APPENDIXES ON SUPPORTING ANALYSIS

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APPENDIX A
DATA ON DAMS AND HYDROPOWER PLANT PROJECTS, SCREENING, AND MULTICRITERIA ANALYSIS

A.1 List of Projects

Table A.1 lists all hydropower projects used in the cumulative impact assessment with the most important data. Twelve projects are completed, and five are under construction. It is believed that the remaining 18 projects are not committed yet.

Table A.1: Hydropower Projects in Cumulative Impact Assessment

Developer	Project name	Status	Date of commercial operation	Capacity (MW)	Annual energy (GWh)	Active storage (m³)
Not known	A Luoi	Commissioned	2012	170	650	60
Not known	Houay Ho	Commissioned	1999	152	450	527
Vietnam-Laos Power Joint Stock Company	Xe Kaman 3	Commissioned	2013	250	980	109
Chaleun Sekong Energy Co. Ltd.	Xe Namnoy 6	Commissioned	2013	5	20	0
Chaleun Sekong Energy Co. Ltd.	Xe Namnoy 1	Commissioned	2014	15	80	0
Électricité du Laos	Houay Lamphan Gnai	Commissioned	2015	88	450	141
Vietnam-Laos Power Joint Stock Company	Xe Kaman 1	Commissioned	2016	290	1,040	1,683
Vietnam-Laos Power Joint Stock Company	Xe Kaman–Sanxay	Commissioned	2017	32	110	0
Chaleun Sekong Energy Co. Ltd.	Nam Kong 2	Commissioned	2017	66	260	29
B. Grimm Power Public Company Ltd.	Xe Namnoy 2–Xe Katam 1	Commissioned	2017	22	120	0
Xe-Pian Xe-Namnoy Power Co., Ltd.	Xe Pian–Xe Namnoy	Commissioned	2019	410	1,800	908

Developer	Project name	Status	Date of commercial operation	Capacity (MW)	Annual energy (GWh)	Active storage (m³)
Chaleun Sekong Energy Co. Ltd.	Nam Kong 3	Commissioned	2020	54	200	471
Chaleun Sekong Energy Co. Ltd.	Nam Emoun	Committed	2022	129	430	1
Électricité du Laos (	Nam Bi 1	Committed	2024	68	290	unknown
Électricité du Laos	Nam Bi 2	Committed	2024	50	210	unknown
Électricité du Laos	Nam Bi 3	Committed	2024	12	50	unknown
Chaleun Sekong Energy Co. Ltd.	Nam Ang	Candidate	2024	55	160	0
Électricité du Laos	Xe Kaman 2A	Candidate	2030	64	250	4
Électricité du Laos	Xe Kaman 2B	Candidate	2030	100	380	217
Vietnam-Laos Power Joint Stock Company	Xe Kaman 4A	Candidate	2030	70	290	14
Vientiane Automation and Solution Engineering	Nam Pangou	Candidate	2025	33	140	20
Vientiane Automation and Solution Engineering	Dakchaliou 1	Committed	2021	11	50	0
Vientiane Automation and Solution Engineering	Dakchaliou 2	Committed	2021	13	60	0
RAO	Sekong 5	Candidate	2030	330	1,500	1,145
Ratch Lao	Sekong 4B	Candidate	2026	175	750	180
Ratch Lao	Sekong 4A	Candidate	2025	165	780	460
AICS	Sekong 3A	Candidate	2027	114	460	12
AICS	Sekong 3B	Candidate	2028	122	400	55
V&H Corporation (Lao) Ltd.	Sekong Downstream B	Candidate	2030	50	210	9
V&H Corporation (Lao) Ltd.	Sekong Downstream A	Candidate	2030	86	380	35

Developer	Project name	Status	Date of commercial operation	Capacity (MW)	Annual energy (GWh)	Active storage (m^3)
China International Water & Electric Co.	Nam Kong 1	Committed	2022	150	560	505
Not known	Xe Namnoy 5	Candidate	2030	20	90	10
Not known	Xe Pian–Houaysoy	Candidate	2025	45	200	285
Not known	Xe Katam	Candidate	2030	81	300	0
Vientiane Automation and Solution Engineering	Lower Xe Pian	Candidate	2030	15	60	0
			TOTAL:	**3,512**	**14,160**	**>6,880**

Note: MW = megawatt; GWh = gigawatt-hour; m^3 = cubic meters.

Information about each hydropower project was sourced mainly from feasibility studies and environmental impact assessment reports (Table A.2). As-built project specifications may vary slightly because there are often alterations in parameters during negotiations for power purchase agreements, licenses, and financing.

Small hydropower projects planned for the Sekong Basin are not included in the analysis because they are mostly run-of-river projects that cause little if any alteration in flows downstream.

