resilience, it remains questionable if this aspect should be taken into the definition for engineering applications.

Distributional Equity

Finally, there is the matter of distributional equity. If, as in the case of Mexico City, what we are measuring is total amount of water delivered to CDMX, then we need to keep track of what is happening within the larger system’s sub-systems. In this example, we might have a resilient supply to the city as a whole, but particular Delegaciones are less resilient than others.

When we adapt in Mexico City in order to achieve greater system-wide resilience (such as shutting down some well fields and opening up others), we may be transferring resilience from one Delegación to another. We think it is not needed to include this into a resilience definition.

Instead it is a matter of defining it as performance objective and translate it in a good performance indicator (next to e.g. EIRR) that can be used to assess tradeoffs with other objectives.

Summary Thoughts

The above discussion is intended for one system output (e.g., hydropower produced or water delivered to CDMX). It can be said that the system *output* is reliable/resilient. But it cannot easily be said that the *system* is resilient.

Saying that the *system* is resilient is often saying too much – it is convoluting. It is only truly useful to say that it is resilient to a *particular purpose*. Precise language is required (see, for example, the Decision Tree book pages 80-81).

We will consider the system output over time for a given infrastructure configuration and operating rule, and report its statistics: 1) cost; 2) reliability; 3) vulnerability; 4) resilience; 5) sustainability; 6) robustness.

	Mean Performance	Performance Variability
Metrics	Reliability Annual Revenue Stream **Sustainability**	Vulnerability Seasonal Dynamics **Resilience**
Example Variables	NPV/IRR Hydropower production Sediment load	Peak flood Peak sediment load Streamflow drought
Adaptation Key Concepts	Robustness Redundancy	Flexibility Modularity

It may be more resilient with an internal re-configuration (e.g., close some wells and open others in CDMX), or if operated in a different way (e.g., flush sediment more regularly, close turbines during high sediment times, in the case of hydropower). So we would report the resilience of the system as its baseline resilience (with historical operating practices), but replace historical operating practices with the best possible operating practices. We would do this because we believe people are intelligent, and responsive to stress, and would alter their operating practice reflexively. Also, operating practices do not need to be constant in time, but we would model them as responsive to climate (or other) conditions, such as flood and drought. Of course, when we do this, we need to record our assumptions, and then be clear about how the operating rules evolve.

If the system requires physical alteration, or hard construction, in order to adapt, we call that an updated system, with a different resilience score. It may be that in the Adaptation Pathways paradigm, the transaction (or transformation) costs from one physical system to another are smaller than another.

We would then propose the use of different pathways, with their resilience and costs, and enable the decision maker to make the best decision he or she can at a number of different planning horizons. For example, in the Kabeli case, there will likely be a decision now that is very attractive on a 20-30 year planning horizon, and a different decision that is attractive on a 50-80 year planning horizon. The Adaptation Pathways logic will help us to smooth the transition from initial design to the design that is likely to be preferred in the longer term, by bringing some of the adaptation costs to the present time.

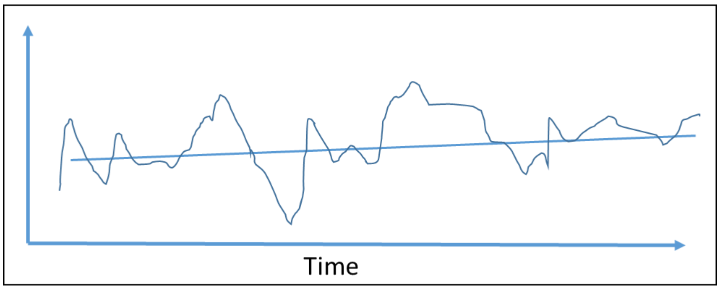
1. $Reliability\ (\alpha) = P[X_t \,\epsilon\, S] \quad = 1 - \frac{\sum Failures}{\sum(Failures + Successes)}$, *where S may be seen as system success and F as system failure*

2. $Relative\ Vulnerability\ (RV) = \frac{\frac{Max(\ Failure\ Magnitude)}{Failure\ Event}}{Performance\ Requirement}$

