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PAANI PROGRAM | पानी परियोजना

SYSTEM SCALE PLANNING METHODOLOGY

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Cover photo: New settlements along the Karnali River.
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1 Background & Purpose

There are three major components of this project, focused on different scales and sectors but intended to inform each other: (1) an options assessment for development of the national power system; (2) system-scale planning (SSP) for hydropower, and other water infrastructure, within the context of multiple objectives; and (3) the identification of High Conservation Value (HCV) rivers. Together the three components are intended to increase the transparency of information on resources and options and to inform decision making in Nepal on energy development, hydropower and river conservation.

The energy options assessment is at the national scale because hydropower projects must be integrated into the electric grid, including their capacity to meet peak demand, provide ancillary services, and to integrate renewable resources. Without this broader, grid-scale perspective, planning at the basin scale could miss opportunities to provide needed services.

The assessment of high conservation value (HCV) rivers is also at the national scale and feeds into the system scale planning for the Karnali Basin. For example, the HCV assessment identifies which rivers and tributaries across Nepal provide habitat for migratory fish and river dolphins, among other values identified by Nepalese river experts and other stakeholders.

The System Scale Planning (SSP) component focuses on the scale of a large basin, the Karnali. It considers financial, energy, social and environmental values in evaluating the trade-offs between different hydropower development options. We also explored preliminary application of SSP to the national scale.

The purpose of this document is to provide an overview of the methodology used to carry out the SSP component of this project.

1.1 What is System Scale Planning?

SSP is a planning framework that is quantitative, multi criteria, multi project and iterative. It is used to inform the decision-making process by visualizing options & making explicit the tradeoffs that are inherent in hydropower development. Combinations of potential future hydropower projects are assessed across multiple criteria. Therefore, SSP allows for the analysis of how each combination of projects (solutions) perform across a range of metrics which assess environmental, social, financial and energy-related dimensions.

1.2 Previous examples of System Scale Planning

System scale planning has been described in manuscripts and applied in geographies around the world.

Early work on system scale planning includes the Power of Rivers report (Opperman et al., 2015) which describes the core concepts and benefits of planning at a river basin scale to minimize impacts for a given amount of hydropower development using examples from Brazil, Columbia and Mexico. This work was extended two years later with a business case example showing the financial benefits that can be realized from planning at the system scale (Opperman et al., 2017), particularly when the delays and cost overruns associated with environmental and social conflicts are considered.

Similar concepts were described in "Using many-objective trade-off analysis to help dams promote economic development, protect the poor and enhance ecological health" (Hurford et al., 2014). This approach leveraged multi-objective evolutionary algorithms to look at reservoir operating policies to find an acceptable balance between the multiple uses and impacts of reservoir operations.

The approaches described in these papers came together in Myanmar in the report Improving Hydropower Outcomes Through System-Scale Planning: An Example from Myanmar (The Nature Conservancy et al., 2016) which assessed system scale planning opportunities using a multi-objective approach.

This framework has since been applied in country-specific contexts in the Republic of Congo, Gabon, Mexico (The Nature Conservancy, 2020) and Columbia.

In Columbia, a basin-scale analysis of hydropower development and its impacts on the Mompós Depression wetlands (Angarita et al., 2018) used a medium-scale water balance model to evaluate how hydropower development options would impact downstream wetlands in addition to impacts to connectivity, sediment loads, and other metrics.

1.3 Why System-scale planning in Nepal and the Karnali basin?

Nepal encompasses significant amount of hydropower potential. Its rivers also support a wide variety of natural resources and human cultural and economic activities. While developing its hydropower resources can help Nepal develop economically and meet its low-carbon energy goals, doing so can also put these natural and social resources at risk.

By quantifying impacts and assessing the entire system simultaneously, SSP has the potential to inform decision makers in Nepal so they can identify development opportunities that strike the best balance between energy development and cumulative impacts.

2 Activity & Task Summary

In order to ensure the metrics being compared for each scenario are relevant in the Karnali Basin, an in-depth, stakeholder-oriented methodology was followed. An overview of the steps undertaken are as follows:

1. Collect and review existing data for the Karnali
2. Meet with stakeholder groups in-person and online
3. Assess institutional landscape and relevant policies in Nepal to inform report framing
4. Develop metrics for various resources and values in Karnali
5. Develop GIS database and river basin model
6. Run full model and generate illustrative results

2.1 Collect and review existing data for the Karnali

A review of existing data sources and possible inputs for the SSP model was undertaken. Beyond the dam database the bulk of the data that were used as inputs for the SSP analysis came from the HCV component of the project. These data were compiled with input from multiple stakeholders to capture important environmental and social values, by river reach, throughout the country. As is detailed in the HCV component report, each river reach is scored for specific components including key species, like otter or dolphins, species groups, like endemic or endangered fish, and social factors, like rafting and commercial fisheries. These in turn, are rolled up to identify reaches that are important for larger themes, such as biodiversity, livelihood, recreation, and socio-cultural values. Finally, these groups are summarized into a single, overarching HCV score. By summarizing multiple environmental and social factors into a river reach-based score, the HCV analysis provides an excellent dataset against which to measure impacts from hydropower development.

2.2 Meet and hold meetings with stakeholder groups

The identification of values and development objectives for the Karnali basin was done with input from stakeholders in Nepal. An open dialogue was facilitated during in-person workshops held in Kathmandu and Surket in July 2019. Participants were tasked with listing the multiple values and objectives for the Karnali Basin, highlighting how these could be affected by hydropower development decisions. Maps of the Karnali basin, showing the primary rivers and locations of proposed hydropower projects were used as a graphic means of identifying important values within the basin. These included environmental, social and economic values. For example, some attendees highlighted key stretches of river for kayaking expeditions and several others identified key floodplain habitats that are critical for rhinos and tigers. A graphic outlining the values identified in the first workshop can be found in Section 4.2.

This initial in-person workshop was followed by virtual workshops in March and November 2020. The March workshop focused on a re-cap of SSP methodology and presentation of initial draft results, in particular highlighting how the SSP metrics are built off of the HCV data. The November workshop focused on a presentation of draft-final results, including an orientation to the parallel axis plots and other products (see Section 3.1).

2.3 Assess policies in Nepal to inform report framing

The purpose of this step of the methodology is to ensure integration of the SSP findings into relevant policy processes. In January 2020, following a stakeholder engagement trip to Nepal in late 2019, the following report was produced: Regulatory, institutional and political context for hydropower, energy and water management planning and development in Nepal: Pathways for uptake of system-scale planning analyses in Nepal. The findings in this report and associated project components are used to support the policy briefs that accompany this SSP report and which serve as a basis to ensure strategic use of the SSP outputs into policy and decision making in Nepal.

2.4 Develop metrics for the freshwater and economic and financial values in the Karnali Basin

Following the initial stakeholder group meeting in Kathmandu and Surkhet, the values and objectives identified were further analyzed. This included the prioritization of objectives depending on ability to model, relevance and data availability.

A lengthy process of cross-checking the HCV and SSP metrics was carried out. This included considerations such as ability to model, data availability and relevance to hydropower. For ease of modelling and streamlining of the project components, a single set of metrics are being used with respect to aquatic biodiversity, riverine biodiversity, social and cultural values, recreational values and livelihood values. These are listed in the HCV methodology component. Within the SSP modelling process additional economic and financial indicators were also considered. Additional detail on the metrics developed is presented in Section 3.2.2

2.5 Develop GIS database and river basin model

The project team invested considerable effort into developing a comprehensive GIS database and river basin model. These components form the analytical foundation for the analysis and each component must be linked to the others. Thus, the dam database, reservoirs and river hydrography must all be able to "talk" to each other. More detail on the GIS database and river basin model is included in Section 4.1.

2.6 Run full model and generate illustrative results

With the dam data, river hydrography, and HCV data ready, the core building blocks for the analysis were in place. Together, these enable future hydropower development solutions to be generated and metrics to be generated for each solution. Note that we use the term "solution" to refer a specific combination of hydropower projects.

3 Results

Within the SSP model, solutions were generated using both a pseudo-random process and a multi-objective evolutionary algorithm (MOEA). These processes are described in further detail in Section 4.3. At their essence, these are simply two approaches for generating combinations of dams. As solutions are generated, the MOEA works to improve the performance of the input metrics, striving to generate Pareto-optimal solutions, that is those solutions where no further improvements could be made to one dimension without further diminishing the performance of other dimension. The MOEA was run for 20,000 iterations which produced approximately 3,500 solutions that were identified as Pareto-optimal solutions.

In addition to the solutions identified by the MOEA, another 20,000 solutions were generated by the pseudo-random process (see 4.3.1) which generations random solutions within different total MW size class bins.

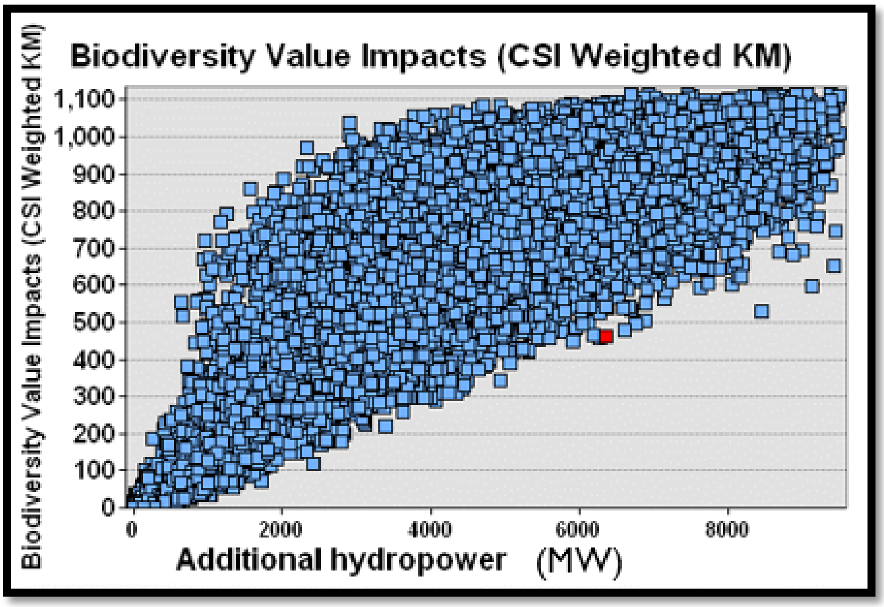
3.1 Viewing and Interacting with the Results

Given the many thousands of solutions included in the results and the quantity of metrics calculated for each of the solutions, simply viewing and understanding the results can be challenging.

3.1.1 Scatter plots

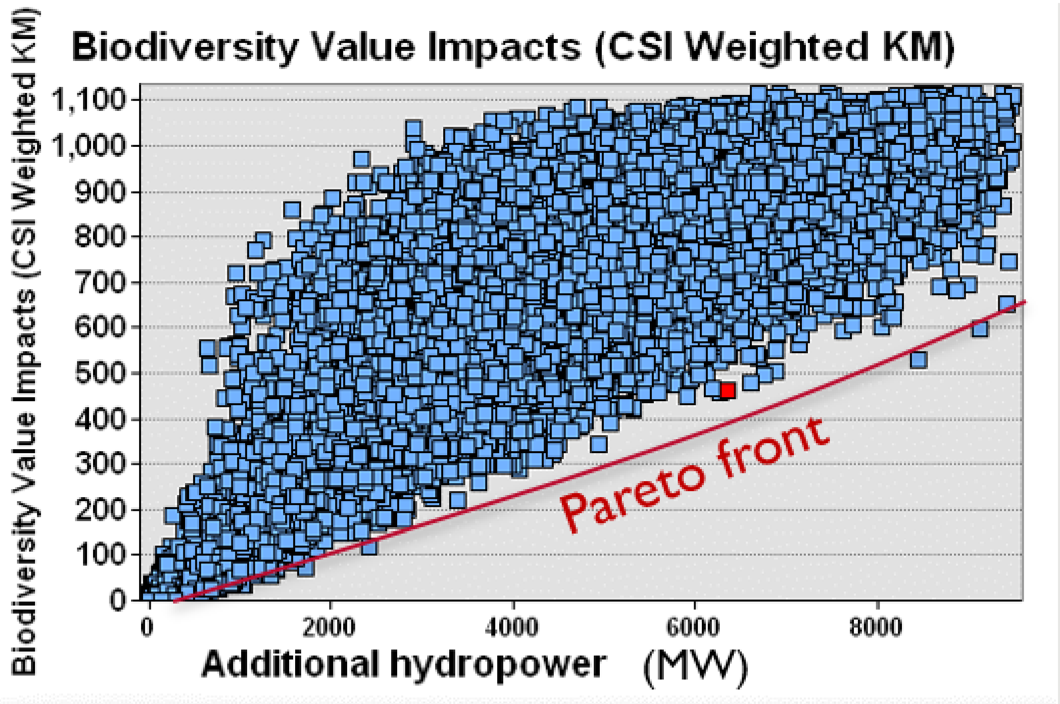
Perhaps the simplest way to view the results is via scatter plots. These simple graphs can be drawn to examine the performance of any given environmental or social metrics against the installed capacity for a solution.

Figure 3-1 Example scatterplot depicting the biodiversity value impacts performance (CSI Weighted KM) of many solutions against the installed capacity for that solution. Each point represents a solution, or combination of potential hydropower projects.



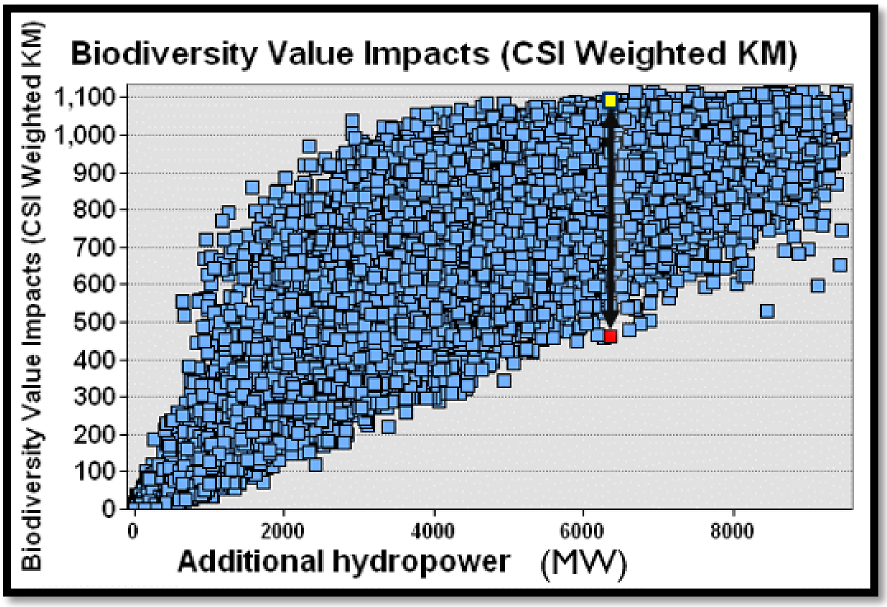
As illustrated in Figure 3-1, each point represents a solution, or combination of potential future dams. The point is located at the intersection of its values for two metrics: additional hydropower (installed capacity in MW) and biodiversity value impacts (CSI, weighted KM, see Section 444.2.8.1). As with most of the environmental and social metrics, it is desirable to minimize the biodiversity impacts metric (e.g. a preferred solution would result in impacts to fewer KM of river). Thus, the solution highlighted in red would represent a top performing metric. For the given installed capacity value (approximately 6,500 additional MW) it has the best performance of all of the solutions. Solutions that perform as well as possible for a given installed capacity value are said to fall along the Pareto front (Figure 3-2).

Figure 3-2 Conceptual illustration of the pareto-front. Solutions along the pareto front perform as well as is possible for biodiversity impacts for a given installed capacity value.



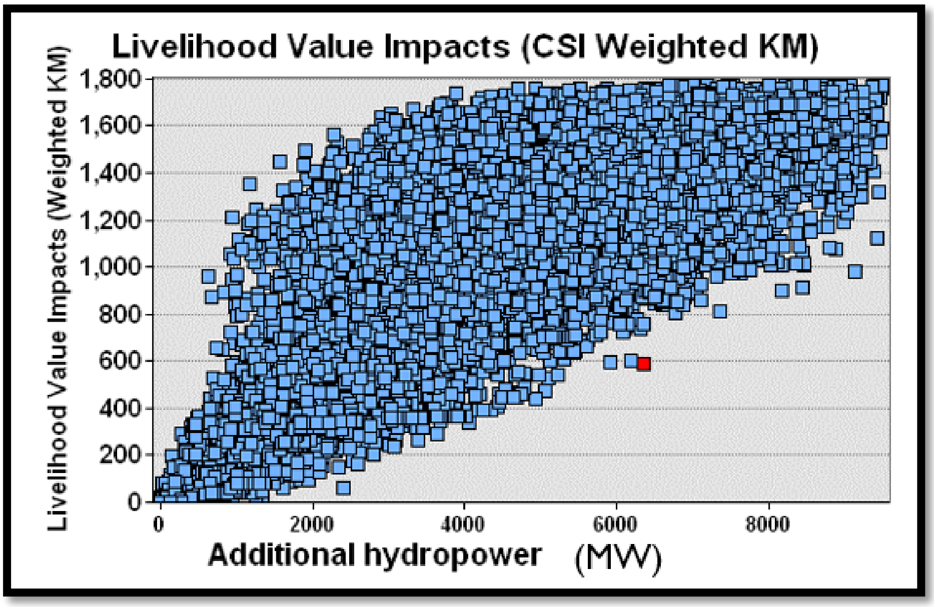
Conversely, the solution show in yellow in Figure 3-3 has a comparable amount of installed capacity, but results in impacts to approximately 1,100 kilometers of river (using the weighted KM approach described in Section 4.2.3.2). Thus, the potential range of improvement between these solutions is approximately 650 km. That is, by strategically selecting dams (i.e., moving from a solution such as the one in yellow and toward the one in red), impacts could be more than cut in half.

Figure 3-3 Scatterplot showing the potential range of improvement for biodiversity value impacts for two solutions, each with a comparable amount of installed capacity.