Table A.2: List of Sources of Information about Hydropower Projects in the Sekong River Basin

Hydropower project	Main sources of information
Nam Emoun	Company webpage https://csenergy.la/our-business/hydropower-plants/power-plants-under-construction/nam-emoun/?lang=en
Houay Lamphan Gnai	Company webpage http://www.edlgen.com.la/project/houaylamphanhgnai-hydro-power-plant
Nam Kong 1	Feasibility study summary report (2010)
Nam Kong 2	Company webpage https://csenergy.la/our-business/hydropower-plants/power-plants-in-operation/nam-kong-2/?lang=en
Nam Kong 3	Company webpage https://csenergy.la/our-business/hydropower-plants/power-plants-in-operation/nam-kong-3/?lang=en
Nam Bi 1	No information available

Hydropower project	Main sources of information
Nam Bi 2	No information available
Nam Bi 3	No information available
Nam Ang	Company webpage https://csenergy.la/our-business/hydropower-plants/power-plants-under-development/nam-ang/?lang=en
Xe Kaman 1	Xe Kaman 1-4 feasibility study summary (no date)
Xe Kaman 2A	Xe Kaman 1-4 feasibility study summary (no date)
Xe Kaman 2B	Xe Kaman 1-4 feasibility study summary (no date)
Xe Kaman 3	Xe Kaman 1-4 feasibility study summary (no date)
Xe Kaman 4	Feasibility study summary report (2017)
Xe Kaman–Sanxay	Xe Kaman 1-4 feasibility study summary (no date)
Nam Pangou	Company webpage http://vaselaos.com/nampangou.htm
Dakchaliou 1	Company webpage http://vaselaos.com/dakchaliou1.htm
Dakchaliou 2	Company webpage http://vaselaos.com/dakchaliou2.htm
Houay Ho	Feasibility study summary report (2011)
Xe Namnoy 1	Company webpage https://csenergy.la/our-business/hydropower-plants/power-plants-in-operation/xe-nam-noy-1/?lang=en
Xe Namnoy 2–Xe Katam 1	Turbine manufacturer's webpage https://www.global-hydro.eu/en/news/press/
Xe Namnoy 6	Project Design Document version 05.0
Xe Katam	Executive summary Xe Katam Hydropower Project, Design Option No 2 (2015)
Xe Pian–Xe Namnoy	Environment and social impact assessment summary report (2011) Feasibility study (2007) Company webpage http://www.pnpclaos.com/index.php/en/project
Lower Xe Pian	Company webpage http://vaselaos.com/lower-xepian.htm
Sekong Downstream A	Feasibility study summary report (2011) HPP summary table, Ministry of Energy and Mines (10/29/2018)
Sekong Downstream B	Feasibility study summary report (2013) HPP summary table, Ministry of Energy and Mines (10/29/2018)
Sekong 3B	Feasibility study summary report (2017) HPP summary table, Ministry of Energy and Mines (10/29/2018)

Hydropower project	Main sources of information
Sekong 3A	Feasibility study summary report (2017) HPP summary table, Ministry of Energy and Mines (10/29/2018)
Sekong 4A	Feasibility study 4A & 4B summary report (2017) HPP summary table, Ministry of Energy and Mines (10/29/2018)
Sekong 4B	Feasibility study 4A&4B summary report (2017) HPP summary table, Ministry of Energy and Mines (10/29/2018)
Sekong 5	Feasibility study summary report (2016) HPP summary table, Ministry of Energy and Mines (10/29/2018)
A Luoi	http://icon.com.vn/en-s83-98943-576/Speed-up-progress-rate-of-A-Luoi-hydropower-project.aspx
Xe Namnoy 5	No information available
Xe Pian-Houaysoy	No information available

Note: HPP = hydropower project

A.2 Project Data Screening

To ensure that the study used realistic figures for key parameters in the analysis, project data were screened; the results are summarized in Table A.3 and Table A.4. This screening is based on rules of thumb for parameters such as installed capacity, plant-use factor, energy output compared with annual inflow, and reservoir size. The cost of each project was also compared with the costs of other projects and construction costs in the Mekong region.

The results of this screening show relatively consistent planning and design principles. For example, because projects have been designed independently of each other without coordinated and integrated reservoir operation strategies, the preference has been for seasonal reservoirs in most projects, rather than a cascade of dams with a large upstream reservoir providing seasonal regulation for power plants downstream. In addition, the larger projects are optimized for maximization of income from power exports according to power purchase agreements with Thailand and Vietnam. The destination power systems in Thailand and Vietnam require hydropower to meet periods of peak demand (for example, weekday evenings). Such agreements also define "firm energy," which is a guaranteed supply from the developer. If this is not supplied as agreed, there is a heavy financial penalty, which leads each developer to build large reservoirs to ensure that each has sufficient seasonal storage to guarantee firm energy commitment through the dry season in a dry year.

The government's dam safety review, which was ongoing when this report was being drafted, is not expected to materially affect the pathway descriptions or cumulative impact assessment analysis results in this study, but they may affect project cost. The extra cost of bringing certain projects to standard, for example, in providing extra spillway gates and larger capacity for future floods, may make some already marginally economical projects less economical, possibly resulting in a few projects being redesigned, delayed a few years, or even shelved indefinitely.