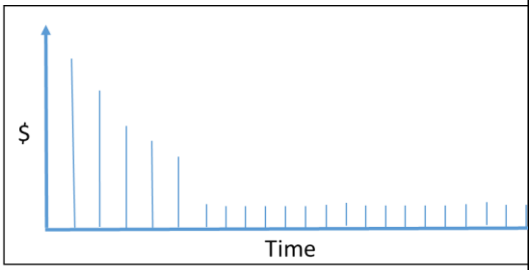
3. $Resilience\ (\beta) = P[X_{t+1} \,\epsilon\, S \mid X_t \,\epsilon\, F] \quad = \frac{\sum Recoveries}{\sum Failures} = \frac{\sum(X_{t+1} \,\epsilon\, S) \mid (X_t \,\epsilon\, F)}{\sum(X_t \,\epsilon\, F)}$

4. $Robustness\ \big(\Lambda\,(d,x)\big) = \begin{cases} 1\,, & x \,\epsilon\, S \\ 0\,, & x \,\epsilon\, F \end{cases}$
   $Robustness\ Index\ (RI_d) = \sum\ \Lambda\,(d,x).\ p(x)$

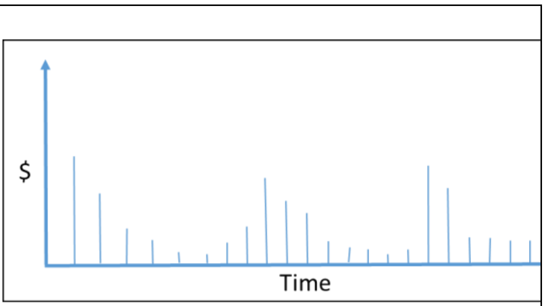
5. $Sustainability\ = Slope\ of\ the\ longterm\ performance$ (if positive, sustainable)



6. $Costs\ and\ benefits$



Build once, operate forever



Build Adaptively

Figure 9-2 illustrates an example tradeoff between mean performance, robustness, and recovery, which could be expanded to higher dimensions to include, for example, sustainability, vulnerability and reliability. While it is worthwhile to scrutinize all 6 performance metrics, there may be reasons that we need to reduce our dimensionality, either for simplicity in communication, or to develop an efficient objective function for an optimization model. Therefore it will be evaluated whether we can reduce the number of metrics.

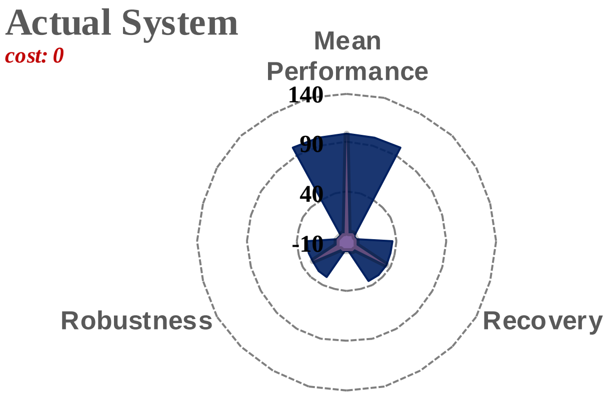


Figure 9-2 Example spider-plot of tradeoffs between mean performance, robustness and resilience/recover (credit: Sarah Freeman)