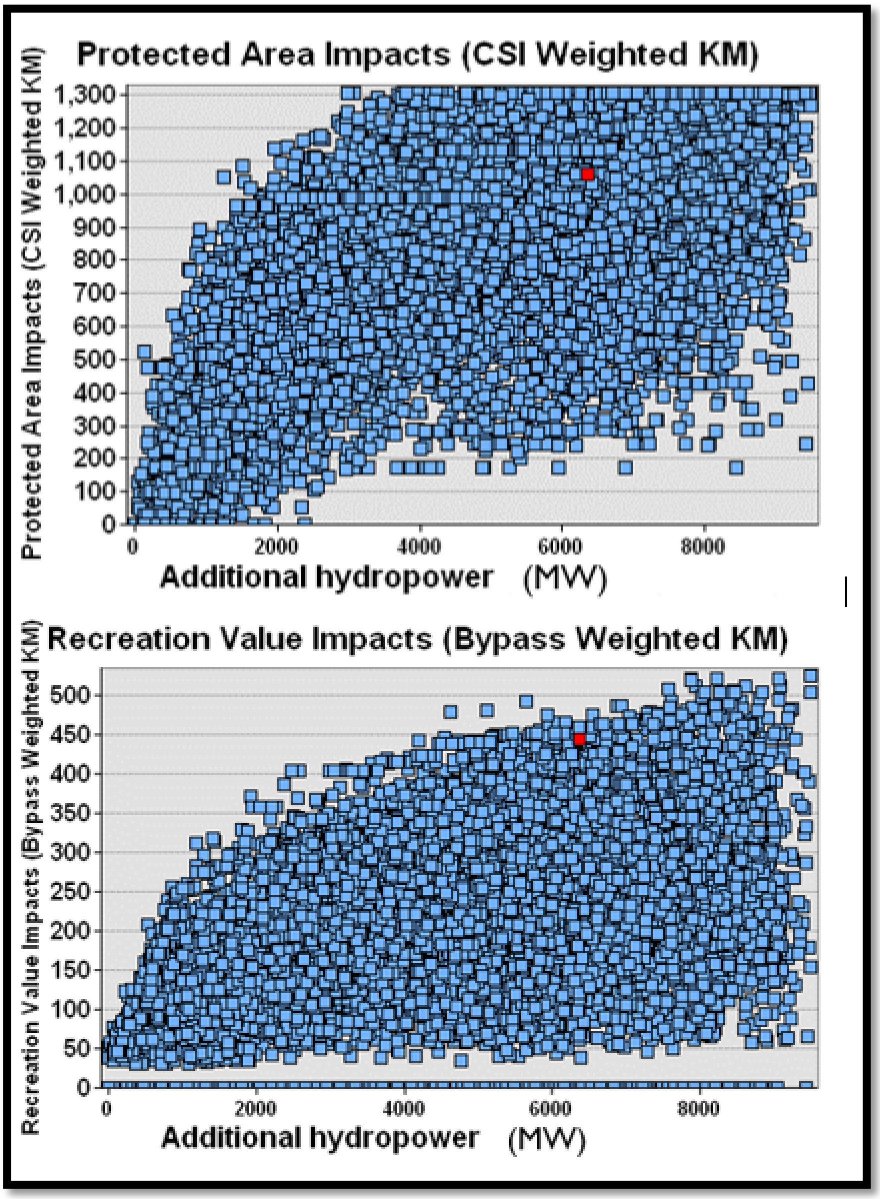
Similar plots can be drawn for other metrics. For example, Figure 3-4 shows livelihood value impacts plotted against additional hydropower. The solution highlighted in red in Figure 3-1 is again highlighted in red in this plot. Figure 3-1Figure 3-3Figure 3-4 As with the biodiversity impacts, this solution performs quite well for its livelihood value impacts – for the given amount of installed capacity, there are no other solutions with fewer impacts.

Figure 3-4 The same solution plotted as Livelihood Value impacts against additional MW of installed capacity.



However, the same solution does not perform as well in terms of its impacts to protected areas or recreation value impacts (Figure 3-5).

Figure 3-5 The same scenario noted above plotted as protected area impacts against additional installed capacity.



The fact that one solution does not perform optimally across all metrics of interest should not be surprising. When evaluating many different impacts across both environmental and social dimensions, it is exceedingly unlikely that there would be any one solution that performs as well as is possible across all of them. This raises the concept of "trade-offs" which is key to the SSP analysis.

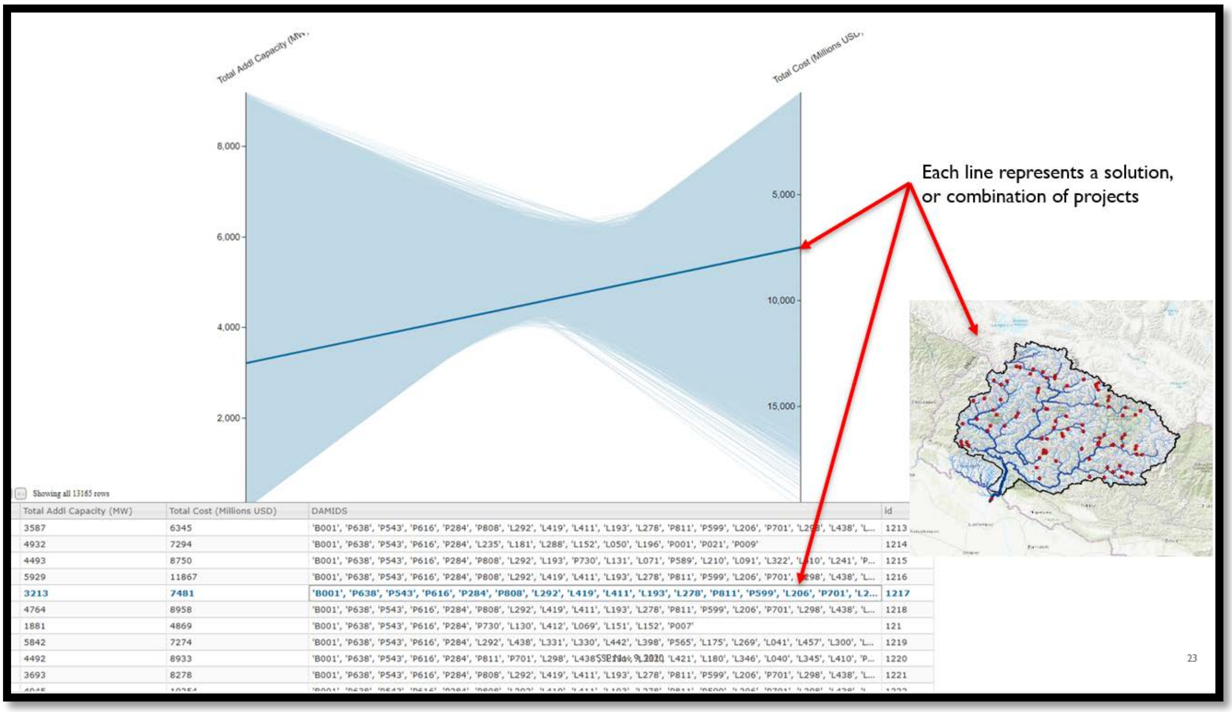
3.1.2 Evaluating trade-offs with parallel axis plot decision support tool

As opposed to a pairwise comparison of objectives as is depicted in the individual figures in Section 3.1.1, in an analysis which involves many objectives (metrics of interest) it is inevitable that there would not be one solution that is ideal across all metrics. To help efficiently explore and evaluate many metrics for many solutions the SSP analysis uses parallel axis plots.

Parallel axis plots are a type of graph that can facilitate the exploration of multiple metrics for many thousands of solutions by simultaneously plotting many metrics for all solutions. These can then be interactively explored by the user to identify solutions and inform discussions around which solutions have acceptable impacts across the multiple criteria.

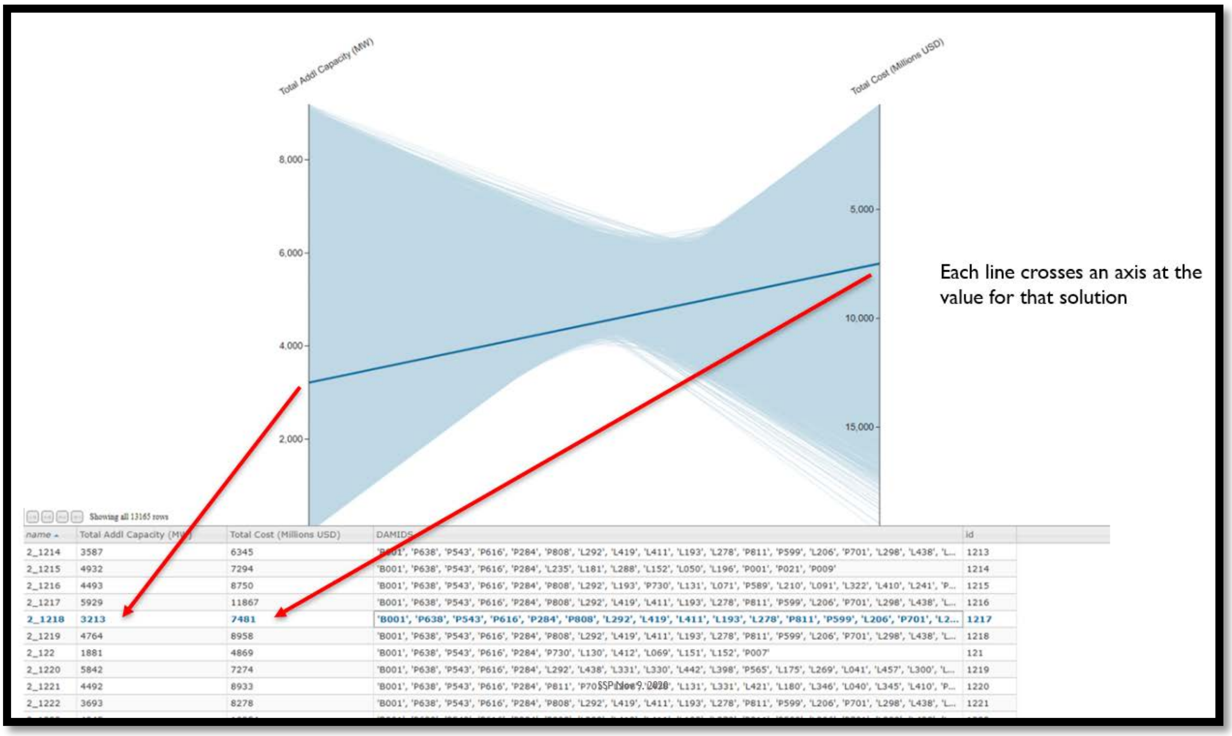
In parallel axis plots, each solution, or combination of dams is displayed as a line, rather than as a point like in scatterplots.

Figure 3-6 Each line in a parallel axis plot represents a solution, or combination of dams



Each of the vertical axes in the plot correspond to a metric. Where each line crosses an axis represents the solution's value for that metric. Figure 3-7 shows a highlighted solution and its values for installed capacity (MW) and total cost (millions of US dollars). The values for the solution are also available in the linked table below the parallel plot.

Figure 3-7 Where each line crosses an axis indicates that solution's value for that metric



Traditionally in SSP analyses, the axes are arranged so that desirable values are oriented at the top of the axis. Thus, the axes that evaluate negative environmental or social impacts are oriented with zero at the top. Similarly, as low-cost projects are desirable, the lowest cost is also at the top of the axis. While the actual "desirable" amount of installed capacity is a function of a number of variables, in this structure we put the highest capacity at the top of the axis since more installed capacity for the same amount of impacts would be preferable. Thus, a hypothetical ideal solution would be represented by a straight line across the top of the graph. This hypothetical ideal is, of course, unobtainable. In this example it would be a solution with the most possible installed capacity for the least possible cost. In fact, the parallel plots reveal an intuitive inverse relationship between installed capacity and total cost.

The power of parallel plots come not from just displaying two metrics, but rather from displaying many metrics simultaneously.

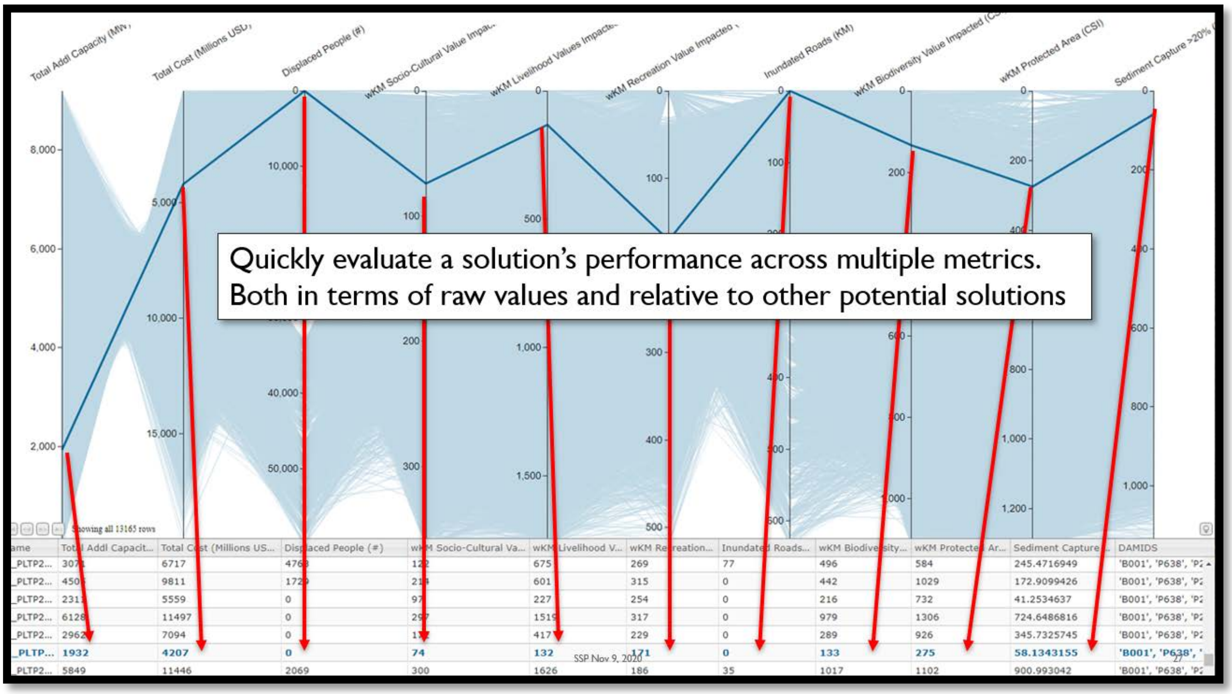


Figure 3-8 shows a scenario highlighted in the parallel axis plot and the corresponding table. Here we can see that the highlighted solution performs very well for people displaced in both absolute terms (zero) and relative terms (no solutions perform better). For recreation value impacts, it performs in roughly the top third of all possible solutions. In absolute terms, we can see from the table that this equates to 171 km impacted (weighted KM, as described in Section 4.2.3.2).

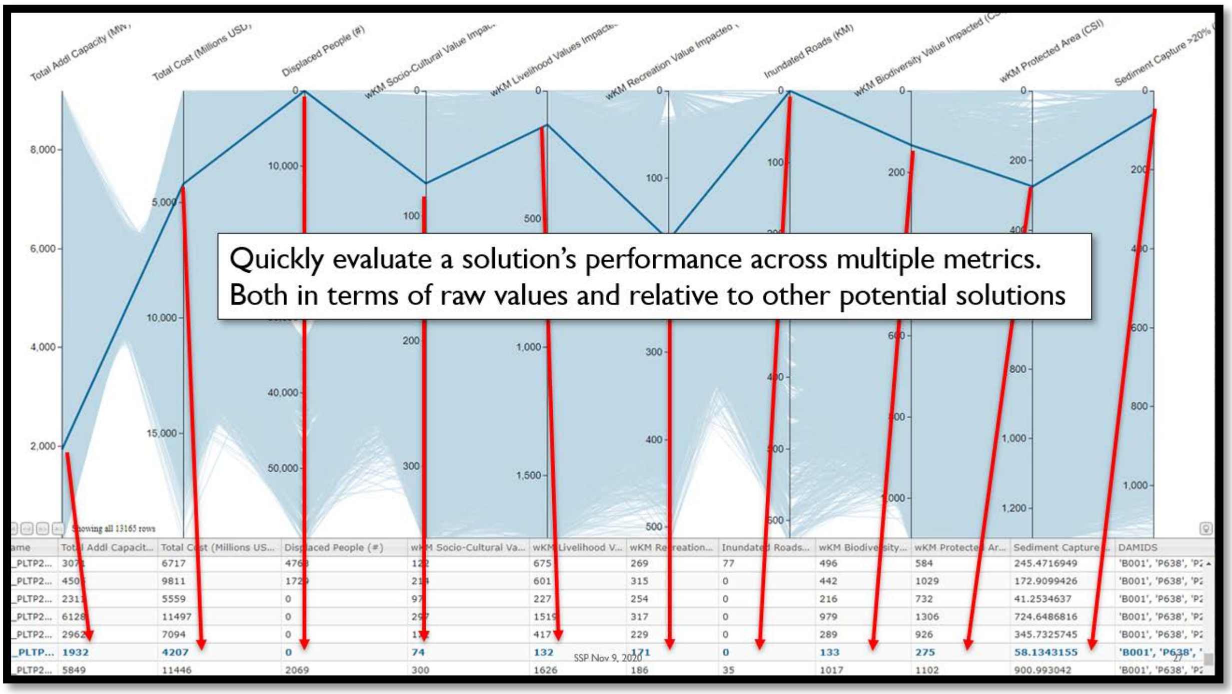
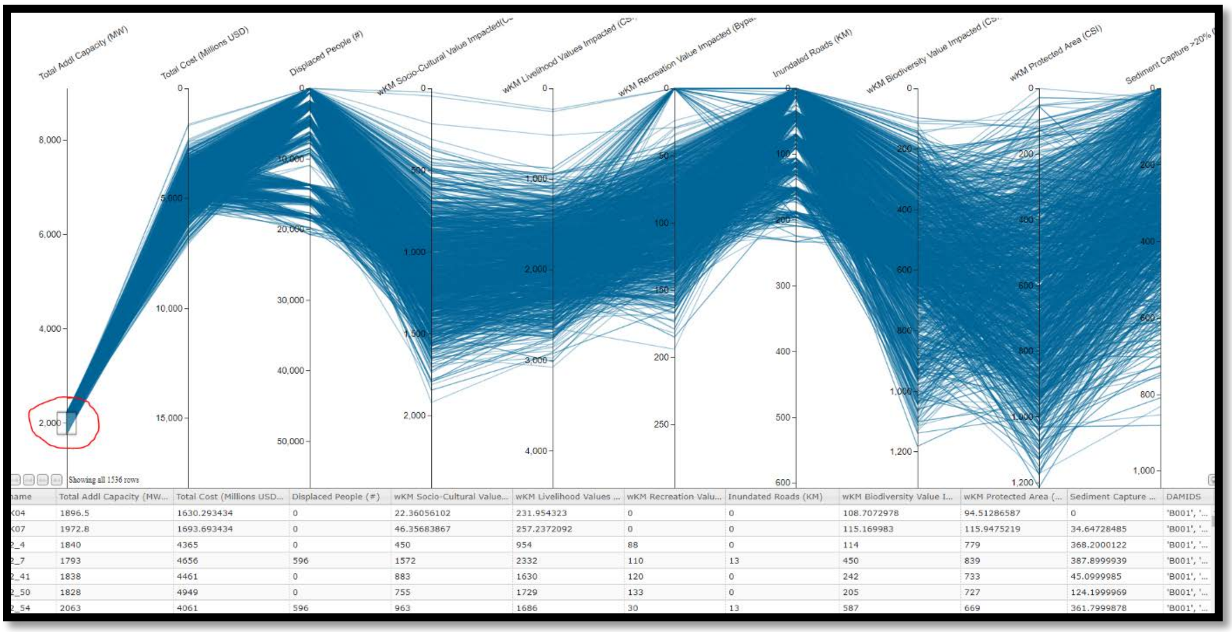


Figure 3-8 Parallel plots and their linked table allow for the quick evaluation of a solution in both absolute and relative terms. (the figure is repeated twice – delete one?)

For many metrics which do not have clear “no-go” thresholds, the parallel axis plots can be used to enable a conversation amongst stakeholders on acceptable impacts.