Table A.3: Key Technical and Hydrologic Data for Each Project

Project name	Date of completion	Catchment area (km^2)	Mean annual inflow (m^3/s)	Design flow (m^3/s)	Percentage of average flow	Median head (m)	Active reservoir volume (m^3)	Installed capacity (MW)	Percentage of theoretical capacity[a]	Generation (GWh per year)	Percentage of theoretical generation[a]
Nam Emoun	2022	462	21	37	**179**	397	1	129	**103**	430	**68**
Houay Lamphan Gnai	2015	237	11	19	**170**	529	122	88	**100**	450	**99**
Nam Kong 1	2022	1,250	42	88	**210**	190	505	150	**105**	560	**89**
Nam Kong 2	2017	861	37	76	**208**	99	31	66	**103**	260	**94**
Nam Kong 3	2020	646	29	61	**210**	101	471	54	**103**	200	**89**
Nam Bi 1	2024	285	11	23	**200**	285		68	**97**	290	**97**
Nam Bi 2	2024	105	9	17	**200**	105		50	**100**	210	**96**
Nam Bi 3	2024	111	4	9	**200**	111		12	**99**	50	**95**
Nam Ang	2024	200	9	19	**209**	338	0	55	**103**	160	**69**
Xe Kaman 1	2016	3,580	149	337	**226**	104	1,683	290	**97**	1040	**93**
Xe Kaman 2A	2030	1,970	78	172	**222**	49	4	64	**89**	250	**99**
Xe Kaman 2B	2030	1,740	68	153	**224**	82	217	100	**94**	380	**97**
Xe Kaman 3	2013	712	30	62.3	**211**	450	109	250	**104**	980	**94**
Xe Kaman 4	2030	216	10	20	**202**	431	14	70	**97**	290	**96**
Xe Kaman-Sanxay	2017	3,740	152	378	**249**	10	0	32	**99**	110	**98**
Nam Pangou	2025	446	20	37	**184**	104	20	33	**100**	140	**89**
Dakchaliou 1	2021	170	7	14	**196**	95	0	11	**97**	50	**102**
Dakchaliou 2	2021	125	5	10	**190**	150	0	13	**102**	60	**100**
Houay Ho	1999	192	10	22	**232**	748	527	152	**108**	450	**78**
Xe Namnoy 1	2014	436	20	24	**122**	75	0	15	**96**	80	**75**
Xe Namnoy 2-Xe Katam 1	2017	256	40	12	**104**	200	0	22	**107**	120	**65**
Xe Namnoy 6	2013	82	1.6	3	**198**	180	0	5	**102**	20	**90**
Xe Katam	2030	263	12	20	**168**	458	0	81	**104**	300	**71**
Xe Pian-Xe Namnoy	2019	820	40	80	**199**	630	908	410	**95**	1,800	**100**
Lower Xe Pian	2030	789	32	70	**190**	25	0	15	**99**	60	**103**
Sekong Downstream A	2030	18,960	796	1,105	**139**	9	35	86	**101**	380	**70**
Sekong Downstream B	2030	9,594	399	688	**173**	8	9	50	**103**	210	**83**
Sekong 3A	2027	5,860	247	532	**216**	25	12	114	**100**	460	**100**
Sekong 3B	2028	8,700	335	900	**269**	16	55	122	**100**	400	**101**

Project name	Date of completion	Catchment area (km²)	Mean annual inflow (m³/s)	Design flow (m³/s)	Percentage of average flow	Median head (m)	Active reservoir volume (m³)	Installed capacity (MW)	Percentage of theoretical capacity[a]	Generation (GWh per year)	Percentage of theoretical generation[a]
Sekong 4A	2025	5,182	227	385	**170**	50	460	165	**100**	780	**92**
Sekong 4B	2026	3,211	132	220	**167**	94	180	175	**99**	750	**82**
Sekong 5	2030	2,518	125	204	**163**	193	1,145	330	**98**	1,500	**85**
A Luoi	2012	331	20	40	**202**	486	60	170	**102**	650	**88**

[a] Should be about 100 percent.

Note: m = meter; m³ = cubic meter; km² = square kilometer; m³/s = cubic meter per second; MW = megawatt; GWh = gigawatt-hour.

Table A.4: Other Information for Estimating Environmental and Social Footprint of Projects

Project name	Transmission voltage (kV)	Transmission line length (km)	Project cost ($ million)	Cost per GWh ($ million per annual GWh)	Reservoir area (km²)	Resettlement number of persons	Persons resettled per annual energy generation (GWh)
Nam Emoun	230	51	142	0.33	0	0	0.0
Houay Lamphan Gnai	115	9	206	0.46	7	1,398	3.7
Nam Kong 1	230	41	178	0.32	22	1,612	2.9
Nam Kong 2	115	36	70	0.27	4	0	0.0
Nam Kong 3	115	14.5	68	0.34	32	104	0.5
Nam Bi 1			146	0.51		0	0.0
Nam Bi 2			108	0.51		0	0.0
Nam Bi 3			26	0.52		0	0.0
Nam Ang	115	25			0	0	0.0
Xe Kaman 1			539	0.52	82	342	0.3
Xe Kaman 2A			119	0.48	1	98	0.4
Xe Kaman 2B			158	0.42	9	0	0.0
Xe Kaman 3			311	0.32	5	342	0.3
Xe Kaman 4	115	12	153	0.53	1	0	0.0
Xe Kaman-Sanxay				0.36		0	0.0
Houay Ho	230	160	166	0.37	37	1,920	4.3
Xe Namnoy 1	115	32			0	0	0.0