D ANNEX IV: R Scripts for generation of Response Surface

```
#Loading required libraries
library(lubridate)
library(readr)
library(dplyr)
library(reshape2)
library(stringr)
library(ggplot2)
library(scales)
library(xlsx)


########################## Settings begin   #################################
# Settings for the inputs and constants
in_dir <- "input_dir"
out_dir <- "output_dir:
GCM_dir <- paste0(in_dir, "\\GCMs\\")
setwd(in_dir)

H <- 112.6                        # meters
e <- 0.9                          # efficiency
Conversion_to_KW <- e*9810*H/1000

Cap_cost <- 102.6e6               # dollars  # Quoted from Hydropower Sustainability
Assessment Report Page 45#
dis_rate <- c(0.1)                # 10%  # Quoted from Hydropower Sustainability Assessment
Report Page 45#
economic_life <- 30               # Economic life of the project is 30 years
price <- 0.062985                 # selling price of electricity in Nepal in Dollars per KWh for
Kabeli
design_discharge <- 37.6          # m3/s

Cost_cap_per_MW <- Cap_cost/(37.6)
Cost_OM <- 0.03*Cost_cap_per_MW        # Literature says 2.2-3% for most of the project
i.e.2.2% *Total Capital cost/(MW).
# Cost_OM <- 2*(125000*(37.6)^0.65)/37.6    #function from Jim Gordan in $2015 - FIXED -
annual value
# A check on the Cost_OM is Fixed Cost_OM = 2-4% of the Capital Investment.
Cost_OM*30/Cap_cost                              # Should be about 2% # Checks out
Cost_OM_annual <- Cost_OM          # Cost per year


########################## Settings end   #################################

#STEP 1: LOAD THE PERTURBED CLIMATE DATA AND CALCUALATE THE
PERFORMANCE OF THE MODEL
```

```
no_of_perturbations <- 63
no_of_trials <- 30

Date <- c(seq(from = as.Date("2006-01-01"), to = as.Date("2035-12-31"), by = "1 day"))
Streamflow <- data.frame(Date = Date)
Streamflow<- Streamflow %>% mutate(Year = year(Date), Month = month(Date), Day =
day(Date))
Nepali_Month <- c(rep(9,15), rep(10,29), rep(11,30), rep(12,30), rep(1,31), rep(2,31),
rep(3,32), rep(4,31), rep(5,31), rep(6,31), rep(7,30), rep(8, 29),rep(9, 15))
Water_Year <- c(rep(0,104),rep(1:29, each = 365), rep(30,261), rep(30,7))
Streamflow$Nepali_Month <- rep_len(Nepali_Month,length.out = length(Streamflow$Month))
Streamflow$Water_Year <- rep_len(Water_Year,length.out = length(Streamflow$Month))

#Seperating Monsoon and Non-Monsoon Months
Monsoon <- c(6,7,8,9)
Season <- function (A) {
  if (is.element(A,Monsoon) == TRUE) {
    B = 1
  } else if (is.element(A,Monsoon) == FALSE) {
    B = 0
  }
  return(B)
}

Streamflow$Season <- (mapply(Season, Streamflow$Month))

#EnergyNepaliMnth <- c(1,  2,     3,    4,    5,    6,    7,    8,    9,  10,  11,  12)
#EnglishMnth <-   c(4,    5,    6,    7,    8,     9,   10,    11,   12,   1,  2,   3 )
Energy_signed <-
c(13784,24649,27445,26587,26587,26587,21950,13490,7680,5289,5147,5957)
Bounce_back <- function(now, past){
  if(now==1 & past ==0){
    c = 1
  }else{
    c = 0
  }
  return(c)
}


NPV_all <- NULL
Performance_metrics_overall_all <- NULL

for(trials in 1:no_of_trials)
  {
  #Reading in all the streamflow