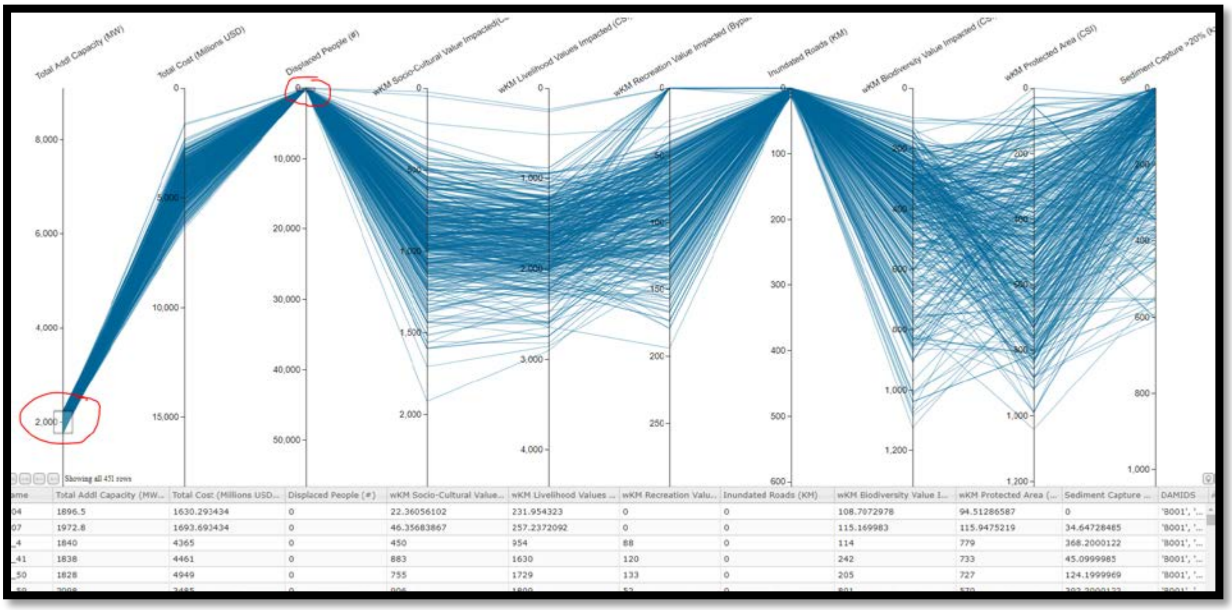
Filters can also be applied to the parallel plots to further explore how these thresholds interact across multiple metrics. These filters can be drawn on one or more of the axes to restrict the solutions displayed to those whose values for that metric fall within the selected range. Figure 3-9 shows how a filter can be applied to a range of values on an axis. Here, only those solutions with a total installed capacity near 2,000 MW are displayed in the graph.

Figure 3-9 A filter applied to limit the displayed solutions to those with a combined installed capacity close to 2,000 MW



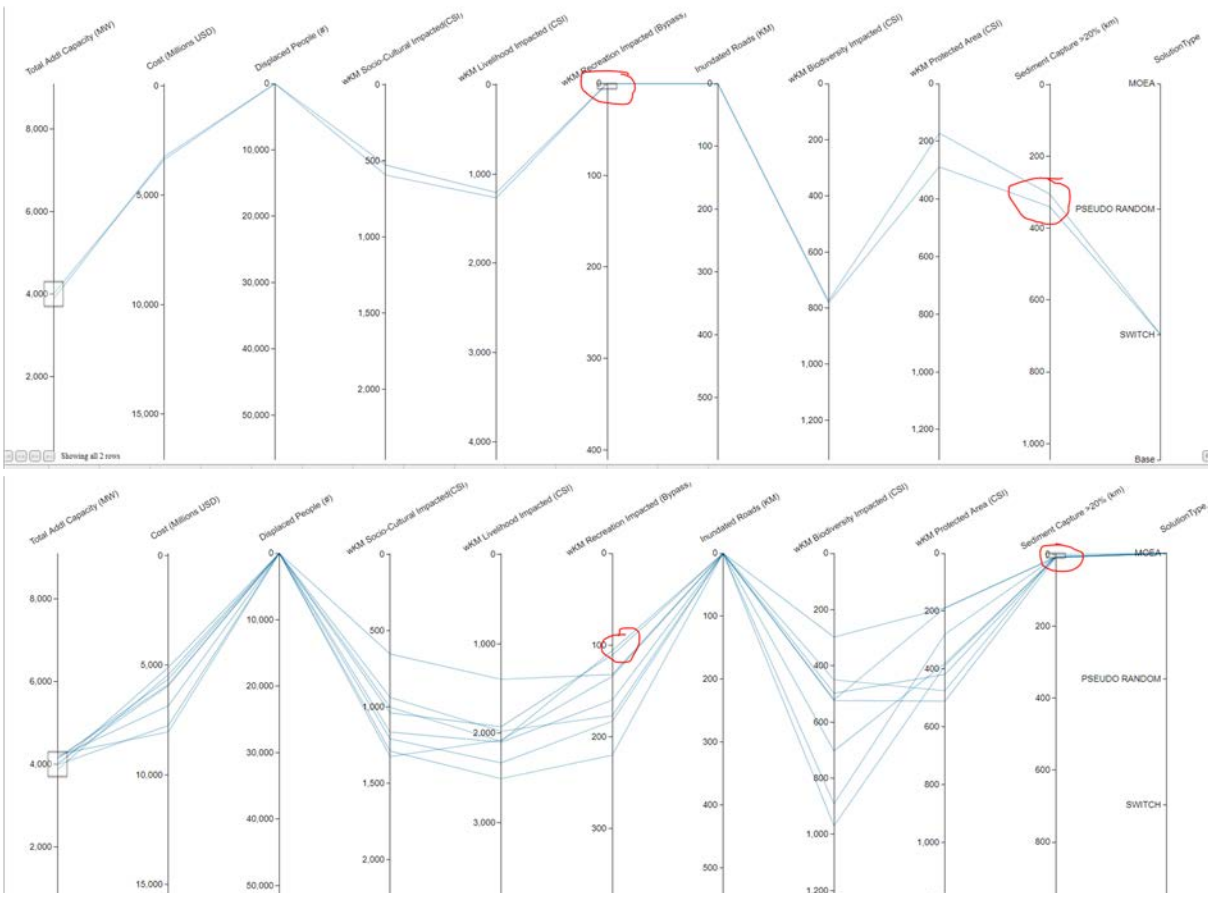
This could be further refined, as in Figure 3-10, where filters are applied to the installed capacity and people displaced axes, to limit those scenarios displayed to those that have around 2,000 MW of installed capacity and that don’t displace any people. Continuing this process, filters can be applied to other metrics to identify solutions that have the most acceptable balance of impacts and highlight thresholds where improving one metric begins to conflict with another.

Figure 3-10 Filters applied to the Installed capacity and people displaced metrics



Applying successive filters can also quickly reduce the many thousands of potential solutions while simultaneously illustrating tradeoffs that are inherent in development in the basin. For

Figure 3-11 Using multiple filters to quickly reduce the number of solutions shown and illustrate one of the tradeoffs that are inherent in hydropower development in the basin



example, as illustrated in Figure 3-11 there is a tradeoff between the impacts to rivers with recreation values and sediment capture for solutions with around 4,000 MW installed capacity. It is possible to minimize one of these impacts, but the solutions that have the lowest impacts for one of these metrics have higher impacts for the other. By quantifying and making this tradeoff visible to decision makers, it can empower them to make the most informed decisions possible that balance the interests of all stakeholders.

The parallel axis plots can be accessed at https://maps.tnc.org/seacap/Karnali/

The password to enter the site is "SSP"

3.1.3 Comprehensive set of geospatial data

The parallel axis plots, as described in the previous section, provide an efficient way to sort through a large amount of data. However, it is not practical to include all of the data that has been generated for each solution. The full suite of metrics that have been calculated for each solution (as described in Section 4.2.8) are included in a table in an ArcGIS map package (.mpk file). In addition to the analysis results, additional contextual layers (e.g. HCV rivers, input dam data) are available to help users understand the spatial context of the individual dams and solutions.

The map package is available for download at:
https://tnc.box.com/s/99ax17uuqh89qszvsikwy9gknyn0570m

Double-clicking on this file on a computer that has ArcGIS installed will unpack the data and automatically open a map document with all of the data and symbology applied. The tool "Extract Package" (link) can be used to extract the contents of the package to a specific folder.

When the map package first opened, two linked scatterplots are open. These represent a pairwise comparison of metrics against installed capacity (see Section 3.1.1). Graphically selecting one point (solution) in one of the scatter plots will highlight that solution in the other scatterplot. The selected solution(s) will also be highlighted in the "results" table. The dams that comprise a solution can be identified by activating a relate between the results table and "options_fc". See the ArcGIS Desktop help for more information about using related tables. Addition scatterplots (one for each of the environmental and social metrics) can be opened under the View>Graphs menu. See the ArcGIS Desktop help for more information about using graphs within ArcMap.

By default the results table is limited with a definition query to those solutions with less than 9,100 MW installed capacity (see Section 4.3.3). This definition query can be removed to access all records and view them in the scatterplots.

Note that due to the quantity of data, the relate between the "results" table and "options_fc" layer, may be slow to respond, particularly with slower computers. If performance is prohibitively slow, users may find significant improvement by turning off the "options_fc" layer until it is needed. Also, rather than using a relate, users may substantially improve performance improved by simply copying the list of dam IDs from the results table "DAMIDS" attribute and pasting them into a selection query or definition query in the "InputDams_Karnali" layer to visualize which dams are included in a given solution.

The following datasets are available in the map package and basic metadata is associated with the layers.

Dataset name	**Type**	**Description**
results	Table	Each row in this table represents one solution, or *combination of dams*. The "SCEID" attribute serves as an identifier for the solution. Each field in the table constitutes a metric. As noted in Section 4.2.2, each metric calculated for the baseline, each solution (or scenario) and the difference between the two. Note that the results table is access from the "List By Source" view of the table of contents in ArcGIS Desktop.
options_fc	Feature class	Each row in the options_fc feature class is an individual dam in a solution. The "SCEID" column corresponds to the SCEID field in the results table. To create a link between the solutions in the results table and the dams in the options_fc table, a "Relate" (one-to-many) relationship must be established between the results table (or results_fc) and options_fc. Once established, highlighting a row in the results table and activating the relate will highlight the dams in that scenario from the options_fc layer.
Rivers by HCV	Feature class group	The river hydrography used in the SSP analysis. This includes the HCV values by reach, as well as additional attributes used by the SSP model. The layer is included several times, each time symbolized using a different HCV attribute by different river sizes.
Inputs	Feature class group	A group of feature classes with the individual input dams, their powerhouses (where available), estimated bypass reaches, and modeled reservoirs.
Rivers by Size	Feature Class	Rivers symbolized by size class

3.1.4 Discussion

As is noted several times in this document, the primary objective of the SSP analysis is not to produce a single result or solution to describe an ideal future hydropower development solution. As opposed to a single finding or result, the SSP products are designed to support decision makers by quantifying the environmental and social impacts of various development solutions and helping to identify the tradeoffs between these solutions. The application of these results in the Nepalese context is discussed further in the SSP policy brief that is associated with this technical report.

Of particular interest from a technical perspective is the integration of the SSP analysis with the energy options analysis.

3.2 Integration with Energy Options

3.2.1 Overview of integration between SSP and SWITCH

The SSP and the energy options model (SWITCH) has been loosely integrated, allowing the exchange of portfolios and scenarios between the two components (Figure 3-12). Using the dam database, HCV database and other relevant layers, such as protected area extents, the SSP team defined 13 "environmental" scenarios that were passed to the SWITCH model for further assessment (see Table 6-1 in the Annex). Each scenario provides specific constraints, for example scenario K03 ("Karnali secondary") would not allow projects that were located on the Karnali main stem. A series of maps are provided in 6.2.2 below that display the constraints and the possible selection of planned dams that could be included in calculating the least-cost solution in SWITCH.

After the SWITCH model finished calculating the least-cost solution given the specific constraints of the scenario, it passes this solution, effectively a selection of dams (or "portfolio") back to the SSP model (see 6.2.3 in the Annex for maps of selected portfolios. The SWITCH model produces four portfolios, one for each investment period (2025 to 2040 in five year increments). The SSP model then calculates the environmental metrics for each portfolio, although we typically employ the 2040 portfolio in this analysis. The results are merged with the optimized results and we produced maps, graphs, and charts, including the decision support tool, that allows to compare the least-cost SWITCH portfolios with other scenarios the MOEA has provided. This allow the user to identify how well the SWITCH scenarios perform relative to pareto-optimal solutions, and relative to each other.

Within a real-world decision-making context, the scenarios and constraints that define an acceptable portfolio of input (potential) projects will likely be redefined multiple times, as the least-cost solution provided by SWITCH is often not the best solution in terms of other environmental and social metrics. In other words. SWITCH does meet the overarching constraint, such as no dams on the Karnali mainstem, but the set of dams across Nepal that it does select are based strictly on least-cost performance; thus the resulting set of dams is a least cost solution for the overarching constraint, but it does not necessarily perform well for other social and environmental criteria that can be explored within SSP. The iteration between the SSP and the SWITCH model eventually leads to minimizing the trade-offs between environment metrics and energy system metric. However, this iteration scheme is not part of this study and was left for future work.

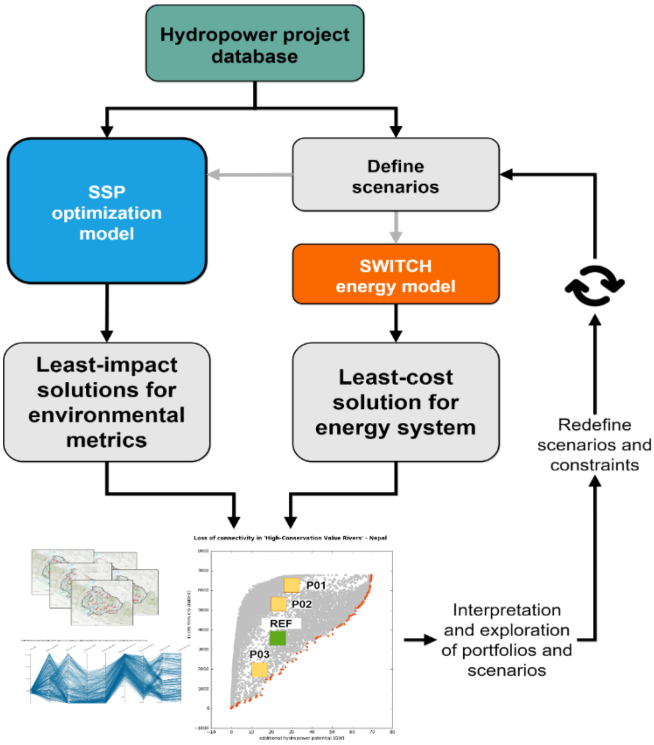


Figure 3-12: Schematic overview of the integration between SSP and Energy option modelling

The least-cost solutions produced by SWITCH were evaluated within the Karnali SSP model for the full suite of environmental metrics (section 4.2). They were then evaluated at the national scale to the Nepal SPP model in a simplified way. One single, integrated environmental metric was used to showcase examples of how the SSP model could inform decision making at the national scale (section 3.2.3).

3.2.2 Integration with Energy Options: Karnali Basin

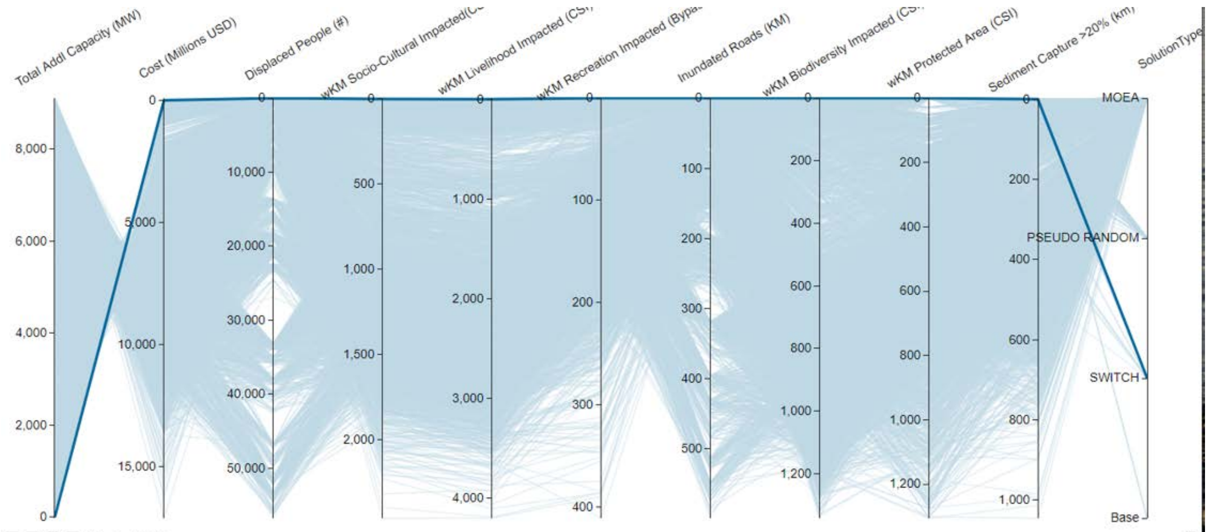
The results from the energy options assessment can be evaluated in the context of the SSP metrics and compared against the environmental and social performance of the solutions generated through the SSP model (as described above). These SWITCH-derived least-cost solutions are presented alongside the SSP-derived solutions in the parallel axis plots. It is important to note that the SWITCH portfolio is proved to be part of a technically feasible power system; in contrast, the SSP solutions may not satisfy basic power system constraints. These SWITCH solutions can be identified in the parallel axis plots by the “SolutionType” axis at the far right which lists the source of each solution. The “name” column in the linked table also lists the scenario name. The solutions included in the parallel axis plots are the least-cost outputs from the SWITCH model for the 2040-time step for each of the scenarios which, in turn, are subsets from Scenario Groups 1 and 2 (described in the Energy Options technical report Table 3-1 or in Table 6-1 in the Annex).

When evaluating the SWITCH results in the context of SSP metrics, it is important to understand that the environmental and social metrics displayed are generated based on impacts occurring in the Karnali basin. Each of the SWITCH solutions also includes hydropower development, to varying degrees, in the rest of the country. Therefore, a solution with low impacts in the Karnali basin might have high impacts in another part of the country that is not captured by Karnali basin metrics. Further, no environmental or social impacts are currently considered from wind, solar, or diesel development (nor from generation impacts in India for solutions which include imports). Therefore, the evaluation of SWITCH outputs in this implementation of SSP should be considered to be an informative example that provides insights into the environmental and social impacts from the SWITCH solutions in a key basin of interest, but does not provide the full picture of impacts across the country. Future implementations of the SSP model could evaluate a broader suite of hydropower impacts across the country as well as impacts form other types of generation.

The scenarios listed in the appendix in Table 6-1, are available for review in the parallel axis plots for the Karnali. A subset of these solutions are described below to highlight some of the findings.

Scenario K01, which is defined by having no new development in the Karnali basin, is identical to the baseline current conditions. As we look across the axes, we see that this scenario includes no new costs, no additional hydropower capacity, and no additional impacts.