Project name	Transmission voltage (kV)	Transmission line length (km)	Project cost ($ million)	Cost per GWh ($ million per annual GWh)	Reservoir area (km²)	Resettlement number of persons	Persons resettled per annual energy generation (GWh)
Xe Namnoy 2–Xe Katam 1					12	92	0.8
Xe Namnoy 6	115	12			0	0	0.0
Xe Katam	115	45	120	0.40	0	0	0.0
Xe Pian–Xe Namnoy	230	167	1,020	0.57	49	9,458	5.3
Sekong Downstream A					14	2,764	7.3
Sekong Downstream B	115	10	82	0.39	9	2,343	11.2
Sekong 3A	115	9	218	0.47	12	1,080	2.3
Sekong 3B	115	9	233	0.58	18	240	0.6
Sekong 4A	230	35	471	0.60	23	2,494	3.2
Sekong 4B	230	136	335	0.45	13	808	1.1
Sekong 5	230	60	765	0.51	33	440	0.3
A Luoi	230		202	0.31	8	872	1.3

Note: kV = kilovolt; km = kilometer; GWh = gigawatt-hour; km² = square kilometer.

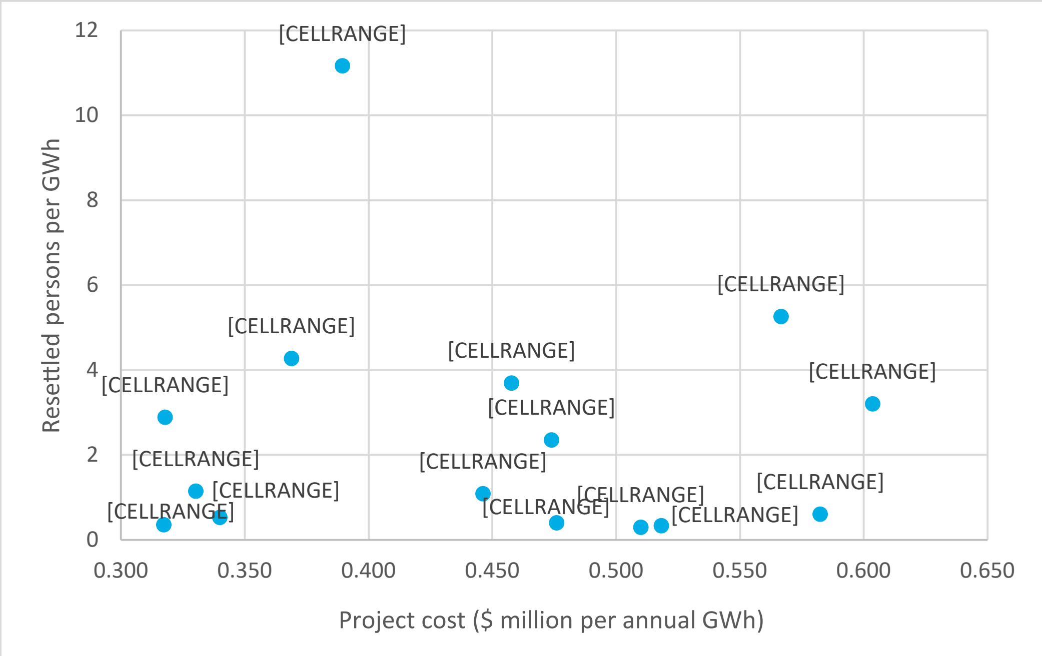
A.3 Multi-Criterion Ranking of Projects

A multi-criterion analysis was conducted to assess the technical and economic characteristics of each project and its environmental and social footprint. Such analysis was limited to available data and was therefore relatively simple. Figures A.1, A.2, and A.3 compare each project's footprint in terms of parameters such as land take and numbers of relocated people with the annual cost per gigawatt-hour as a measure of the economic efficiency of a project and a surrogate parameter for the levelized cost of energy.

The important part of this analysis is not the accuracy of the data and figures presented but the comparison of the projects that this technique provides, enabling us to identify which projects are more efficient without having to know the actual energy cost being negotiated in the power purchase agreement (which is not available for commercial reasons).