  Streamflow_dir <- paste0(in_dir,"\\Streamflow\\TRIAL_",trials)
  files <- list.files(Streamflow_dir)

  for(i in 1:no_of_perturbations){
    Stream_daily <- read.csv(paste0(Streamflow_dir,"\\", files[i]), header = F)
```

```
  Stream_daily<- Stream_daily %>%
    filter(V1 > 2005) %>% filter(V1 < 2036)  # Filter out the first four years as they are warm-
up period
  Stream_daily <- cbind(Streamflow, Stream_daily[4])

  # 10% of the monthly minimum flow for Ecological Flow
  Min_monthly_flow <- Stream_daily %>% group_by(Year, Month) %>%
summarise(Monthly_flow = mean(V4)) %>%
    group_by(Year) %>% summarise(Min_flow = min(Monthly_flow))
  Stream_daily<- merge(Stream_daily, Min_monthly_flow)
  Stream_daily$Hydropower_flow <- sapply(Stream_daily$V4 , function(x) max((x-
0.1*Stream_daily$Min_flow), 0))
  Stream_daily$Energy_per_day <- Conversion_to_KW*Stream_daily$Hydropower_flow*24
#KWHr

  # Maximum energy per day with the hyropwer facility
  Stream_daily$Energy_cap <- sapply(Stream_daily$Energy_per_day , function(x) min(x,
Conversion_to_KW*37.6*24))

  ## Selling energy to satisfy the Power Purchase Aggrement with NEA
  Monthly_energy <- Stream_daily %>%
    filter(Water_Year >0)%>%
    group_by(Nepali_Month, Water_Year) %>%
    summarise(Energy_cap = sum(Energy_cap), Month = round(mean(Month),1), Year =
round(mean(Year),0), Season = round(mean(Season),0))%>%
    arrange(Water_Year,Year, Nepali_Month, Month, Energy_cap)

  Monthly_energy$Saleable_energy <- Monthly_energy$Energy_cap/1000          #Energy in
GWh
  Monthly_energy <- Monthly_energy %>%
    select(Water_Year, Nepali_Month, Year, Month, Season, Saleable_energy)%>%
    arrange(Water_Year, Nepali_Month, Year, Month, Season, Saleable_energy)

  Monthly_energy$Signed_energy <- rep_len(Energy_signed, length.out =
length(Monthly_energy$Nepali_Month))
  Monthly_energy <- Monthly_energy %>%
    mutate(Excess_Energy = Saleable_energy - Signed_energy, Success =
as.numeric(Saleable_energy >= Signed_energy))
  Monthly_energy$Spring_back <- mapply(Bounce_back, Monthly_energy$Success,
c(0,lag(Monthly_energy$Success,1)[2:length(Monthly_energy$Success)]))

  #Performance_Evaluation
  Performance_metrics <- Monthly_energy %>%
    group_by(Season) %>%
    summarise(Vulnerability = min(Excess_Energy),
              Total_cases = length(Success),
              Success = sum(Success),
              Recoveries = sum(Spring_back))

  Performance_metrics <- Performance_metrics %>%
    mutate(Reliability = Success/Total_cases,
```

```
       Failure = Total_cases-Success,
       Resilience = (Recoveries/Failure),
       Recovery_time = 1/Resilience) %>%
   mutate(Calendar_Months = c('October-June (8) ','June-September (4)'), Season = c('Non-
Monsoon', 'Monsoon')) %>%
   select(Calendar_Months, Season, Total_cases, Success, Failure, Recoveries,
Vulnerability, Reliability, Resilience, Recovery_time) %>%
   arrange(Calendar_Months, Season, Total_cases, Success, Failure, Recoveries,
Vulnerability, Reliability, Resilience, Recovery_time )

  Performance_metrics_overall <-  Monthly_energy %>%
   ungroup() %>%
    summarise(Vulnerability = min(Excess_Energy),