Figure 3-13 Scenario K01: no new hydropower development in the Karnali basin. This is identical to the baseline (current conditions solution)

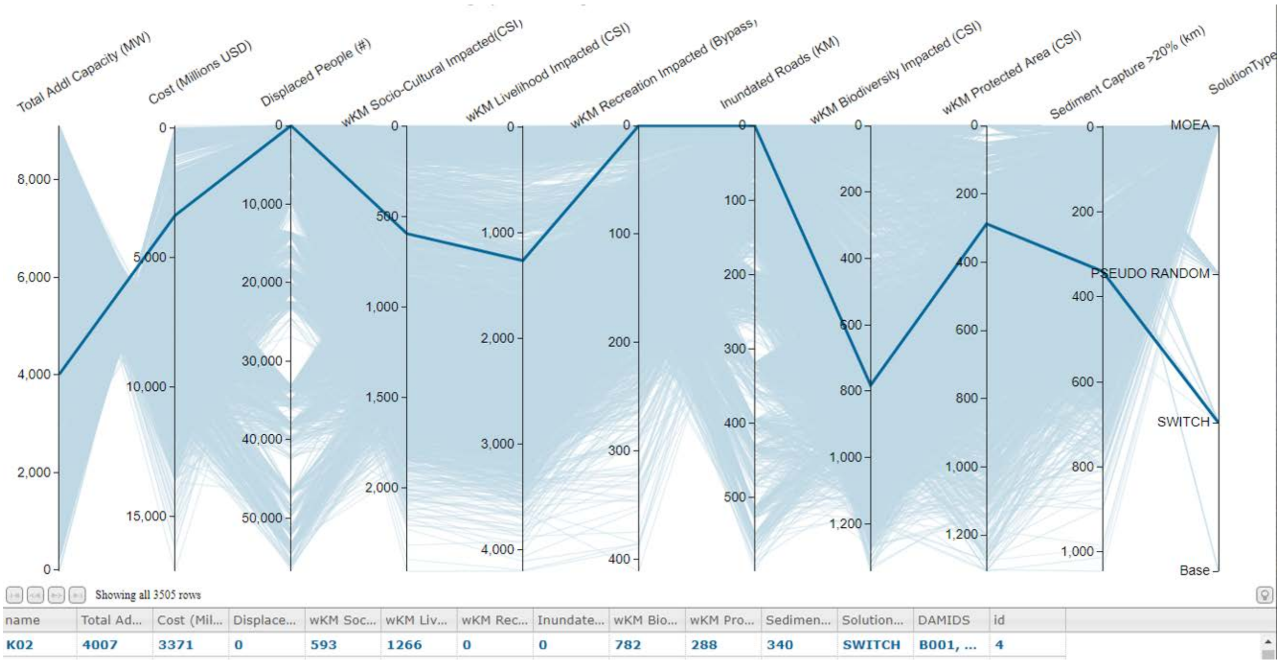


Showing all 3505 rows

name	Total Ad...	Cost (Mil...	Displace...	wKM Soc...	wKM Liv...	wKM Rec...	Inundate...	wKM Bio...	wKM Pro...	Sedimen...	Solution...	DAMIDS	id
Existing...	-20	-94	0	-5	-11	0	0	0	0	-3	Base	B001, P...	0
AllUnder...	977	1007	0	349	559	0	0	34	0	0	Base	B001, P...	1
Baseline...	0	0	0	0	0	0	0	0	0	0	Base	B001, P...	2
K01	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**SWITCH**	**B001, ...**	**3**

Scenario K02 allows for the development of only non-storage hydropower projects in the Karnali basin. The least cost solution shown includes five new projects with a total installed capacity of 2.7 GW and a total cost of all the projects of 2.2. billion USD. Looking at the environmental and social performance of these projects, the model correctly shows low impact on metrics related to reservoir inundation – people displaced and existing roads inundated, since the scenario does not allow storage reservoirs. However, these savings come at the cost of connectivity and flow alteration impacts across other metrics. Biodiversity impacts, in particular, are quite high relative to the other solutions identified by the SSP model, with impacts to approximately 800km of river (using the weighted kilometer approach described in in Section 4.2.3.2).

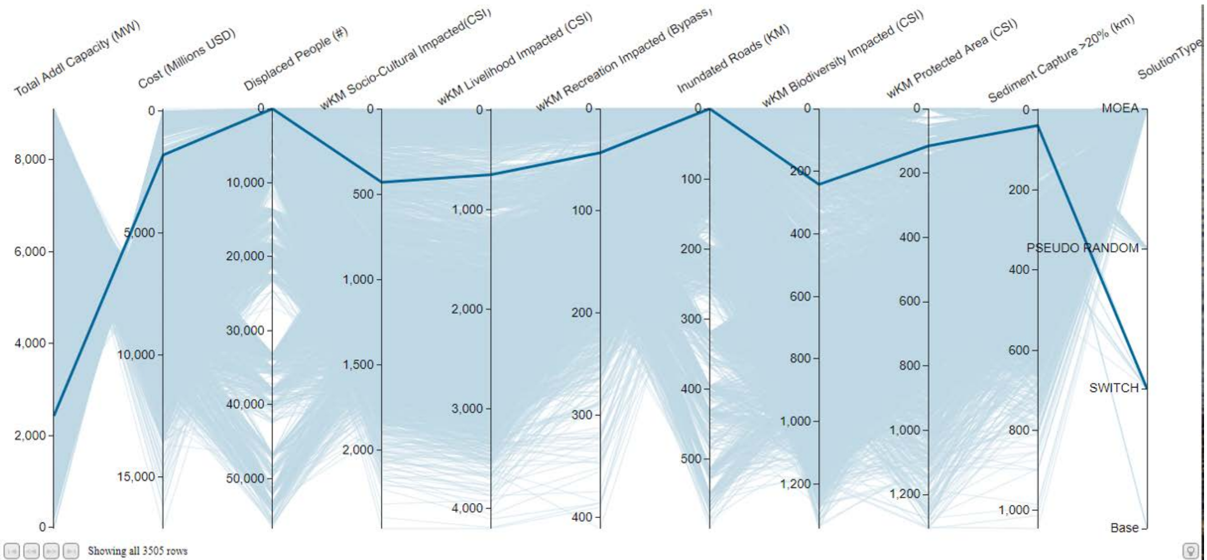
Figure 3-14 SWITCH least-cost solution for Scenario K02



Scenario N01, defined by a restriction from building projects on any free-flowing rivers in Nepal performs quite well based on the SSP metrics. When one considers that much of the Karnali is free-flowing, and therefore very few projects are allowed in the Karnali basin in this scenario, the model results show modest impacts. As one might expect given this scenario, the model also shows the total installed capacity to among the lowest of all the solutions in the SSP analysis, at 234 MW.

Scenario K03 is a particularly interesting scenario. It is defined by a development restriction on the mainstem rivers in the Karnali basin, only allowing for the development of projects on secondary river systems in the basin. This scenario produces results that perform quite well against SSP-derived solutions with a similar installed capacity value (approximately 2.4 GW). For this amount of power, there are no reservoir impacts calculated, which can be attributed to the fact that the proposed storage reservoirs are all located in the lower reaches of large rivers in the basin. Despite the lack of storage reservoirs, the connectivity and flow-alteration impacts, as measured by CSI, are also quite modest relative to the solutions generated by the SSP model. Applying a filter to a narrow band of solutions with comparable installed capacities produces a handful of SSP-identified solutions that perform worse on some metrics and better on others. This shows that the policy restrictions applied in scenario K03 perform reasonably well, based on the environmental and social criteria measured in the analysis. By simply restricting hydropower development on mainstem rivers, it is possible to produce solutions which perform relatively well compared to other solutions. It also starts to illustrate the tradeoffs that begin to emerge. While the K03 solution performs better than other solutions across some metrics, it doesn't always perform better across all metrics. This highlights the need for decision makers and stakeholders to evaluate and balance what impacts are acceptable.

Figure 3-15 SWITCH least cost solution for Scenario K03



name	Total Ad...	Cost (Mil...	Displace...	wKM Soc...	wKM Liv...	wKM Rec...	Inundate...	wKM Bio...	wKM Pro...	Sedimen...	Solution...	DAMIDS	id
K02	4007	3371	0	593	1266	0	0	782	288	340	SWITCH	B001, P...	4
K03	**2428**	**1805**	**0**	**427**	**650**	**43**	**0**	**242**	**116**	**39**	**SWITCH**	**B001, ...**	**5**

Finally, an interesting next step would be to re-run the SSP analysis with the universe of projects restrained to the same criteria as K03: take all mainstem projects "off the table". This could potentially identify other solutions that perform even better than the least-cost solution under the K03 parameters.

3.2.3 Integration with Energy Options: National scale

We developed a simplified SSP model, "Nepal SSP" to showcase examples of how the SSP model could inform decision making at the national scale (section 3.2.3). We included one single, integrated environmental metric, that measures the impact on a suite of HCV.

We first used SSP to calculate a range of portfolios at the national scale to provide boundaries and reference for comparison (3.2.3.1). We then used the produced least-cost portfolios using the SWITCH model for 13 conservation policy scenarios and calculated the environmental impact metric and compared the results to the other optimized portfolios and to the reference scenario (3.2.3.2).

We then focused on the scenario "Karnali secondary" (K03), to demonstrate the approach in more detail at the national scale. We ran the National SSP for each investment period, represented by the final years 2025, 2030, 2035, and 2040, showing the trends of increasing installed capacity and environmental impact relative to other portfolio (see Section 3.2.3.3).

Further refinement and optimization can be achieved by analyzing so-called "solution pools". A solution pool is a set of portfolios produced by SWITCH as intermediate solutions that are not least-cost but that satisfy the criteria of the scenario. These technically feasible alternatives may cost only slightly more but offer better environmental performance. It is time-consuming to produce and analyze these solution pools. As an illustrative example, we produce the solution pool for scenario K03 (Karnali mainstem free-flowing) and demonstrate the use of analyzing the outcomes within a national context (section 3.2.3.4)

3.2.3.1 Nepal SSP: Overview of portfolios and scenarios

A simplified SSP model was created to demonstrate the system-scale planning approach at the national scale in Nepal. This model does not calculate the full range of individual environmental and social metrics as in the Karnali basin, but instead uses a single metric to represent the impacts of hydropower development on HCV rivers in an integrated way thereby capturing impacts on a variety of environmental and social values in a single metric. The model calculates the length of river where the CSI index is below the threshold of 95% and calculates the weighted sum using the integrated HCV score (see 4.2.3.2 for details on the calculation).

The graph in Figure 3-16 shows an overview of a wide range of possible solutions in Nepal, each represented by a point in the lightest gray shade and including up to 67 GW of additional installed capacity. Red-colored dots represent pareto-optimal solutions, where environmental cost is minimized for the amount of installed capacity. The intermediate dark grey dots show

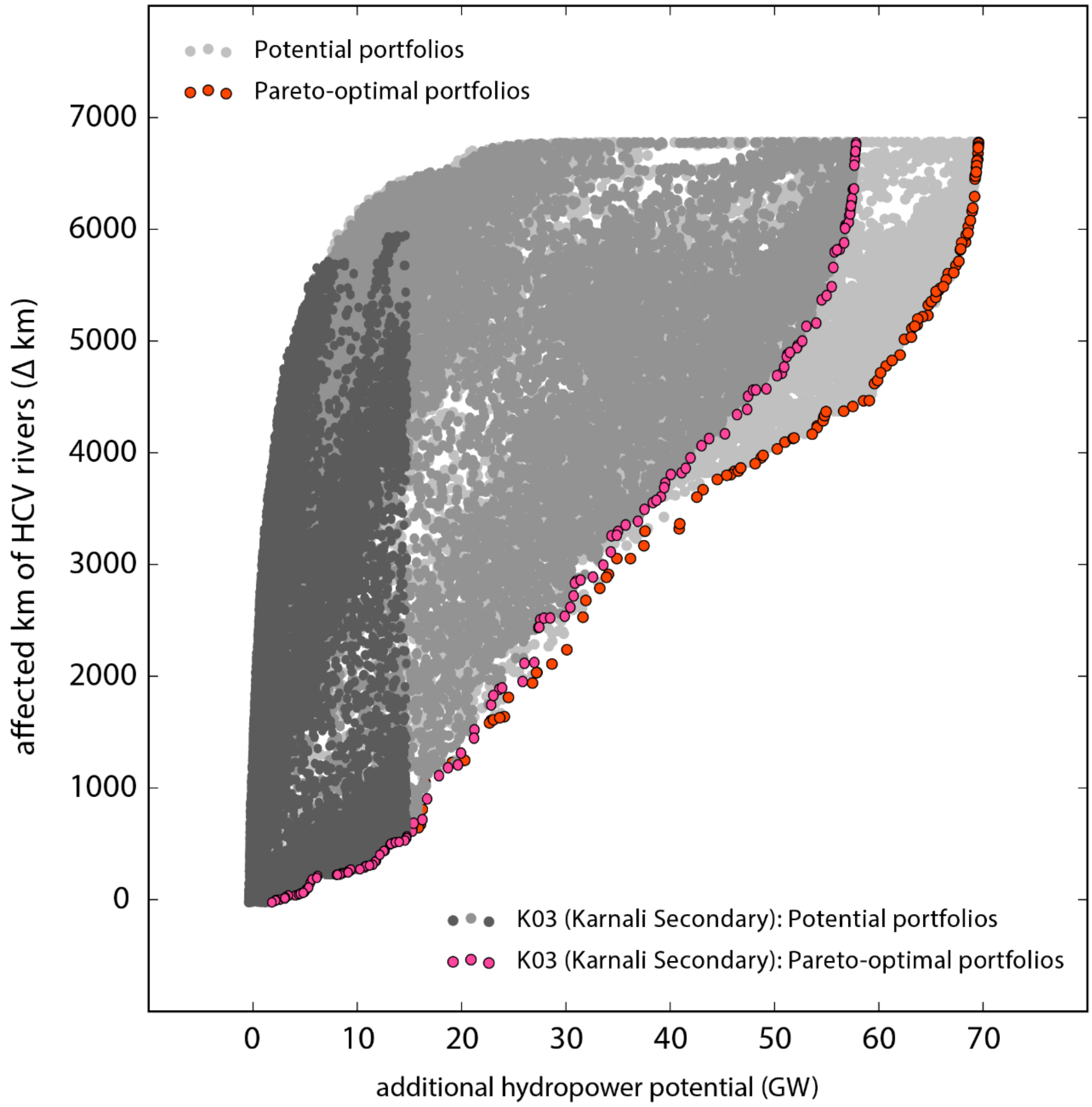


Figure 3-16: Trade-offs between hydropower benefits and environmental impact. The portfolios in grey show a selection of all possible scenarios, making use of the full range of projects listed in the hydropower database.

portfolios that match the constraints of the K03 scenario, with the pink dots representing the pareto-optimal solutions that match those constraints.

An important conclusion to draw from this smaller range of portfolio is that this type of constraint can still satisfy more than 50 GW of additional hydropower. In other words, many potential alternatives exist to avoid building dams on the mainstem Karnali, e.g. other dams in tributaries could replace these projects within the Karnali river, or other projects could be built outside the Karnali basin.

The darkest grey solutions in Figure 3-16 match the constraints of K03 *and* have no more than 15 GW of additional installed capacity. The energy options analysis concludes that it is unlikely that Nepal will install more than 15 GW of additional hydropower between now and the year 2040. This is due to both the expected load forecast and that other sources of energy can also be deployed, including imports of energy.

3.2.3.2 Scenario results

We generated the integrated environmental metric for the 14 conservation policy scenarios (2040 time step) within the National SSP model. The portfolios show a range of installed capacity between 5 and 7.5 GW, and a range of environmental impacts on rivers between 400 and 1,600 km (Table 3-1). Even though the range of impact are high – a quadrupling of impacts can be observed between the scenarios with the lowest and highest impacts – we can observe that all least-cost solutions are relatively close to the pareto-optimal from (Figure 3-17).

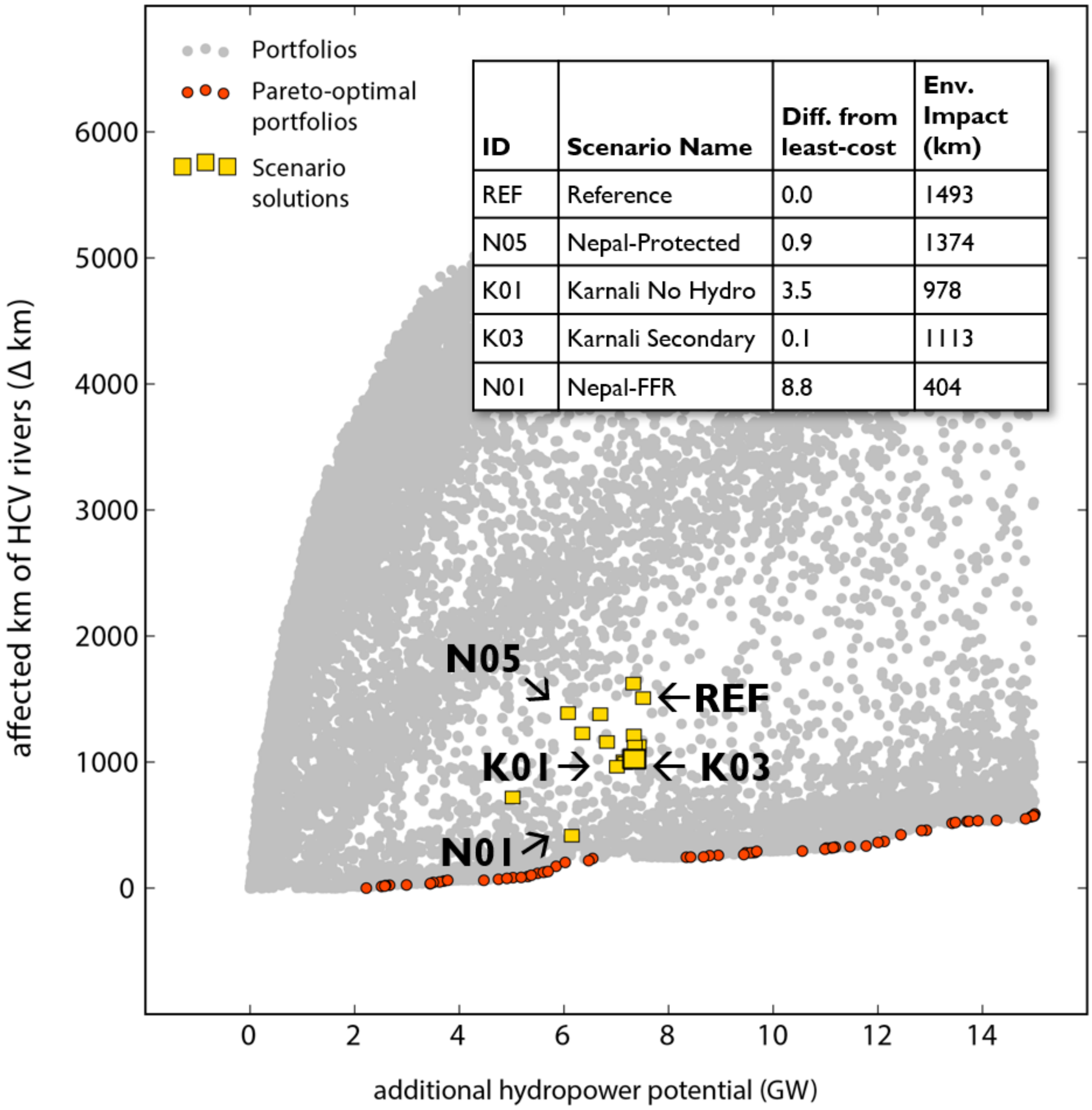
We do not see a clear correlation between installed capacity and environmental impact, which means that environmental impacts are dependent on the location and the characteristics of the chosen projects. This is the benefit of using an SSP model because SWITCH does not internalize in its cost function the individual, or cumulative, impacts that vary by the spatial location of the projects it selects.

The reference scenario ("REF") is the least-cost scenario from an energy system perspective but shows almost the highest cost from an environmental viewpoint. The other scenarios were designed to minimize environmental impacts on rivers, and SWITCH produced alternative portfolios, which indeed cause lower environmental impacts. For example, the "Nepal-FFR" scenario (N01) shows only 404 km of affected rivers at producing more than 6 GW of additional capacity. However, it has a higher system cost of about 8.8% compared to the reference scenario. These two examples highlight the trade-offs when optimizing for both environmental and energy system cost.

The scenario K03 (Karnali secondary) avoids dams on the Karnali main stem, a High-Conservation River, and shows reduced, medium-high environmental impacts at 1113 km of affected HCV rivers and 7.2 GW of additional capacity. However, it is only 0.1% more costly than the reference scenario, making it a seemingly good option for further analysis (see more detailed trade-off analysis for this scenario in 3.2.3.3 and 3.2.3.4).

The K01 scenario (Karnali No Hydro) shows similar environmental impact and capacity statistics. However, at 3.5% increased cost, the downside of shifting development from the Karnali into other basins is far higher than for K03 scenario. This suggests that strategic management of the Karnali basin could achieve environmental and cost benefits.

Another interesting scenario outcome is N05 ("Nepal-protected"). Even though no dam development is allowed in protected areas for this scenario, which raises the cost by 0.9%, we still observe very high environmental impacts. This shows that in their current configuration, protected areas in Nepal cannot sufficiently protect HCV rivers from impacts of future hydropower development, because HCV rivers are not sufficiently protected, and because dam development may occur upstream, or along protected areas.



ID	Scenario Name	Diff. from least-cost	Env. Impact (km)
REF	Reference	0.0	1493
N05	Nepal-Protected	0.9	1374
K01	Karnali No Hydro	3.5	978
K03	Karnali Secondary	0.1	1113
N01	Nepal-FFR	8.8	404

Figure 3-17: Least-cost environmental scenarios from the SWITCH energy options model evaluated in the SSP context

Table 3-1: Overview of National scale assessment of energy options. Color scheme indicates high/low values as a visual guide.