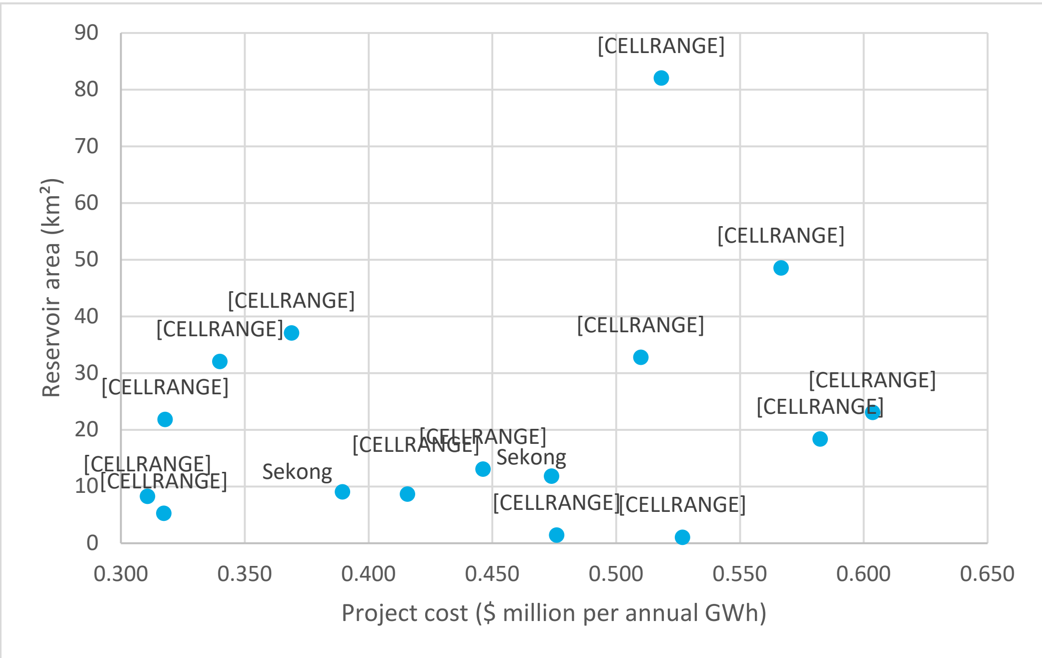
Project costs for some of the projects are uncertain because some cost estimates are from feasibility studies conducted up to 10 years ago. Projects with a high degree of uncertainty regarding cost include the Nam Kong projects and Sekong Downstream B.

Figure A.1: Resettled Persons per Gigawatt-Hour Versus Project Cost



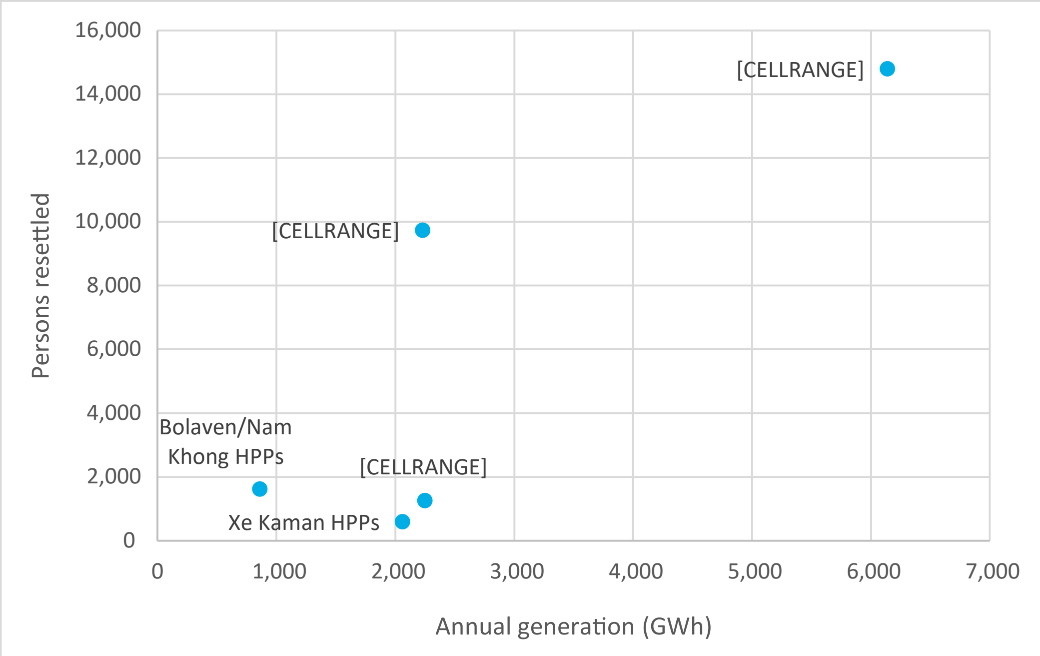
Note: GWh = gigawatt-hour.

Figure A.2: Reservoir Area Versus Project Cost



Note: km^2 = square kilometer; GWh = gigawatt-hour.

Figure A.3: Resettlement per Project Portfolio Versus Power Generation



Note: Completed 2020 is the project portfolio for present situation. GWh = gigawatt-hour.