         Total_cases = length(Success),
         Success = sum(Success),
         Recoveries = sum(Spring_back))

   Performance_metrics_overall <- Performance_metrics_overall %>%
   mutate(Reliability = Success/Total_cases,
       Failure = Total_cases-Success,
       Resilience = (Recoveries/Failure),
       Recovery_time = 1/Resilience) %>%
   mutate(Calendar_Months = c('Whole Year (12) '), Season = c('All')) %>%
   select(Calendar_Months, Season, Total_cases, Success, Failure, Recoveries,
Vulnerability, Reliability, Resilience, Recovery_time) %>%
   arrange(Calendar_Months, Season, Total_cases, Success, Failure, Recoveries,
Vulnerability, Reliability, Resilience, Recovery_time )

  Performance_metrics_overall <- rbind(Performance_metrics_overall,
Performance_metrics)

  Performance_metrics_overall$Trace <- rep(trials, 3)
  Performance_metrics_overall$Precipitation <- rep(as.numeric(str_extract_all(files[i],"\\(?[0-
9,.]+\\)?")[[1]][1]),3)
  Performance_metrics_overall$Temperature <- rep(as.numeric(str_extract_all(files[i],"\\(?[0-
9,.]+\\)?")[[1]][2]),3)

  Performance_metrics_overall_all <- rbind(Performance_metrics_overall_all,
Performance_metrics_overall)

  #To calculate the Net Present Value
  Monthly_energy$Sold_energy <- mapply(min, Monthly_energy$Saleable_energy,
Monthly_energy$Signed_energy)

  Annual_energy_sold <- aggregate(Sold_energy~Water_Year, Monthly_energy, FUN =
"sum")
  Annual_energy_sold$produced_energy <- aggregate(Saleable_energy~ Water_Year,
Monthly_energy, FUN = "sum")$Saleable_energy
  Annual_energy_sold$Year_no <- seq(1:length(Annual_energy_sold$Water_Year))
```

```
    Annual_energy_sold$Sold_NPV <- ((Annual_energy_sold$Sold_energy*0.062985*10^3)-
Cost_OM_annual)*(1+dis_rate)^(-Annual_energy_sold$Year_no)
    Annual_energy_sold$Opportunity_NPV <-
((Annual_energy_sold$produced_energy*10^3*0.062985)-Cost_OM_annual)*(1+dis_rate)^(-
Annual_energy_sold$Year_no)

    NPV <- Annual_energy_sold %>%
      summarise(Sold_energy = mean(Sold_energy), Produced_energy =
mean(produced_energy), Sold_NPV = (sum(Sold_NPV)-Cap_cost)/10^6, Opportunity_NPV =
(sum(Opportunity_NPV)-Cap_cost)/10^6)

    NPV$Trace <- trials
    NPV$Precipitation <- as.numeric(str_extract_all(files[i],"\\(?[0-9,.]+\\)?")[[1]][1])
    NPV$Temperature <- as.numeric(str_extract_all(files[i],"\\(?[0-9,.]+\\)?")[[1]][2])

    NPV_all <- rbind(NPV_all, NPV)
    print(i)
  }

}
out_dir <-
"E:\\Kabeli\\Phase_3\\Resilience_Reliability_Vulnerability_Robustness_Metrics\\Complete_re
sponse_surface\\"

# Writing to files
write.csv(NPV_all, paste0(out_dir, "NPV_and_energy.csv"), row.names = F)
write.csv(Performance_metrics_overall_all, "Performance_metrics.csv", row.names = F)

NPV_all_avg <- NPV_all %>% group_by(Precipitation, Temperature) %>%
summarise_all(mean)

Performance_metrics_overall_all_avg <- Performance_metrics_overall_all %>%
  mutate(Calendar_Months = rep(c(12, 4, 8), length.out =
length(Performance_metrics_overall_all$Total_cases)))%>%
  mutate(Season = rep(c(12, 1, 0), length.out =
length(Performance_metrics_overall_all$Total_cases)))%>%
  group_by(Precipitation, Temperature, Season) %>%