ID	Scenario Name	Diff. from least-cost (%)	Env. Impact (km)
K01	Karnali No Hydro	3.5	978
K02	Karnali No Storage Hydro	0.2	1608
K03	Karnali-secondary	0.1	1113
K04	Karnali-alltrib	0.7	950
K05	Karnali FFR Tributary 1	0.5	1197
K06	Karnali FFR Tributary 2	0.5	1010
K07	Karnali FFR Tributary 3	0.5	993

ID	Scenario Name	Diff. from least-cost (%)	Env. Impact (km)
K08	Karnali FFR Tributary 4	0.1	1109
N01	Nepal-FFR	8.8	404
N02	Nepal-HCV1	9.0	706
N03	Nepal-HCV2	4.8	1365
N04	Nepal-Benchmark	2.8	1145
N05	Nepal-Protected	0.9	1374
N06	Nepal-Benchmark and Protected	7.2	1214
REF	Reference	0.0	1493

3.2.3.3 Scenario results by period (scenario K03)

In this step, we focus the analysis to the scenario "Karnali secondary" (K03). SWITCH produces portfolio investment decisions for five year periods. In each period, a number of additional projects are added to the previous set, increasing the number of dams within the portfolio. While SWITCH has perfect foresight when making these decisions, partitioning investments in periods resembles more closely the actual investment cycles in power systems.

The endpoints of the five-year investment periods are shown in Figure 3-18. The yellow squares represent the least-cost solutions produced by SWITCH at the end of the investment period and show the benefits of the given portfolio (additional hydropower potential on the x-axis), and the environmental cost (affected kilometers of HCV rivers) on the y-axis.

Two observations from this analysis are worth reiterating: First, the least-cost scenarios calculated by SWITCH are based on criteria that optimize the energy system and are not least-cost for the environment. In the year 2040, the least-cost solution from SWITCH affects incurs more than 5 times the HCV river kilometers than a potential pareto optimal solution. However, it is also unknown if this hypothetical pareto-optimal portfolio represents a feasible solution for the energy system. Nevertheless, compared to all potential portfolios, the proposed least-cost solution is located relatively close to the pareto-optimal front, where the impact on the environment is minimized for any given portfolio that achieves similar installed capacity. Other portfolios in that range of installed capacity could potentially inflict far more environmental damage (up to 5,600 km of affected rivers) than the least-cost portfolio by SWITCH.

Second, the trendline shows that the environmental impact of incremental project deployment can vary substantially depending on whether projects are placed at spatially optimized locations (for example in rivers where other projects already operate). The periods from 2025 to 2030, and the periods from 2035 to 2040 show that up to 2 GW of additional hydropower can be developed without much increase of environmental cost. However, steep increases in environmental cost occur due to expansion decisions in the first and third investment period. This dynamic suggests that policy makers can benefit not only from long-term planning applications of SSP, but also from short- to medium-term planning that reveals the incremental impact of dam siting decisions.

This graph can be interpreted to show that if the least cost solutions are taken, then the increase of environmental cost in the first period may be tolerable for the environment,

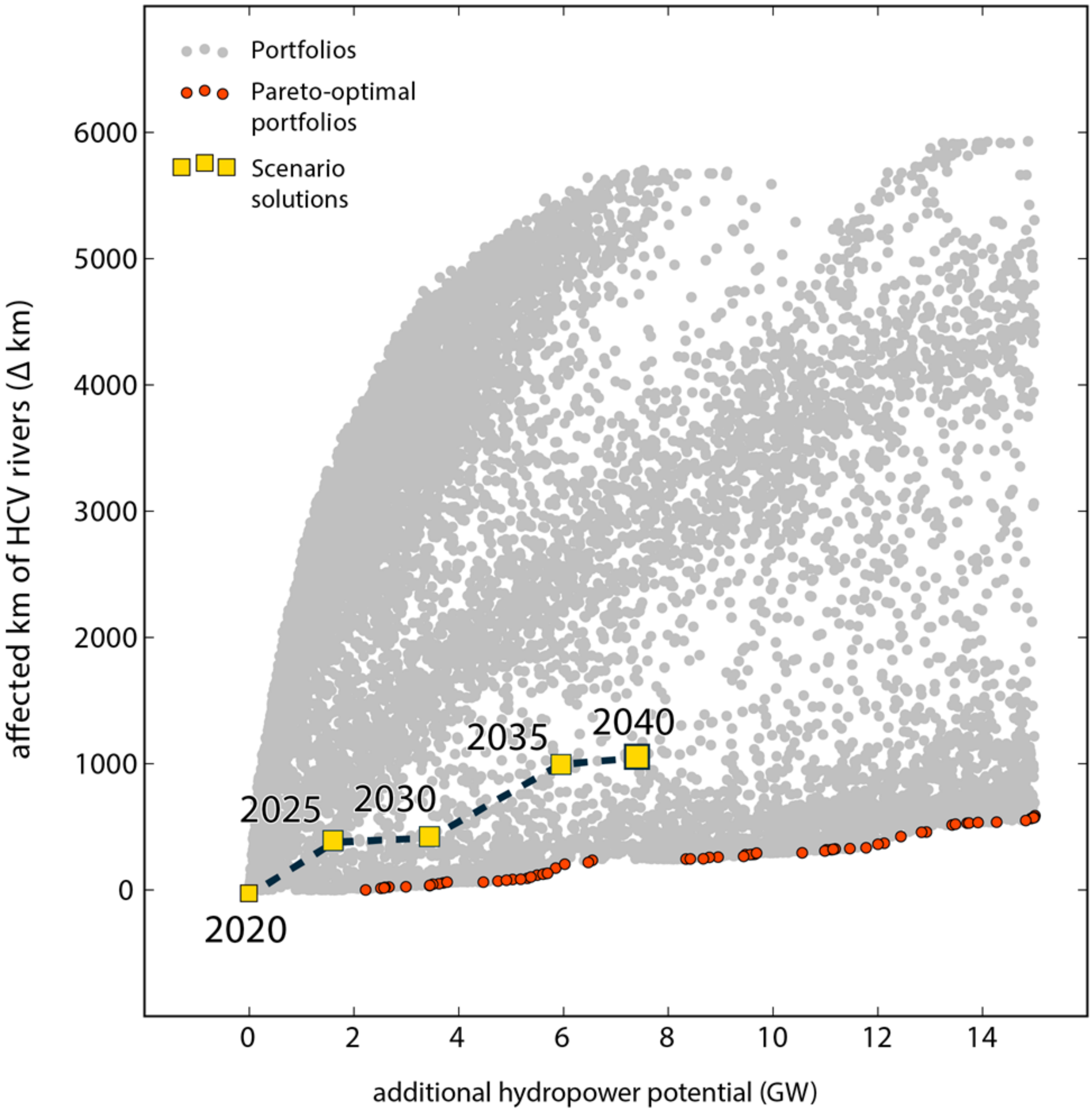


Figure 3-18: K03 scenario portfolios (grey) and pareto-optimal portfolios (red) that are limited to a capacity of up to 15 GW. The yellow portfolios represent the most cost-efficient energy system option at five-year intervals from today (2020) to 2040.

however an even higher environmental cost occurs in the third period, which could lead to the conclusion to only advance hydropower development to a level of 3.8 GW of additional hydropower capacity. If the hydropower portfolio is augmented with additional projects by 2035 the environmental cost would more than double compared to the 2030 situation. Further analysis and exchange of results between the SWITCH and SSP models might identify other solutions with comparable amounts of installed capacity and cost but lower impacts.

The example shows that decision makers need to carefully evaluate investments and their potential impact to avoid unnecessary hydro-environmental impacts and that hydropower planning should also look at temporal trends and their trade-offs.

3.2.3.4 Scenario solution pools (scenario K03)

A scenario solution pool is a set of portfolios produced by SWITCH that correspond to intermediate solutions that are not least-cost but satisfy power system and policy scenario constraints. These alternate solutions are accessible when SWITCH is run as a mixed integer linear program (see the Energy Options Analysis chapter for details). These alternatives may prove to cost only slightly more but offer better environmental performance.

Table 3-2: Overview of K03 scenario pool solutions and difference from least-cost solution (ID 1)

ID	Difference from least-cost (%)
1	0.00
2	9.36
5	0.12
6	0.05
7	0.03
10	0.01
18	0.47
19	0.41
20	0.26
22	0.22
23	0.20
24	0.15
25	0.06
26	0.05
28	2.00
29	0.18
30	0.15
31	0.07
32	0.05
33	0.05
34	0.02
35	0.01

We produced the solution pool for scenario K03 (Karnali mainstem free-flowing) for the year 2040 and show a subset of the produced pool solutions in Table 3-2. Many of these pool solutions are within a small fraction of the cost of the reference scenario (ID 1), however, some solutions stand out at 2.0% (ID 28) and 9.36% (ID 2), respectively.

The environmental cost for each solution pool alternative is shown in Table 3-2. In the case of scenario ID 2, which produces far less hydropower and draws from other fuel sources, we observe similar environmental cost, making this alternative less interesting given its high additional energy cost. In the case of scenario ID 28, we can observe more installed capacity than ID 2, but still do not observe better environmental performance.

The scenarios with ID 6, 26 and 31 are promising, in the sense that their system cost is only slightly higher (0.05%, 0.05% and 0.07%) but produce less environmental impact than the reference K03 scenario (ID 1), based on this high-level analysis.

These and other examples show that the National SSP tool can be used to identify and further minimize trade-offs by analyzing the energy models least-cost solutions in regards of the environmental cost.

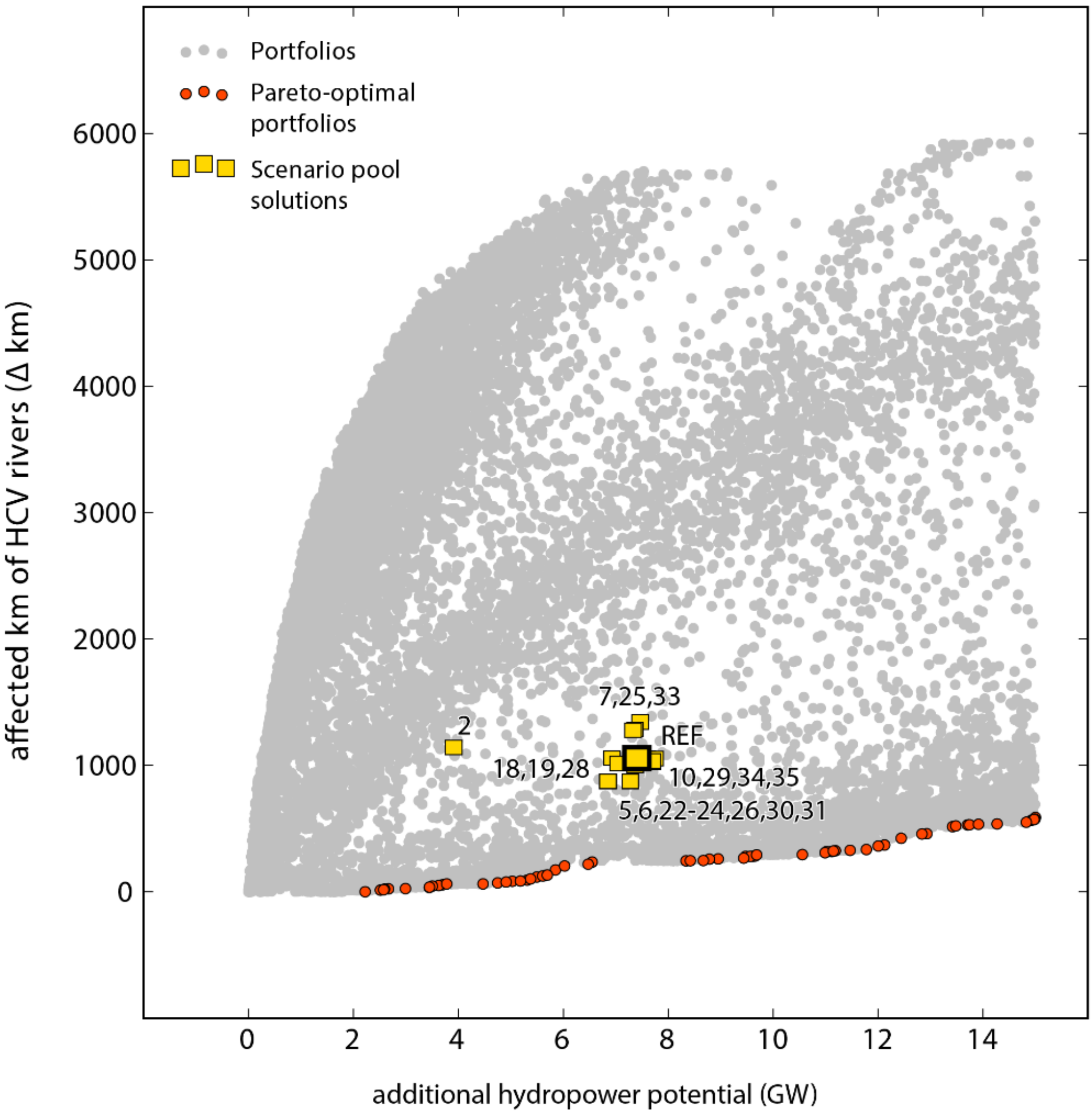


Figure 3-19: Relative location of scenario pool solution to least-cost solution and other portfolios

Regardless of whether solutions are identified from a particular SWITCH time step or from one of the SWITCH solution pools, the potential in each case is similar: the opportunity is there to identify solutions that have a similar amount of installed capacity and overall power system performance with fewer impacts, at only marginally higher costs. Further analysis and integration between SWITCH and SSP could be performed to test low-impact SSP-derived solutions in the SWITCH model to evaluate whether they satisfy the demands of the electric grid and at what cost, relative to the least-cost reference solution.

4 System Scale Planning Model Technical Description

4.1 GIS Database and river basin models

4.1.1 Dam Database

Substantial effort went into developing a dam database that would serve as a primary input to the SSP analysis. Initially, data were compiled from multiple sources including DoED, Open Street Maps (OpenStreetMap contributors, 2020), and the GRanD global database of dams (Lehner et al., 2011). In July of 2020 the project team was able to acquire more refined data on proposed dams from Tractabel (formerly Lahmeyer) from their project to identify candidate hydropower locations throughout the country. This data largely replaced the data that had been compiled from multiple sources. However, the Tractabel data did not include existing projects, nor did it include some projects in some areas that had been previously identified as candidate locations. Thus, it was necessary to combine the Tractabel data with data from DoED.

Once dam data were compiled, it was necessary to classify each dam as existing, under construction, or planned. For the purpose of the SSP analysis, dams that currently exist or which are under construction are "locked in" to all future development solutions while those that are planned constitute the decision variables that can be "turned on" or "off" in each solution. Considerable effort went into classifying these projects, particularly defining which projects should be considered "under construction."

This was done based on license status: whether permits for survey or generation had been applied for or issued. When a generation license had been issued, the project was considered to be "under construction" and therefore locked into each future development scenario. Confounding this approach, however, a generation license issued does not necessarily mean that a project will actually get built. Further, the more projects that get "locked" into each solution, the fewer degrees of freedom are available to identify alternate development solutions that have fewer environmental and social impacts. Thus, for the purpose of generating future development solutions, it was decided to only consider the handful or projects that were in the later stages of development as "under construction" to form the baseline of current conditions. An additional, stand-alone solution was also run to evaluate the "business-as-usual" case that considers all generation-license issued projects as "locked in". This solution is included in the parallel axis plots, along with the thousands of alternate solutions identified in the analysis.

4.1.2 Modeling & Attributing Reservoirs

Reservoirs were modeled for the storage projects identified in the Tractabel data. Reservoir footprints were modeled based using a 90m digital elevation model (Jarvis et al., 2008) and the dam location and reservoir water surface elevation provided to the project team by Tractabel (formerly Lahmeyer) under coordination with WECS. In essence, elevations less than the water surface elevation within the upstream watershed of the dam location were classified as reservoir.

Information on storage volume, which is necessary to model environmental impacts, was not available for all projects. In order to fill these data gaps, we used a power regression between installed capacity and storage volume that was based on information provided by Tractabel data points (Figure 4-1). The relationship used for the regression — installed capacity and storage volume — is based on the assumptions that dams with larger installed capacity tend to also have larger storage reservoirs. Even though there are exceptions to these rules, in particular for run-of-river dams, the estimated storage volumes are within an acceptable range of the observed storage volumes and therefore serve to provide a first-order estimate of the storage capacity in the context of this project.

Attributes that were used to generate environmental or social metrics were generated for each reservoir. For example, as described further in Section 4.2.4, reservoirs were intersected with the WorldPop gridded population data (Tatem, 2017) to estimate the number of people displaced by inundation.

The attributes for each reservoir were then join to the dam associated with the reservoir. These attributes could then be were then summed within the SSP model to produce a value for a given solution.