The resettlement numbers are a combination of resettlement numbers in various environmental and social impact assessment reports and geographical information system analysis of affected villages and houses. Number of households recorded in resettlement reports were converted to persons by assuming an average of six persons per household. From the satellite imagery, individual houses were identified and the number of residents was estimated using average household size.

A.4 Clustering of Power Projects

The projects in the development pathways have been grouped into spatially defined clusters (Table A.5). The purposes of clustering power projects are to facilitate systematic, manageable analysis of the cumulative environmental and social effects of different power development pathways (see Chapter 5) for the Sekong Basin and to explore the benefits of joint operation of hydropower plants and management of water resources at the (sub)-basin level.

Existing and committed hydropower projects will easily meet Lao People's Democratic Republic's electricity demand until 2030, so new hydropower in the Sekong Basin will be for export to neighboring countries, particularly Thailand and Vietnam. Clusters were therefore selected to provide significant export capacity with minimal economic, environmental, and social costs and risks. A minimum size of 300 megawatts (MW) per cluster has been set as a reasonable limit.

The hydropower project clusters are summarized in Table A.5, illustrated in Map A.1, and described in the subsequent sub-sections.

Table A.5: Project Clusters

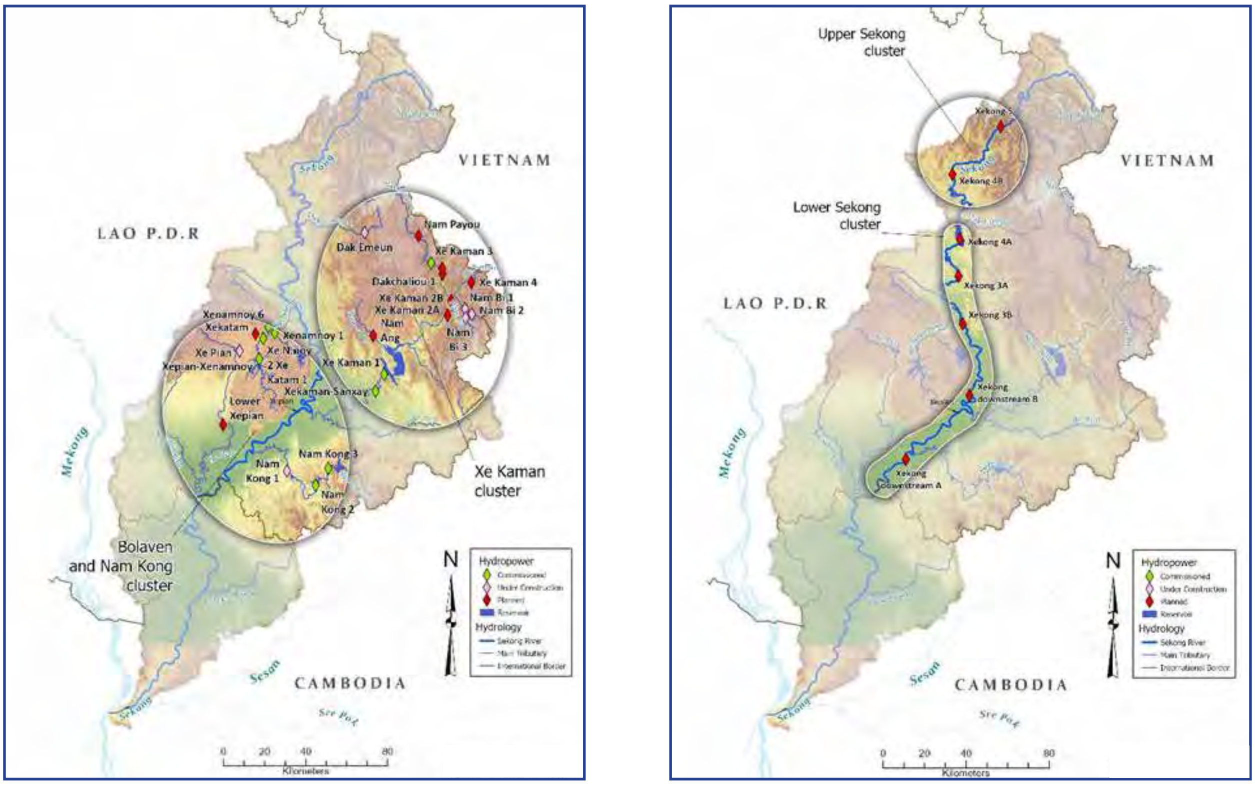
Project name	Projects included	Installed capacity (MW)	Generation (% TWh per year)	Active reservoir volume (% m³)	Total reservoir area (km²)	Development pathway
Present situation	12 projects commissioned, as listed in Table A.1	**1,554**	6.16 (43)	3,928 (57)	224	
Upper Sekong cluster	Sekong 4B & 5	**505**	2.25 (16)	1,325 (19)	46	Full and intermediate
Lower Sekong cluster	Sekong 4A, 3A, 3B, Downstream A & B	**537**	2.20 (16)	571 (8)	76	Full
Xe Kaman cluster	Nam Emoun, Nam Bi 1,2,3, Nam Ang, Xe Kaman 2A, 2B, 4, Nam Pangou, Dachaliou 1,2	**605**	2.31 (16)	256 (4)	13	Full, conservative, and intermediate
Bolaven and Nam Kong cluster	Xe Katam, Xe Pian H Chot, Lower Xe Pian, Xe Namnoy 5, Nam Kong 1	**311**	1.21 (9)	800 (12)	23	Full, conservative, and intermediate
Totals	**35 projects**	**3,512**	**14.13**	**6,880**	**382**	

Note: MW = megawatt; TWh = terawatt-hour; m³ = cubic meter; km² = square kilometer.