  summarise_all(mean)

Performance_metrics_monsoon <- Performance_metrics_overall_all_avg %>% filter(Season
== 1)
Performance_metrics_other <- Performance_metrics_overall_all_avg %>% filter(Season ==
0)
Performance_metrics_annual <- Performance_metrics_overall_all_avg %>% filter(Season ==
12)

write.csv(NPV_all_avg, paste0(out_dir, "Avg_NPV_and_energy.csv"), row.names = F)
write.csv(Performance_metrics_monsoon, paste0(out_dir,  "Monsoon_Performance.csv"),
row.names = F)
write.csv(Performance_metrics_other, paste0(out_dir, "Non_monsoon_Performance.csv"),
row.names = F)
```

```
write.csv(Performance_metrics_annual, paste0(out_dir, "Annual_Performance.csv"),
row.names = F)


##############################################################################
#STEP 2: LOAD THE PERTURBED DATA FOR PLOTTING THE RESPONSE SURFACE

out_dir <- output_dir
setwd(out_dir)

# Reading the files for Response Surface.
NPV_all <- read.csv("Avg_NPV.csv")

#Arranging the data in the format required in the Surface Plot
P_change_num <- c(0.6,0.7, 0.8,0.9,  1, 1.1, 1.2, 1.3, 1.4)
T_change_num <- c(0, 1, 2, 3, 4, 5, 6)

##############################################################################

#STEP 3: LOAD GCM SHIFTS FOR EACH IPCC SCENARIO, ORGANIZE THEM, AND
PLOT THEM

setwd(GCM_dir)

GCMs <- "Kabeli_Basin_Climate_ClimatolChange_Hist(1950-2000)_RCP(2036-2065).xlsx"
sheets <- c("pr_historical","pr_rcp26",
"pr_rcp45","pr_rcp60","pr_rcp85","tas_historical","tas_rcp26", "tas_rcp45", "tas_rcp60",
"tas_rcp85")

GCM_list <- list()
for(i in 1:length(sheets)) {
  print(sheets[i])
  GCM_list[[i]] <- read.xlsx(GCMs, sheetName = sheets[i])
}


P_hist <- GCM_list[[1]] #Units are mm
P_hist[14] <- rowMeans(P_hist[,2:13])
P_RCP26 <- GCM_list[[2]]
P_RCP26[14] <- rowMeans(P_RCP26[,2:13])
P_RCP45 <- GCM_list[[3]]
P_RCP45[14] <- rowMeans(P_RCP45[,2:13])
P_RCP60 <- GCM_list[[4]]
P_RCP60[14] <- rowMeans(P_RCP60[,2:13])
P_RCP85 <- GCM_list[[5]]
P_RCP85[14] <- rowMeans(P_RCP85[,2:13])

DP_RCP26 <- array(NA,dim(P_RCP26)[1])
for (i in 1:dim(P_RCP26)[1]) {
  index <- which(as.vector(P_hist[,1]) == as.vector(P_RCP26[i,1]))
  DP_RCP26[i] <- (P_RCP26[i,14]) / P_hist[index,14]
```

```
}
DP_RCP45 <- array(NA,dim(P_RCP45)[1])
for (i in 1:dim(P_RCP45)[1]) {
  index <- which(as.vector(P_hist[,1]) == as.vector(P_RCP45[i,1]))
  DP_RCP45[i] <- (P_RCP45[i,14]) / P_hist[index,14]
}
DP_RCP60 <- array(NA,dim(P_RCP60)[1])
for (i in 1:dim(P_RCP60)[1]) {
  index <- which(as.vector(P_hist[,1]) == as.vector(P_RCP60[i,1]))
  DP_RCP60[i] <- (P_RCP60[i,14]) / P_hist[index,14]
}
DP_RCP85 <- array(NA,dim(P_RCP85)[1])
for (i in 1:dim(P_RCP85)[1]) {
  index <- which(as.vector(P_hist[,1]) == as.vector(P_RCP85[i,1]))
  DP_RCP85[i] <- (P_RCP85[i,14]) / P_hist[index,14]
}

T_hist <- GCM_list[[6]] #Units are mm
T_hist[14] <- rowMeans(T_hist[,2:13])
T_RCP26 <- GCM_list[[7]]
T_RCP26[14] <- rowMeans(T_RCP26[,2:13])
T_RCP45 <- GCM_list[[8]]
T_RCP45[14] <- rowMeans(T_RCP45[,2:13])
T_RCP60 <- GCM_list[[9]]
T_RCP60[14] <- rowMeans(T_RCP60[,2:13])
T_RCP85 <- GCM_list[[10]]
T_RCP85[14] <- rowMeans(T_RCP85[,2:13])