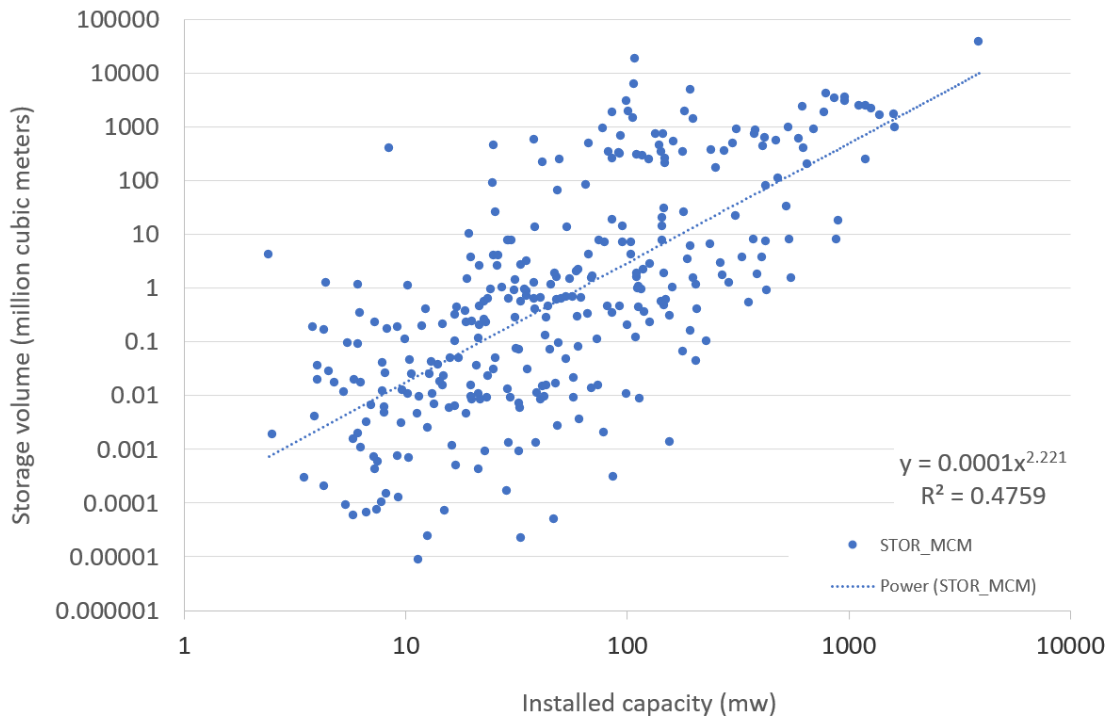


Figure 4-1: Estimation of storage volume using a power relationship based on data from Lahmeyer (2020)

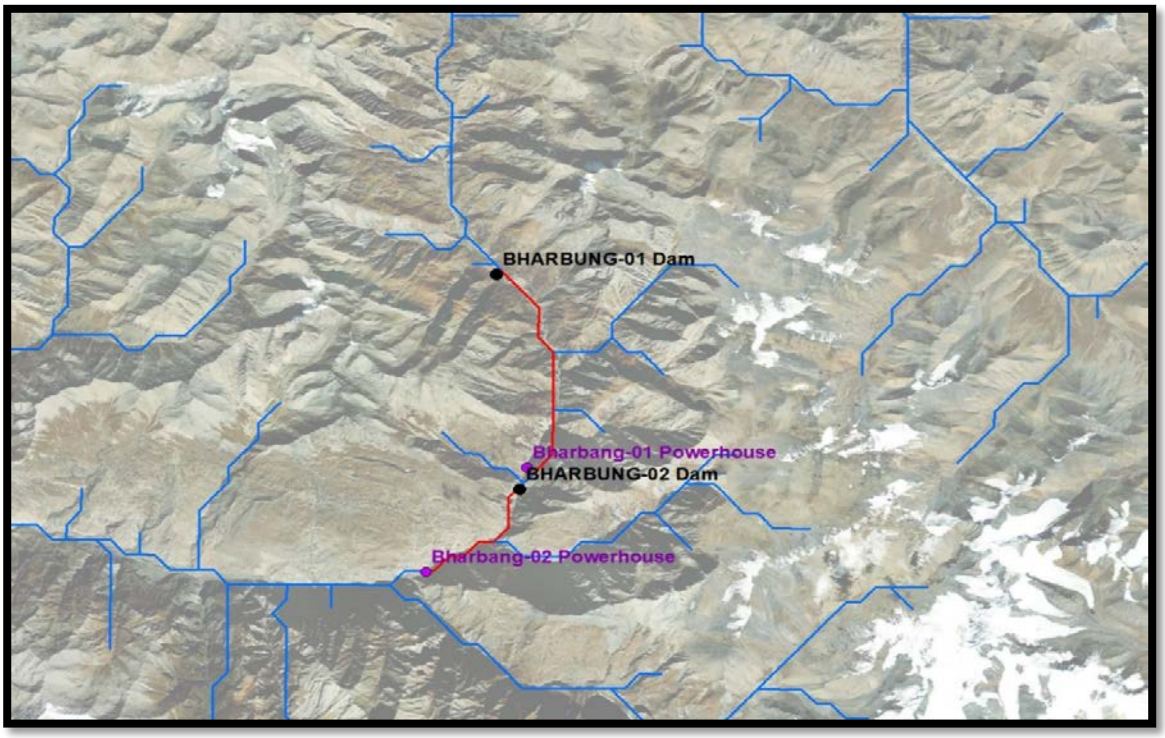
4.1.3 Modifying the river network

The river network used for the SSP analysis in the Karnali basin was extracted from the HCV river data. However, in order to delineate the bypass reaches (i.e. those river reaches between a dam and a separate powerhouse that have the potential to experience substantial flow alteration; see the section below) it was necessary to split each river reach at the dam and powerhouse locations in order to have sufficient precision for the exercise. Subsequent to splitting the necessary reaches, the topology of the river network was rebuilt with new attributes to defined from- and to-nodes and the next up- and down-stream river reaches. This modified network was used as the input to the SSP model. This modified network retained the HCV attributes that were used to develop the environmental and social metrics.

4.1.4 Estimating bypass reaches

Among the impacts that can stem from hydropower development are bypass reaches. Bypass reaches are formed by diversion projects where water is taken from the river at a dam and diverted to a powerhouse further downstream via a tunnel or canal. The river reaches between the dam and powerhouse are at risk of substantial flow alteration due to the water diversion. While it is not possible to know the exact extent of impacts from flow alteration, which depend on how the project is operated, it is possible to say that bypass reaches are at high risk for impacts from flow alteration. Many of the potential projects that were obtained from Tractabel for the SSP analysis are diversion type schemes. These reaches were delineated for the SSP analysis (see Figure 4-2) in the Karnali basin and used to generate metrics which assess impacts to HCV (see Section 4.2.3.1).

Figure 4-2 Example of bypass reaches delineated in red between dams (black) and their powerhouses (purple) on the Barun Khola river

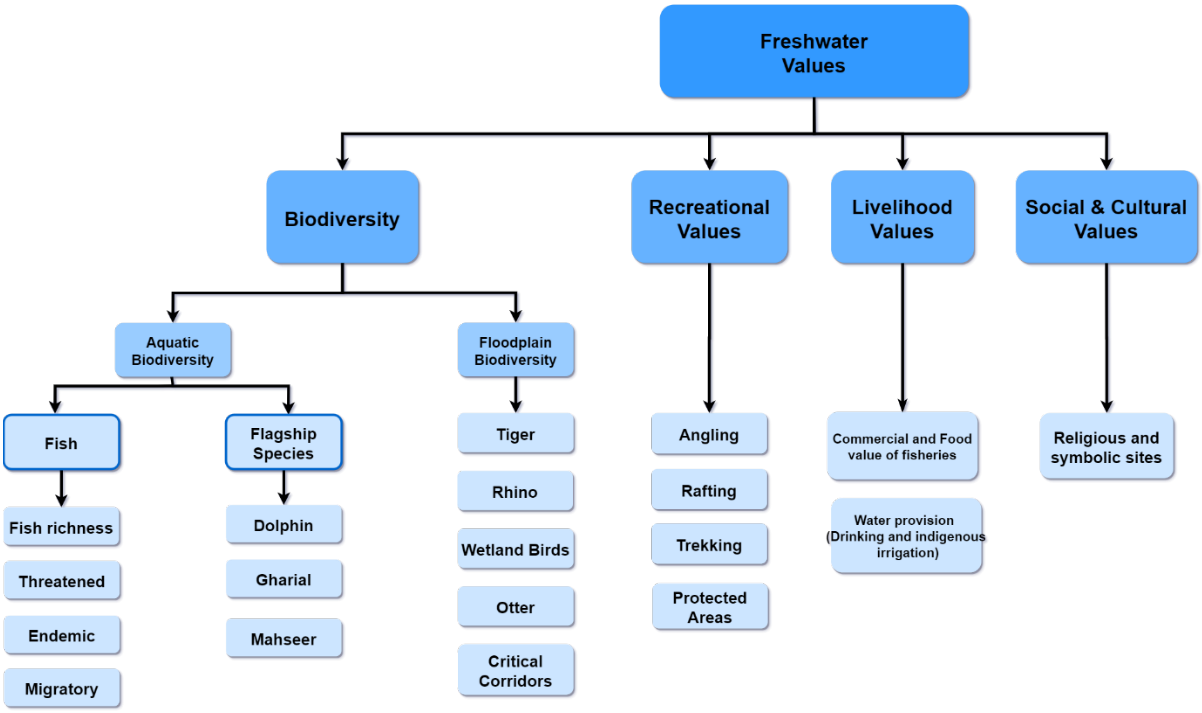


4.2 Values and metrics

4.2.1 Values

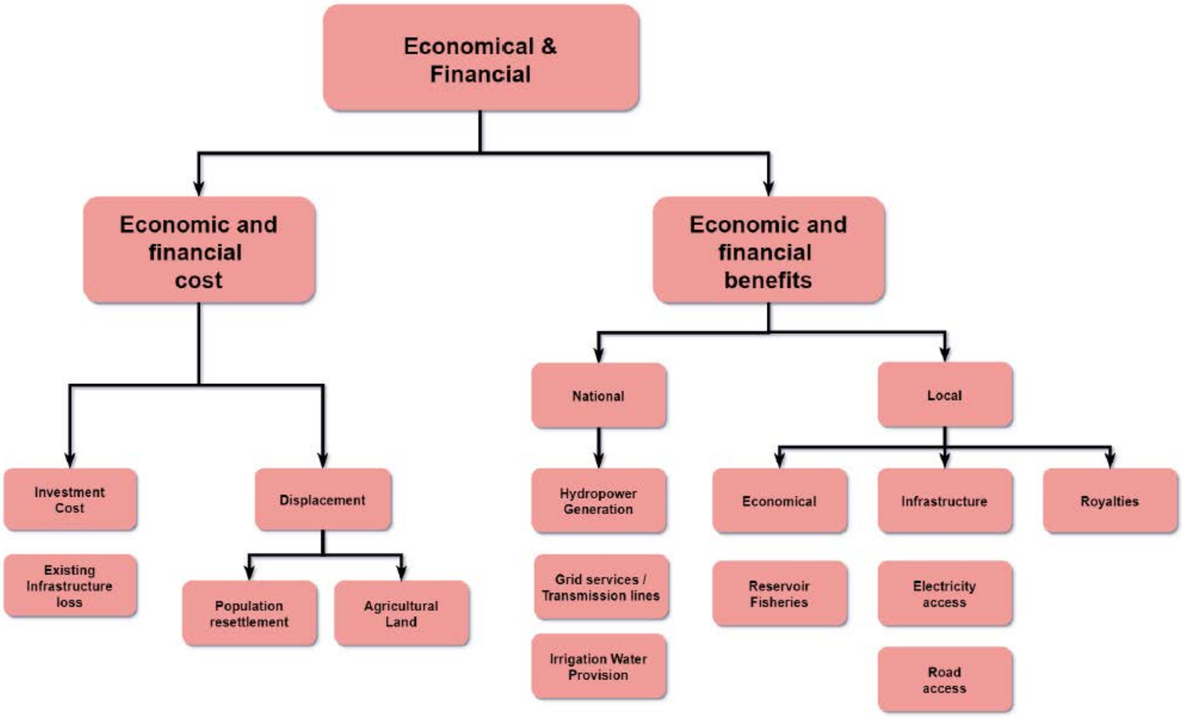
The values identified by stakeholders for the rivers are aligned with those being used in the HCV process. They are biodiversity values, recreational values, livelihood values and social and cultural values. Several data layers were included in each of these four key thematic areas (Figure 4-3).

Figure 4-3 Freshwater values identified for Nepal.



In addition to the values used in the HCV process, specific economic and financial values were assessed as shown in Figure 4-4.

Figure 4-4 Economic and Financial Values assessed in the Karnali Basin



4.2.2 Metrics

Following the identification of the values attributed to the river, a selection of HCV-based metrics were chosen to evaluate impacts to these values. These are shown in Table 4-1below. In essence, each HCV component was evaluated against the three types of hydropower impacts described below. Further, each metric was calculated for baseline (current) conditions, for each future development solution, and the difference between the two. All of these are available for examination, metrics are generally expressed as the difference from baseline.

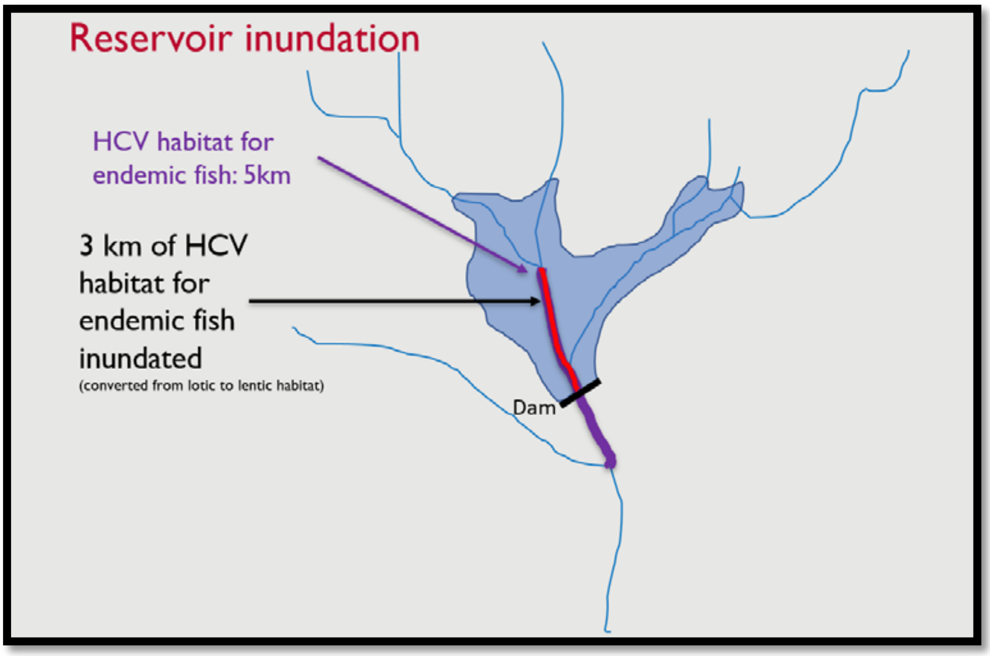
4.2.3 HCV River-based Metrics

4.2.3.1 Types of Impacts Evaluated

Impacts to HCV river reaches were primarily derived from three general types of impacts that can result from hydropower development. These include:

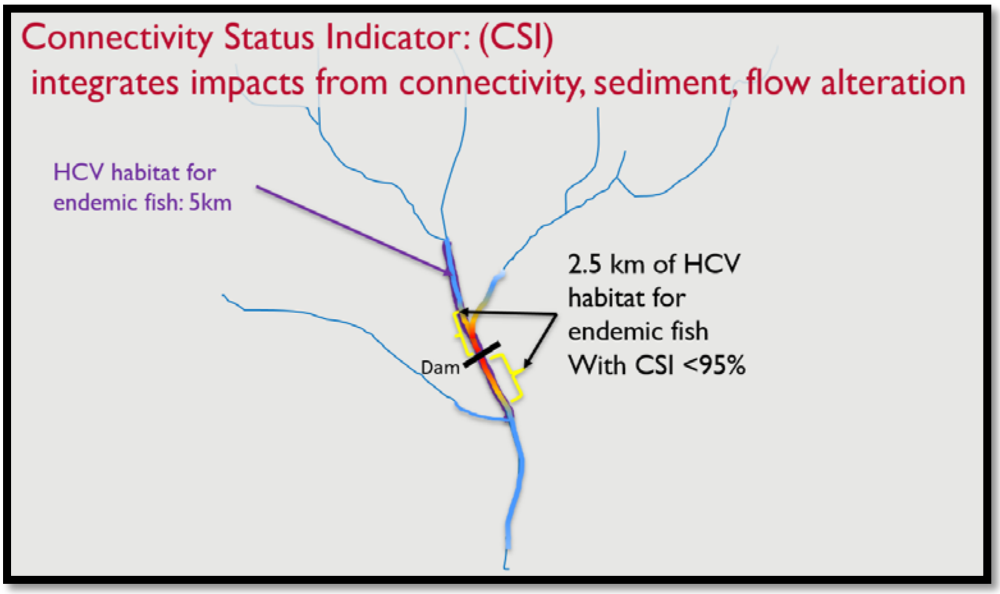
1. Reservoir Inundation. When a hydropower project includes a reservoir, it is often the most obvious type of environmental and social impact. People living in the footprint of the reservoir may have to relocate. Terrestrial biota may be lost due to inundation of habitats and aquatic biota may be displaced by the conversation from lotic to lentic habitat. Impacts to HCV rivers were evaluated by intersecting reservoir footprints with HCV rivers. See Section 4.1.2 for more detail on the modeled reservoirs.

Figure 4-5 Conceptual illustration of a metric assessing reservoir impacts to river reaches identified as HCV for endemic fish (purple line). In this example, 3km of the 5km of endemic fish HCV are impacted from reservoir inundation.



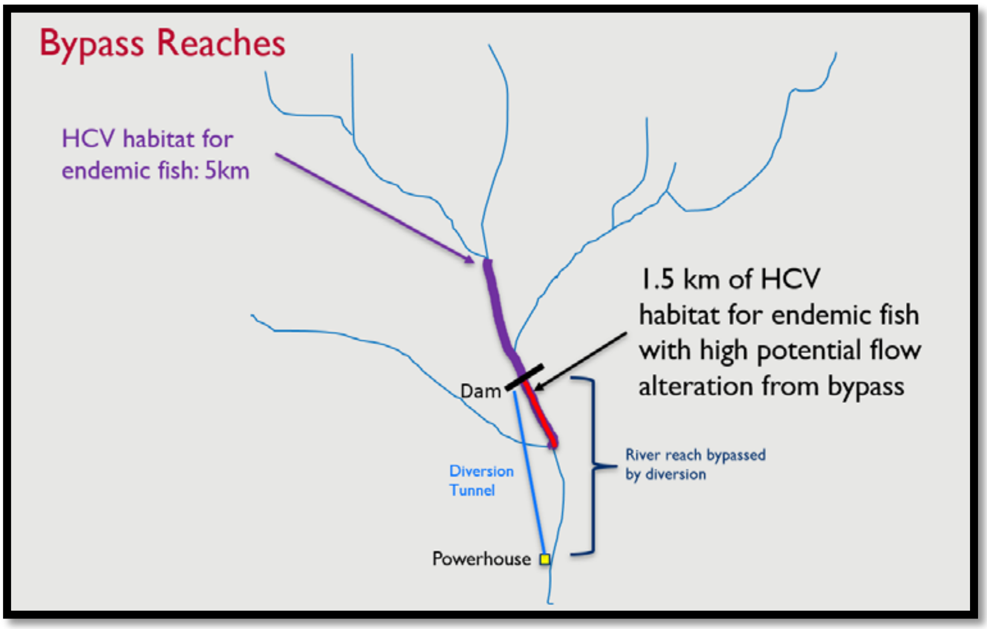
2. River Connectivity. The ability of aquatic organisms to move freely up- and down-stream is critical for access to feeding and spawning habitats, thermal refugia, and meta population dynamics. Construction of a hydropower dam can restrict movement of aquatic organisms and prevent organisms from reaching these critical habitats. Likewise, disruption to river connectivity can impact human uses of the river such as transportation or access to fishing grounds. Connectivity impacts were measured using the Connectivity Status Indicator (CSI), an integrated connectivity metric which incorporates fragmentation, urbanization, flow alteration, road density, consumptive water use and sediment. The CSI produces a continuous value along a 0-100% scale. In keeping with the methods described by Grill et al (2019) a threshold value of 95% was used to determine impacted reaches. Thus, a river reach with a CSI score of 90% in a solution was considered to be impacted.

Figure 4-6 Conceptual illustration of a metric assessing connectivity impacts to reaches identified as HCV for endemic fish



3. Bypass Reaches. Many of the proposed hydropower projects in Nepal are diversion schemes, where water is diverted at a dam, enters a bypass tunnel that flows to the powerhouse, where it spins the turbines before re-entering the river. The river reach between the dam and the powerhouse is the bypass reach, within which there is the potential for substantial flow alteration, depending on how the project is operated (e.g. environmental flow prescription). The HCV river values within the bypass reaches are evaluated by intersecting the bypass reach with the HCV values in that reach.

Figure 4-7 Conceptual illustration of a metric assessing bypass reach impacts to river reaches identified as HCV for endemic fish



4.2.3.2 Weighted KM

As is described further in the HCV technical report, each river reach is given a numeric score for each HCV component. For example, the HCV "Otter" attribute scores each river reach on a 0-5 scale for river otter where a 0 is no value for otter and 5 is highest value for otter. Based on guidance from the HCV team, the HCV score for each component was used as a multiplier when calculating the length of river affected by a given hydropower impact. For example, a reservoir that inundates a reach that has an HCV value of 5 for otter would be considered a more significant impact than a reservoir that inundates an equal length of HCV 1 for otter. The resulting unit was considered "weighted kilometers" of HCV impacted and was calculated as:

$$\text{weightedKM} = \sum_{i=0}^{n} L_i V_i$$

where:
L = length impacted at reach *i*
V = HCV value at reach *i* (e.g. 0 – 5)

As each solution is comprised of multiple projects, each with its own impacts, the KM affected for a given HCV component in a solution must be summarized across all of the projects. Thus, in practice the weighted KM for otter HCV river impacted by reservoir inundation might look like:

HCV value
Total KM impacted in solution

$$(5 * 1.2) + (4 * 0.8) + (3 * 0) + (2 * 2.1) + (1 * 3.1) + (0 * 9.8) = 16.5$$

The weighted KM approach was used to evaluate all three hydropower impacts: reservoir inundation, bypass reaches, and connectivity impacts.