Map A.1: Project Clusters

a. Tributary

b. Mainstream



A.4.1 Upper Sekong Cluster

This cluster comprises two large projects providing 505 MW, with a large seasonal reservoir (Sekong 5) located in the upper headwaters of the mainstream Sekong in a relatively remote part of the basin. Current access is by gravel road only, and the mountain region where these projects are located is sparsely populated. There are many mining concessions in the region, including coal mining that would be associated with a new coal-fired power plant near Kalum, also designed for power exports to Vietnam.

A.4.2 Lower Sekong Cluster

This cluster comprises a cascade of five large projects providing 537 MW, with several small reservoirs in cascade along the lower Sekong. These projects use lower heads, and the lowest projects in the cascade will have particularly low available heads in the flood season, when the river rises. The reservoirs will inundate some agricultural land along the banks of the mainstream Sekong and require resettlement of approximately 9,300 people.

A.4.3 Xe Kaman Cluster

This cluster comprises eight projects of varying size providing 605 MW, with only limited reservoir capacity for seasonal regulation, mainly at the Xe Kaman 2B site. All but one of these projects are located upstream of the large Xe Kaman 1 reservoir, which has already been impounded, and involve medium head use in tributary rivers near the border with Vietnam. Because of its proximity to Vietnam and the Xe Kaman sub-basin, the study includes in this cluster the Nam Emoun project on the Nam Emoun tributary, where construction recently started. Many of these projects can be accessed from the main highway linking Attapeu with Vietnam by short access roads. There is some need for resettlement, and there are some forest conservation areas in the catchment.

A.4.4 Bolaven and Nam Kong Cluster

This cluster comprises four projects providing 311 MW, with one seasonal reservoir at Nam Kong 1. It includes hydropower resources in the lower part of the Sekong Basin not yet committed or finalized. The cluster consists of projects with lower economic efficiency remaining in three tributary rivers—Nam Kong, Xe Pian, and Xe Namnoy—after the more profitable projects have been constructed. The economic return on these projects is likely to be low.

APPENDIX B
SEKONG BASIN HYDROLOGY AND FUTURE CLIMATE SCENARIOS

B.1 Approach and Methodology

B.1.1 Overall Approach

Data modeling undertaken for this study is summarized in Figure B.1 and described in Chapter 1, Section 1.2.5. Daily rainfall data over a 24-year period was fed into a U.S. Army Corps of Engineers, Hydrologic Engineering Center, Hydrologic Modeling System (HEC-HMS) hydrological model together with climate change data. The results of this model provide inputs to a Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) model, which is used to assess effects on ecological values, sediment, and floods.

B.1.2 Climate Change Modeling and Assessment

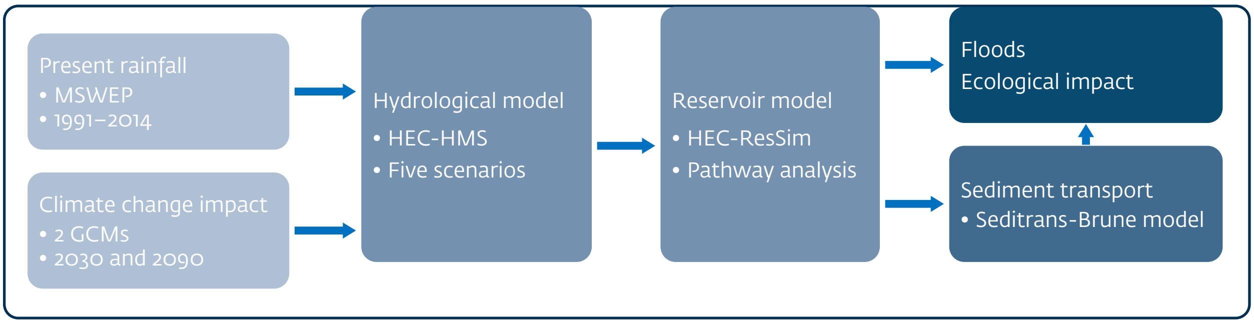
The climate change assessment started with an evaluation of information available from former projects and reports. In particular, several relevant Mekong River Commission (MRC) initiatives were identified.