DT_RCP26 <- array(NA,dim(T_RCP26)[1])
for (i in 1:dim(T_RCP26)[1]) {
  index <- which(as.vector(T_hist[,1]) == as.vector(T_RCP26[i,1]))
  DT_RCP26[i] <- T_RCP26[i,14]
}
DT_RCP45 <- array(NA,dim(T_RCP45)[1])
for (i in 1:dim(T_RCP45)[1]) {
  index <- which(as.vector(T_hist[,1]) == as.vector(T_RCP45[i,1]))
  DT_RCP45[i] <- T_RCP45[i,14]
}
DT_RCP60 <- array(NA,dim(T_RCP60)[1])
for (i in 1:dim(T_RCP60)[1]) {
  index <- which(as.vector(T_hist[,1]) == as.vector(T_RCP60[i,1]))
  DT_RCP60[i] <- T_RCP60[i,14]
}
DT_RCP85 <- array(NA,dim(T_RCP85)[1])
for (i in 1:dim(T_RCP85)[1]) {
  index <- which(as.vector(T_hist[,1]) == as.vector(T_RCP85[i,1]))
  DT_RCP85[i] <- T_RCP85[i,14]
}

################################################################################
#ORGANIZE THE GCMS (just RCP 4.5 and RCP 8.5) FOR PLOTTING
```

```
#FIT PDF TO GCMS (just RCP 4.5 and RCP 8.5)
#put both RCPs for all GCMs into a single dataframe
RCP45_dataframe <-
data.frame(RCP=rep("RCP45",times=length(DT_RCP45)),GCM=T_RCP45[,1],DT=DT_RCP4
5,DP=DP_RCP45)
RCP85_dataframe <-
data.frame(RCP=rep("RCP85",times=length(DT_RCP85)),GCM=T_RCP85[,1],DT=DT_RCP8
5,DP=DP_RCP85)
GCMs_dataframe <- rbind(RCP45_dataframe,RCP85_dataframe)

#calibrate the delta P's for the axis used in Climate Response Surface
DP_RCP26 <- DP_RCP26 + 1
DP_RCP45 <- DP_RCP45 + 1
DP_RCP60 <- DP_RCP60 + 1
DP_RCP85 <- DP_RCP85 + 1


############################# Plotting Net Present Value   ##################
# Setting up the trigger for response surface

NPV_trigger <- 0
NPV_matrix <- matrix(data = NPV_all[,5], nrow = 9, ncol = 7, byrow = TRUE)
colnames(NPV_matrix) <- c("T1","T2","T3","T4","T5","T6", "T7")
clim_resp_surf_data <- NPV_matrix

Trigger <- NPV_trigger #For Base_Design
units <- 1 # Million US Dollars

#FOR CASES IN WHICH THE TRIGGER LEVEL IS WITHIN THE RANGE OF ZZLIM
zzlim <- c(min(clim_resp_surf_data/units),max(clim_resp_surf_data/units))
zzlim

Trigger_level = Trigger/units
Trigger_level

a <- 8
b <- 8
mylevel <-
c(seq(zzlim[1],Trigger_level,length.out=a),seq(Trigger_level,zzlim[2],length.out=b)[-1])
mycolors <- c(colorRampPalette(c("red","white"))(a)[-
a],colorRampPalette(c("white","blue"))(b)[-1]) #if bigger numbers are better

plot_title <- paste0("Net Present Value with current PPA (Million US $) ")
plot_tile_save <- paste0(out_dir,"Net Present Value Sold Energy Response Surface.png")

#windows(8,7)
png(plot_tile_save, width = 6, height = 4.65, units = "in", res = 400, pointsize = 8)
filled.contour(x=P_change_num,y=T_change_num,z=clim_resp_surf_data/units,
          levels=mylevel,col=mycolors,
          plot.axes={points(x=DP_RCP26,y=DT_RCP26,pch=16,col="green");
                points(x=DP_RCP45,y=DT_RCP45,pch=16,col="cyan");
```

```
                        points(x=DP_RCP60,y=DT_RCP60,pch=16,col="yellow");
                       points(x=DP_RCP85,y=DT_RCP85,pch=16,col="magenta");
                      axis(1);axis(2)},
                main=plot_title,xlab="Precipitation (Fraction of Historic/Baseline)",ylab="Change in Temperature (C)")
text(1,.1, paste0("Baseline = ", round(NPV_all[29,5], 1)), cex = 1)

dev.off()
```

www.deltares.nl