4.2.4 Non-HCV-based Environmental and Social Impacts

In addition to the HCV-based environmental and social metrics that were generated for each solution, a handful of metrics were generated for each solution which do not use the HCV data. These include the following:

4.2.4.1 Sediment

Maintaining a natural sediment regime is critical to allowing geomorphic processes and associated river functions to continue. Dams can retain a large proportion of both suspended and bedload sediments moving through a river system. This can result, for example, in riverbed incision and changes in the bed material, which impacts spawning opportunities for fish. On larger scales, sediment originating from the Himalaya and conveyed in Nepal's rivers contributes to the health of the Ganges-Brahmaputra delta. Thus, sediment retention in dams can impact water users and biodiversity from local to regional scales.

The associated sediment technical report includes further insights into how sediment transport in all rivers of Nepal was estimated. For that purpose, we used a global erosion model to estimate suspended load (Grill et al., 2019), (Borrelli et al., 2017), and an empirical equation to estimate bed load (Turowski et al., 2010). For the purposes of the SSP analysis, a metric was developed that evaluates the percentage of total sediment withheld from each river reach by upstream dams. For that, we estimated suspended sediment trapping rates (percent of incoming sediment trapped in a dam) using a common empirical approach (Brune, 1953). For run-of-river projects with small reservoirs, this approach is not applicable, and we thus assumed a fixed 2 % trapping rate. For bedload we assumed the same trapping rate as for suspended load, even though the trapping rate might be higher in reality.

For each solution, we then defined a sediment objective, expressed as kilometers of river reaches that have greater than 20% of their natural sediment retained by upstream dams.

4.2.4.2 Connectivity by Length

In addition to using the CSI, river connectivity was also evaluated for each solution using the length of connected river network (where networks are those uninterrupted river sections bounded by dams, headwaters, or the river mouth). Specifically, the longest river length in the study region (e.g. Karnali Basin or Nepal-wide, respectively) and the length of river that remains connected to the downstream system.

4.2.4.3 Free Flowing Rivers

Each solution was evaluated for the length of free-flowing rivers (Grill et al., 2019) that would remain in each development solution. Free flowing rivers are defined as those rivers which have a CSI >95% along their length.

4.2.4.4 People Displaced

As noted above, hydropower projects with reservoirs have the potential to displace people living within the footprint of the reservoir or other infrastructure. To evaluate the potential impacts on resettlement, each reservoir was intersected with WorldPop gridded population data (Tatem, 2017) to produce an estimate of the number of people displaced by the reservoir. For a given solution, the number of people displaced was summed for each reservoir in the solution.

4.2.4.5 Agricultural Land Displaced

Agricultural lands that local residents depend on can be inundated by reservoir development. The magnitude of agricultural land inundated in each solution was evaluated by intersecting each reservoir footprint with the Land cover of Nepal (ICIMOD, 2013) and summing the agricultural land cover within each reservoir for the projects in the solution.

4.2.4.6 Existing Infrastructure Inundated

Beyond people and natural resource values, reservoir also have the potential to displace existing infrastructure, adding cost and disrupting the lives of local residents. The impact of reservoir inundation on existing infrastructure was evaluated through the intersection of existing roads (OpenStreetMap contributors, 2020) and reservoirs and expressed as the summed length of inundated roads in each solution.

4.2.5 Energy & Financial Metrics

4.2.5.1 Installed Capacity

Key to the SSP analysis is the amount of power that would be available under each solution. This metrics was expressed as the cumulative installed capacity, in megawatts, in each solution. The installed capacity was obtained from the source dam databases.

4.2.5.2 Investment Cost

The total cost of projects in each solution is presented as the sum of the individual project costs in each solution. Where available, the project cost was taken from the Tractebel / Lahmeyer (Tractebel, 2020) data. Where not available, project cost was estimated using a regression based on project size (installed capacity) and type (storage, run of river, peaking run of river). See Section 2.1 “Estimating hydropower project costs” in the Energy Options technical report for more detail on the methods used to estimate project costs.

4.2.6 Values not Evaluated

Additional values were identified during stakeholder meetings held in Nepal in November 2019 that were not included in the analysis. These values were generally omitted due to data or analytical constraints. A brief description of these follows:

4.2.6.1 Irrigation Water Provision

The project team was unable to develop a metric which assessed the benefits that would be provided by irrigation projects due to the lack of specific information on what areas would benefit from each irrigation project. However, in the Karnali basin, there were no additional irrigation projects included in the final input dam dataset.

4.2.6.2 Electricity Access

Increased access to electricity, particularly for rural populations, is an important objective to consider as the electric system is built out. However, the data available at the national and basin scale for the SSP project did not include information on how the electricity would be tied into the grid (e.g. no spatial alignment for transmission lines) nor whether new capacity would be made available to local communities separate from or in addition to feeding the grid.

4.2.6.3 Road Access

Increased road access can both benefit local communities and lead to additional impacts. For the SSP analysis, the project team investigated modeling access roads from each dam point to the nearest existing road, based on data from Open Street Maps (OpenStreetMap contributors, 2020). However, it was determined that the precision of the input data (dam locations, particularly for dams obtained from DoED data) was insufficient to support this kind of site-scale analysis. Further, the majority of potential projects in the Karnali basin (approximately 80%) were within 1 km of an existing road. Thus, it was decided that due to low confidence in any resulting modeled access roads and the relatively few dams that would involve the creation of substantial new access roads to omit this metric.

4.2.6.4 Royalties

Royalties were identified by stakeholders as a benefit of hydropower projects. Financial costs and benefits were assessed as part of the broader energy options component of the project.

4.2.6.5 Reservoir Fisheries

While reservoir alter freshwater habitats and can have a negative impact on native fish species, they can also provide habitat for commercial, recreational, or subsistence fisheries. However, there was no information available to describe which potential reservoirs might provide more of a fishery than other reservoirs. Therefore, it was determined that area of reservoirs could be a surrogate for reservoir fisheries.

4.2.7 Direction of Optimization

When incorporating these metrics into the SSP analysis, it is necessary to define whether the objective for each metric is to maximize or minimize values in the solutions. For example, it is an objective to produce electricity so in each solution it is desirable to maximize the installed capacity. Simultaneously, it is also desirable to minimize cost and environmental and social impacts. Therefore, when solutions are identified, the SSP model strives to minimize values for these metrics.

4.2.8 List of Metrics Generated

4.2.8.1 HCV-Based Metrics

Table 4-1 lists the HCV-based metrics calculated for each solution in the SSP analysis. Each of these metrics are calculated for the baseline solution (current conditions), the future development solution, and the difference between the two. Metrics highlighted in green were used as inputs to the objective function of the Multi-Objective Evolutionary Algorithm (See Section 4.3.2). These metrics are what the MOEA uses to define performance. That is, as the MOEA generates each new solution, it retains those solutions that outperform other solutions for these 10 metrics. These are the 10 metrics that are available in the parallel axis plots. All the other metrics are generated for each solution, but they do not influence how the MOEA selects which solutions are retained as Pareto-optimal. All metrics are available in the result map package for all solutions.

Table 4-1 List of HCV-based metrics calculated for each solution. Metrics highlighted in green were used in the MOEA objective function. Each of these metrics are calculated for each solution generated for the baseline, or current conditions, solution (BASE) , the solution in total (SCEN), and the difference between the baseline and solution (DIFF).

	CSI <95% (Weighted KM)	Reservoir Inundation (Weighted KM)	Bypass Reaches (Weighted KM)
HCV	CSI_WEIGHTEDKM_HCV	INUND_WEIGHTEDKM_HCV	BYPASS_WEIGHTEDKM_HCV
Biodiversity	CSI_WEIGHTEDKM_BIODIV	INUND_WEIGHTEDKM_BIODIV	BYPASS_WEIGHTEDKM_BIODIV
Aquatic Biodiversity	CSI_WEIGHTEDKM_AQUABIO	INUND_WEIGHTEDKM_AQUABIO	BYPASS_WEIGHTEDKM_AQUABIO
Fish	CSI_WEIGHTEDKM_FISH	INUND_WEIGHTEDKM_FISH	BYPASS_WEIGHTEDKM_FISH
Fish Richness	CSI_WEIGHTEDKM_FISHSP	INUND_WEIGHTEDKM_FISHSP	BYPASS_WEIGHTEDKM_FISHSP
Threatened Fish	CSI_WEIGHTEDKM_FISHTHRTND	INUND_WEIGHTEDKM_FISHTHRTND	BYPASS_WEIGHTEDKM_FISHTHRTND
Endemic Fish	CSI_WEIGHTEDKM_FISHEND	INUND_WEIGHTEDKM_FISHEND	BYPASS_WEIGHTEDKM_FISHEND
Migratory Fish	CSI_WEIGHTEDKM_FISHMIG	INUND_WEIGHTEDKM_FISHMIG	BYPASS_WEIGHTEDKM_FISHMIG
Long Migratory Fish	CSI_WEIGHTEDKM_FISHMIGLNG	INUND_WEIGHTEDKM_FISHMIGLNG	BYPASS_WEIGHTEDKM_FISHMIGLNG
Medium & Short Migratory Fish	CSI_WEIGHTEDKM_FISHMIGSHRT	INUND_WEIGHTEDKM_FISHMIGSHRT	BYPASS_WEIGHTEDKM_FISHMIGSHRT
Mahseer	CSI_WEIGHTEDKM_MAHSEER	INUND_WEIGHTEDKM_MAHSEER	BYPASS_WEIGHTEDKM_MAHSEER
Dolphin	CSI_WEIGHTEDKM_DOLPHIN	INUND_WEIGHTEDKM_DOLPHIN	BYPASS_WEIGHTEDKM_DOLPHIN
Gharial	CSI_WEIGHTEDKM_GHARIAL	INUND_WEIGHTEDKM_GHARIAL	BYPASS_WEIGHTEDKM_GHARIAL
Floodplain/Wetland-Dependent Biodiversity	CSI_WEIGHTEDKM_FLOODBIO	INUND_WEIGHTEDKM_FLOODBIO	BYPASS_WEIGHTEDKM_FLOODBIO
Tigers	CSI_WEIGHTEDKM_TIGER	INUND_WEIGHTEDKM_TIGER	BYPASS_WEIGHTEDKM_TIGER
Rhinos	CSI_WEIGHTEDKM_RHINO	INUND_WEIGHTEDKM_RHINO	BYPASS_WEIGHTEDKM_RHINO
Wetland Birds	CSI_WEIGHTEDKM_BIRD	INUND_WEIGHTEDKM_BIRD	BYPASS_WEIGHTEDKM_BIRD
Otter	CSI_WEIGHTEDKM_OTTER	INUND_WEIGHTEDKM_OTTER	BYPASS_WEIGHTEDKM_OTTER
Critical Corridors	CSI_WEIGHTEDKM_CRITCOR	INUND_WEIGHTEDKM_CRITCOR	BYPASS_WEIGHTEDKM_CRITCOR
Recreation	CSI_WEIGHTEDKM_REC	INUND_WEIGHTEDKM_REC	BYPASS_WEIGHTEDKM_REC
Angling	CSI_WEIGHTEDKM_ANGLING	INUND_WEIGHTEDKM_ANGLING	BYPASS_WEIGHTEDKM_ANGLING
Rafting	CSI_WEIGHTEDKM_RAFT	INUND_WEIGHTEDKM_RAFT	BYPASS_WEIGHTEDKM_RAFT
Trekking	CSI_WEIGHTEDKM_TREK	INUND_WEIGHTEDKM_TREK	BYPASS_WEIGHTEDKM_TREK
Protected Areas (Large Rivers)	CSI_WEIGHTEDKM_PROT	INUND_WEIGHTEDKM_PROT	BYPASS_WEIGHTEDKM_PROT
Livelihood	CSI_WEIGHTEDKM_LIVELI	INUND_WEIGHTEDKM_LIVELI	BYPASS_WEIGHTEDKM_LIVELI
Commercial and Food Value of Fisheries	CSI_WEIGHTEDKM_FISHCOMMFOOD	INUND_WEIGHTEDKM_FISHCOMMFOOD	BYPASS_WEIGHTEDKM_FISHCOMMFOOD
Water Provision	CSI_WEIGHTEDKM_PROVISION	INUND_WEIGHTEDKM_PROVISION	BYPASS_WEIGHTEDKM_PROVISION
Socio-Cultural	CSI_WEIGHTEDKM_SOCIO	INUND_WEIGHTEDKM_SOCIO	BYPASS_WEIGHTEDKM_SOCIO
Religious and Cultural Sites	CSI_WEIGHTEDKM_RELIG	INUND_WEIGHTEDKM_RELIG	BYPASS_WEIGHTEDKM_RELIG

4.2.8.2 Non-HCV-Based Metrics

In addition to the HCV metrics calculated for each scenario, the following additional metrics were calculated for each solution. The metrics highlighted in green were used in the MOEA objective function.

Table 4-2 List of non-HCV-based metrics calculated for each solution. Metrics highlighted in green were used in the MOEA objective function.

Metric	Description	GIS Metric Name
Capacity	Installed Capacity in MW	SCEN_TOT_MW_ADDED
Investment Cost	Total investment cost (Millions USD)	SCEN_COST_USD_MIO
Basin Connectivity	Length of the longest connected river entwork	BASIN_CON_KM
Free Flowing Rivers	Length (km) & number of free flowing rivers	FFR_KM / FFR_NUM
CSI Weighted by Water Volume	Reach-based CSI score weighted by river volume	WCSI_KM
Sediment Retention	KM of rivers with greater than 20% of their natural sediment load retained by upstream dams	WSED_KM
People Displaced	Number of people displaced by reservoir inundated	INUNDATED_WORLDPOP_SUM
Forest Inundated	Area of forest inundated (m²)	INUNDATED_FOREST_M2
Grassland Inundated	Area of grassland inundated (m²)	INUNDATED_GRASSLAND_M2
Shrubland Inundated	Area of shrubland inundated (m²)	INUNDATED_SHRUBLAND_M2
Agriculture Inundated	Area of agricultural land inundated (m²)	INUNDATED_AGRICULTURE_M2
Roads Inundated	Length of existing raods inundated (km)	INUNDATED_ROADSLENGTH_KM

4.3 Identifying Solutions

The number of possible future development solutions given the almost 300 input candidate hydropower projects is astronomical (4.9×10^{86}). It is therefore not feasible to evaluate the benefits and impacts for every possible scenario. Instead, two approaches are used for identifying solutions: pseudo-random generation and a multi-objective evolutionary algorithm (MOEA).

4.3.1 Pseudo-Random

The pseudo-random algorithm selects candidate projects randomly, structured within different size class bins. This process ensures that solutions span the full breadth of potential development options, ranging from solutions that only have a small amount of installed capacity to those that approach a full build-out of the basin (where all potential projects are built). Furthermore, this initial set of portfolios is used as a seed for the subsequent multi-objective optimization algorithm.

In order to focus on the results from the MOEA and improve performance of the parallel axis plots (see Section 3.1.2), only those pseudo-random solutions with an installed capacity less than the lowest installed capacity value generated by the MOEA are included in the parallel axis plots.

4.3.2 Multi-Objective Evolutionary Algorithm

A second approach to identify solutions uses a multi-objective evolutionary algorithm (MOEA). An MOEA is a computer algorithm that optimizes for two or more (often conflicting) objectives, based on processes inspired by natural selection and evolutionary biology. In this project, the MOEA was used to filter through the large number of mathematically possible scenarios and identify the solutions that perform best across multiple metrics. When applied to multiple metrics in this fashion, MOEAs do not provide a single solution that is optimal for all metrics. Rather, they provide alternative solutions that represent the universe of options approaching optimal performance for pairs of metrics among the broad group of metrics being considered. MOEAs do however eliminate scenarios that perform poorly across all metrics, minimizing the number of scenarios that need to be further evaluated by stakeholders. For example, given two scenarios with equal energy generation potential, the MOEA will retain the scenario with better environmental performance and drop the scenario with lower environmental performance.

The SSP model was written in Python (2.7.16) to leverage the Platypus (Hadka, 2020) MOEA - a free and open source framework for evolutionary computing in Python with a focus on MOEA applications. Platypus supports the integration of an array of multi-objective algorithms. We used the εNSGA II algorithm within the Platypus framework, as we have gained familiarity with its use in other HbD applications.

The MOEA applies an iterative analytical process. After evaluating the performance of metrics for the initial set of solutions selected, it sorts the solutions based on their metric performance and retains the better performing scenarios in an archive. It then evaluates another set of scenarios with a different combination of candidate projects, repeating this process and continuing to update the archive with new scenarios that perform better than previous scenarios, and dropping outperformed scenarios.

The best performing scenarios are defined as "pareto-optimal," or non-dominated scenarios. Non-dominated scenarios are those for which no further improvements can be made in the performance of one metric without simultaneously decreasing the performance of another metric.

For practical purposes, the MOEA was limited to ten metrics. Thus, the technical team went through a selection process to choose a set of metrics that evaluated all dimensions of interest (social, environmental, energy, financial) using the most relevant impacts (see Table 4-1 and Table 4-2). While eliminated metrics were not used to drive the selection of scenarios for consideration, they were evaluated after the selection of scenarios and included in the overall results (see "Illustrating trade-offs among scenarios," below).

After the MOEA identified the pareto-optimal solutions for metrics among scenarios based on the ten identified priority metrics, the remaining metrics were processed for each scenario and included for exploration of results and trade-off analysis.

4.3.3 Maximum Installed Capacity

Based on results from the SWICTH model, solutions were constrained to a maximum of 9,100 MW. This is the maximum hydropower developed by SWITCH in the Karnali by 2040 in any of the least-cost solutions (this was from the "no imports" scenario). Across all SWITCH solutions, the median installed capacity in the Karnali by 2040 is 2,200 MW, the mean is 2,800 MW and the 3rd quartile is 3,000 MW. Thus, limiting the maximum installed capacity to 9,100 MW still allows for solutions that are at the highest end of realistic, while allowing the model to better improve on solutions within the installed capacity range of greatest interest.

In the MOEA, this constraint was applied as each solution was generated – if a solution had a cumulative installed capacity >9,100 MW, it was immediately discarded. For the pseudo-random results, however, the full breadth of installed capacity ranges were calculated (from very small to up to 29 GW). These are included in the results table in the map package (see Section 3.1.3) but are filtered out by default with a definition query. This definition query can be removed to access pseudo-random solutions with cumulative installed capacity >9,100 MW. Doing so will also update the linked scatter plot graphs.

4.4 Source code of model on GitHub

The source code for the SSP model, known by the project team as "SABER" is available on GitHub at: https://github.com/ggrill/SABER-PAANI. Access to the source repository is available upon request.

In order to run the code, it is necessary to install several dependencies including arcpy (Esri's ArcGIS python package) and Platypus, an open source framework for multi-objective evolutionary algorithms.

5 Citations

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6 Annex

6.1 Workshops and meetings

6.2 Integration with Energy Options

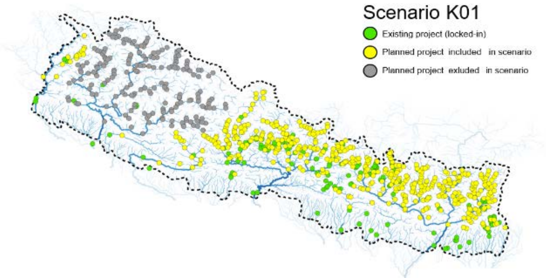
6.2.1 Scenarios

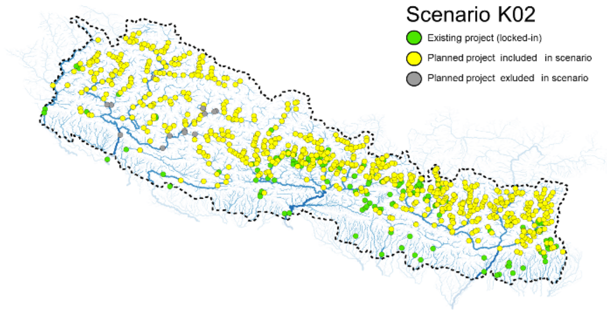
Table 6-1: Full list of integration scenarios

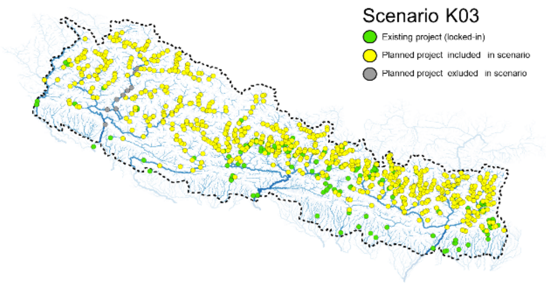
Group	ID	Scenario name	Short description	Explanation
SG 1 - Karnali basin	K01	Karnali No Hydro	No new hydro in Karnali basin	In this scenario we assess only new projects outside the Karnali river basin
	K02	Karnali No Storage Hydro	No new storage hydro in Karnali basin	No new storage projects are assessed, but Peaking-run-of-river and run-of-river projects may be developed, even on mainstem Karnali
	K03	Karnali-secondary	No mainstem projects - only development in secondary river systems in Karnali basin	Secondary river systems are rivers that drain into the mainstem of each major river. For example, projects located on rivers that drain into the Karnali may be included as option (including Humla Karnali)
	K04	Karnali-alltrib	No mainstem projects and no additional projects in all four tributaries of the Karnali	Bheri and Thuli Bheri Thuligad Westi Seti and Budiganga Tila
	K05	Karnali FFR Tributary 1	No mainstem projects and at least one tributary of the Karnali free flowing (1)	Bheri and Thuli Bheri
	K06	Karnali FFR Tributary 2	No mainstem projects and at least one tributary of the Karnali free flowing (2)	Thuligad
	K07	Karnali FFR Tributary 3	No mainstem projects and at least one tributary of the Karnali free flowing (3)	West Seti and Budiganga
	K08	Karnali FFR Tributary 4	No mainstem projects and at least one tributary of the Karnali free flowing (4)	Tila
SG 2 - Nepal wide	N01	Nepal-FFR	Keep existing FFR in Nepal	No development in rivers that are classified as free-flowing as a result of free-flowing river analysis. Project development on stretches with "good connectivity" is still possible
	N02	Nepal-HCV1	Develop only rivers with HCV value below 1	Projects can only be developed in rivers that have an aggregated HCV value below or equal to 2. However, in this scenario, projects could be developed on rivers that are free-flowing.
	N03	Nepal-HCV2	Develop only rivers with HCV value below 2	Projects can only be developed in rivers that have an aggregated HCV value below or equal to 3.
	N04	Nepal-Benchmark	No additional dams in so-called "benchmark/candidate" rivers as well as in rivers of	"Benchmark/candidate" rivers are rivers which match the definition of HCVR according to the experts (Karnali, Humla Karnali, Budhi Gandaki, West Seti and Tamor). Some other rivers have been

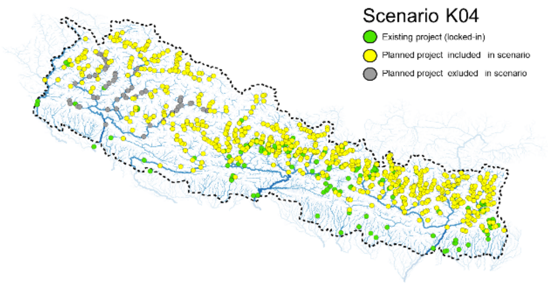
			national importance for biodiversity	added in this scenario based on the importance of those river for biodiversity (Tila, Bheri, East Rapti, Thuligad, Babai, Thulo Bheri)
	NO5	Nepal-Protected	No additional projects in protected areas or on bordering rivers	Hydropower producers should leave 50% of mean monthly flow if structures built within PAs. So, less HP production in these rivers, and more impact on biodiversity dependent on these rivers. Also includes boundary rivers of PAs, which need conservation in the opposite bank of PAs.
	NO6	Nepal-Benchmark and Protected	NO4+NO5	

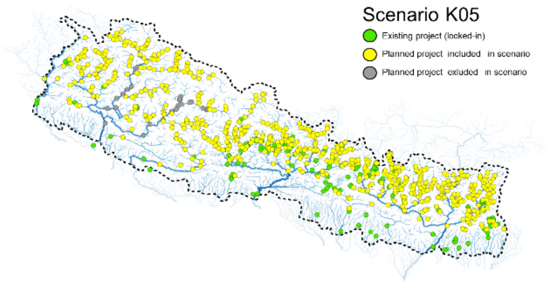
6.2.2 Scenario constraint maps

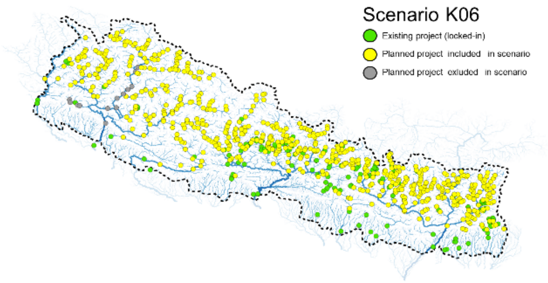


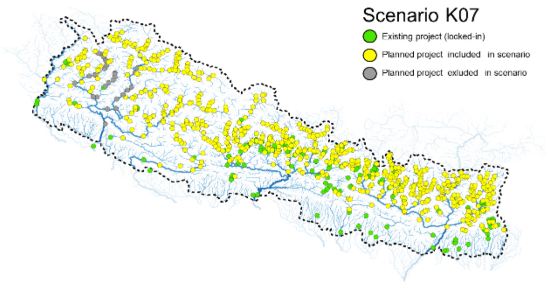


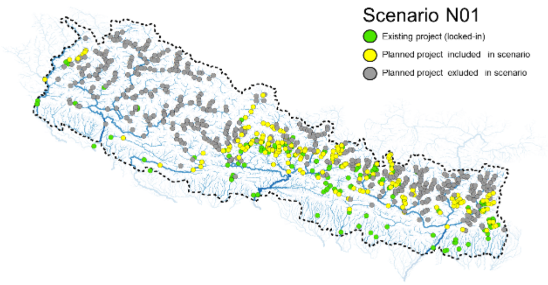


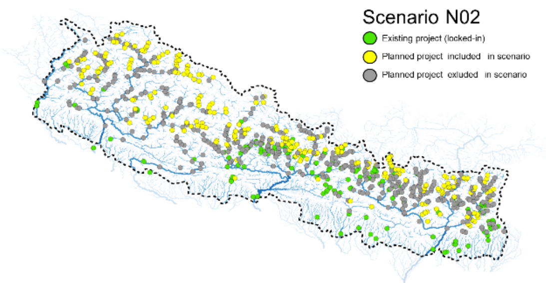


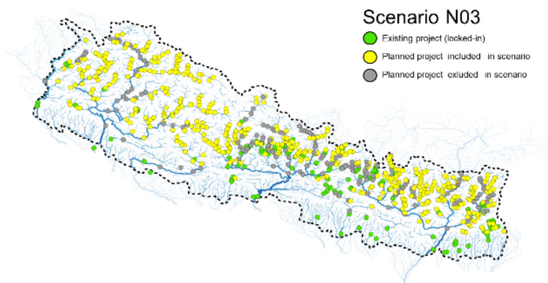












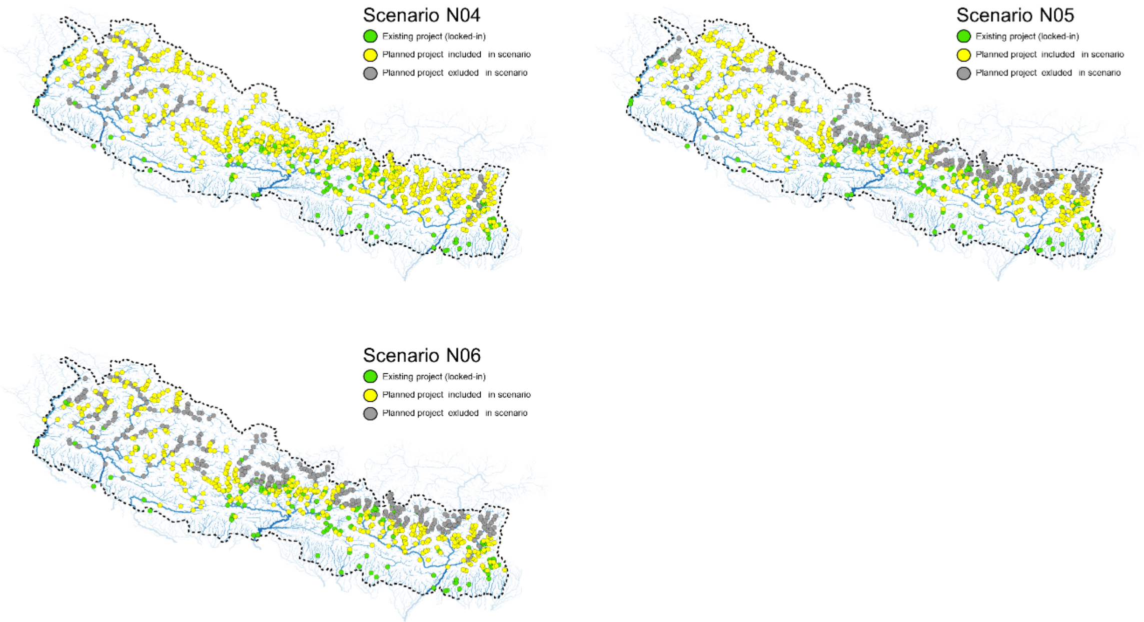
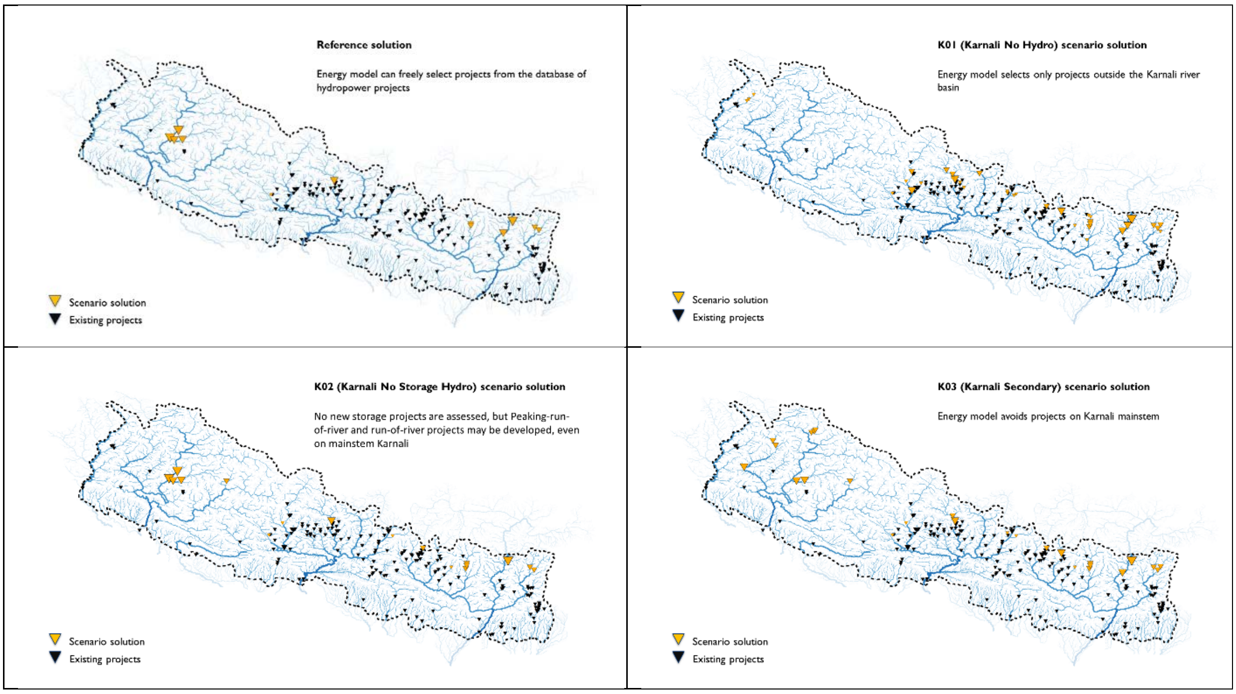


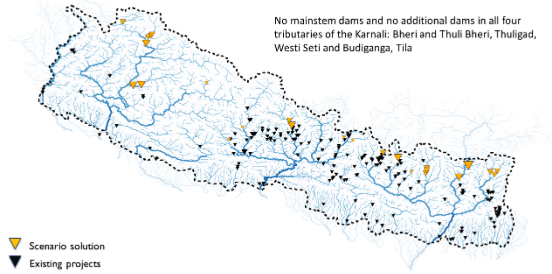
Figure 6-1: Overview of scenario constraints for 13 environmental scenarios. For a description of the scenarios see 6.2.1.

6.2.3 Maps of portfolios of least-cost SWITCH solutions



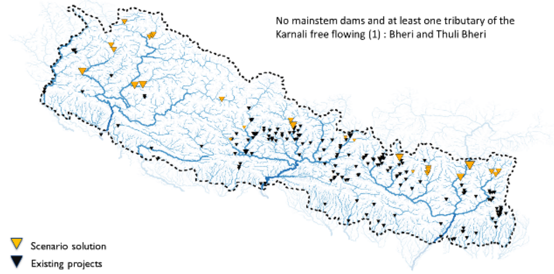
K04 (Karnali-alltrib) scenario solution

No mainstem dams and no additional dams in all four tributaries of the Karnali: Bheri and Thuli Bheri, Thuligad, Westi Seti and Budiganga, Tila



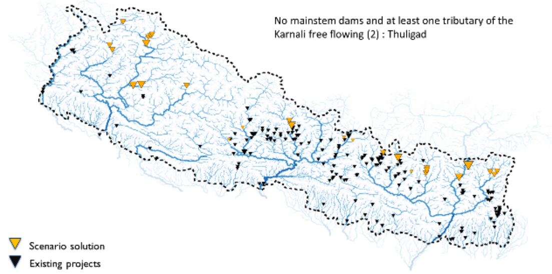
K05 (Karnali FFR Tributary 1) scenario solution

No mainstem dams and at least one tributary of the Karnali free flowing (1) : Bheri and Thuli Bheri



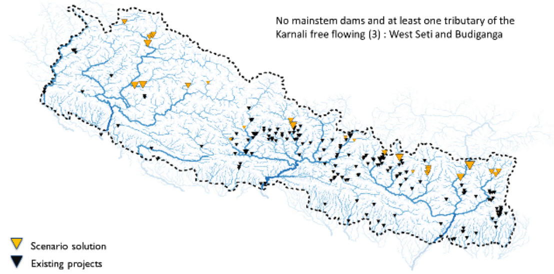
K06 (Karnali FFR Tributary 2) scenario solution

No mainstem dams and at least one tributary of the Karnali free flowing (2) : Thuligad



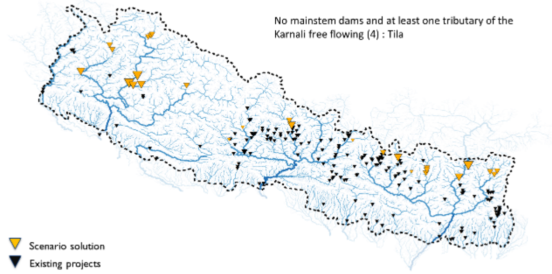
K07 (Karnali FFR Tributary 3) scenario solution

No mainstem dams and at least one tributary of the Karnali free flowing (3) : West Seti and Budiganga



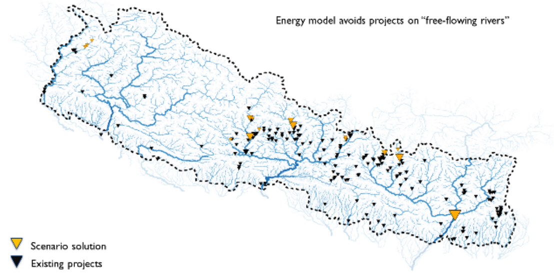
K08 (Karnali FFR Tributary 4) scenario solution

No mainstem dams and at least one tributary of the Karnali free flowing (4) : Tila



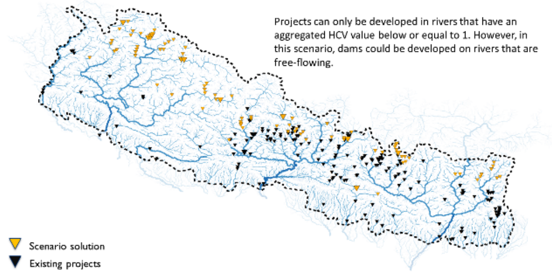
N01 (Nepal-FFR) scenario solution

Energy model avoids projects on "free-flowing rivers"



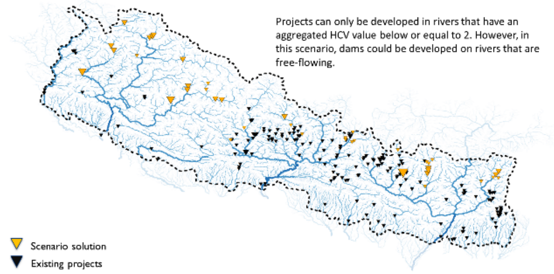
N02 (Nepal-HCV1) scenario solution

Projects can only be developed in rivers that have an aggregated HCV value below or equal to 1. However, in this scenario, dams could be developed on rivers that are free-flowing.



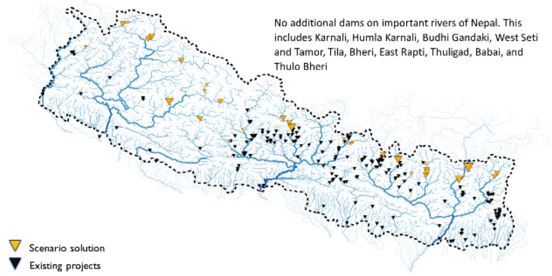
N03 (Nepal-HCV2) scenario solution

Projects can only be developed in rivers that have an aggregated HCV value below or equal to 2. However, in this scenario, dams could be developed on rivers that are free-flowing.



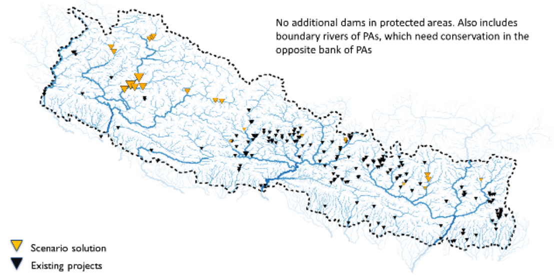
N04 (Nepal- Benchmark) scenario solution

No additional dams on important rivers of Nepal. This includes Karnali, Humla Karnali, Budhi Gandaki, West Seti and Tamor, Tila, Bheri, East Rapti, Thuligad, Babai, and Thulo Bheri



N05 (Nepal-Protected) scenario solution

No additional dams in protected areas. Also includes boundary rivers of PAs, which need conservation in the opposite bank of PAs



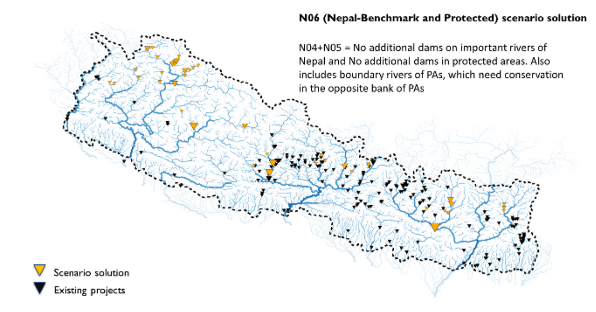


Figure 6-2: Portfolios resulting from the SWITCH energy model for the reference scenario and 13 environmental scenarios. For a description of the scenarios see 6.2.1.