- The MRC is working on the Mekong Adaptation Strategy and Action Plan, which includes a climate impact analysis and covers the entire Mekong Basin.
- The MRC is starting small local and regional adaptation initiatives that are in line with the Mekong Adaptation Strategy and Action Plan.
- Potential climate change effects on the basin, and more specifically the hydropower sector, are discussed in the MRC Basin Development Strategy 2016–2020 (MRC 2016b).

In support of the Mekong Adaptation Strategy and Action Plan, an extensive climate impact analysis based on general circulation model (GCM) simulations that contributed to the International Panel on Climate Change fifth assessment report (IPCC 2014) was conducted for the entire Mekong Basin. The future changes that the GCMs simulated are based on representative concentration pathways (RCPs) that belong to pre-defined emission scenarios (Van Vuuren et al. 2010). The MRC focused on RCP4p5 and RCP8p5:

- RCP4p5: representing moderate change with a global average temperature increase of 2°C by the end of this century; radiative forcing stabilizes before 2100 because of the introduction of technologies and strategies that reduce greenhouse gas emissions
- RCP8p5: representing extreme change with a global average temperature increase of 4°C by the end of this century; there is continuously increasing radiative forcing

Figure B.1: Modeling Chain for Impact Analysis



Note: MSWEP = multi-source weighted-ensemble precipitation; GCM = general circulation model; HEC-HMS = Hydrologic Engineering Center, Hydrologic Modeling System; Hec-ResSim = Hydrologic Engineering Center, Reservoir System Simulation.

From all available scenarios, three combinations of GCMs and RCPs were chosen, representing the following changes in conditions: wetter throughout the year, less rain in the dry season, and drier throughout the year. These scenarios were run through a basin-wide soil and water assessment tool hydrological model.[1] The results showed large variations in projected flows, on the order of –20 percent to +20 percent in annual average discharge, and thus there was a large variation in the effect on the hydropower sector as well. Adverse effects were shown to be greatest in the Sekong, Sesan, and Srepok river basins because of decreases in food security and decreasing water availability as the region depends greatly on crops and fishing.

For the Sekong cumulative impact assessment, the study followed an approach for the climate impact assessment similar to that of the MRC. The study used the datasets from the GCM simulations that support the International Panel on Climate Change fifth assessment report as inputs to a HEC-HMS model set up for the Sekong Basin because this enabled a more precise assessment of the effect of climate change on the flow characteristics of the Sekong River.

Data were obtained from the Inter-Sectoral Impact Model Intercomparison Project, which developed future climate change projections by bias-correcting the output of GCM simulations. The Inter-Sectoral Impact Model Intercomparison Project data portal[2] contains open data for four GCMs—Geophysical Fluid Dynamics Laboratory (GFDL)-ESM2M, Institut Pierre Simon Laplace (IPSL)-CM5A, Met Office Unified Model HadGEM2-es, and the Norwegian Climate Center Earth System Model-m—for 2006 to 2100.

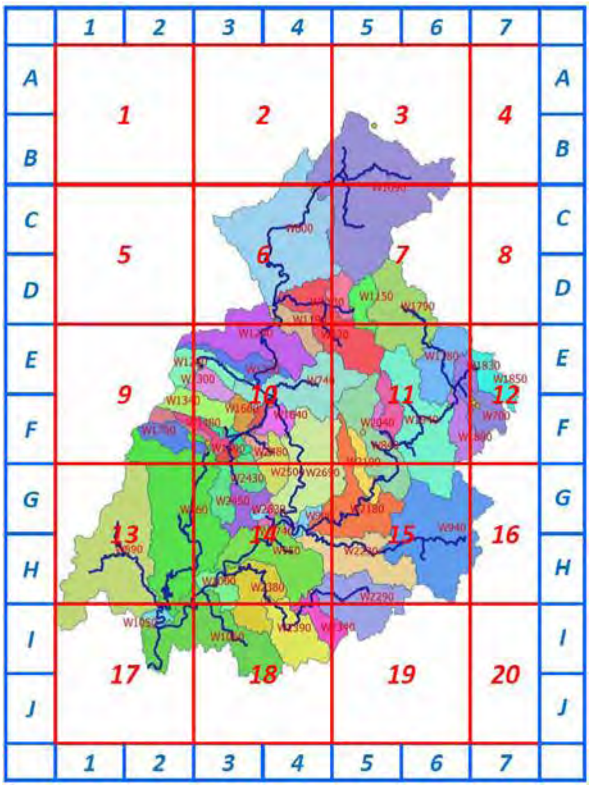
Future precipitation time-series data were obtained for these GCMs, and simulations for each GCM resulted in different projections for the Sekong River Basin. It was decided to base our scenario analysis on two GCMs that performed well according to the MRC analysis and provided a reasonable spread of potential changes (Table B.1). Two scenarios were selected because of the high computational demand of running multiple scenarios, especially because all simulations need to be run for all pathway and climate scenario combinations.

Table B.1: General Circulation Models Selected

General circulation model	Representative concentration pathway	Precipitation changes
Institute Pierre Simon Laplace Model CM5A-MR	8p5	Slight decrease in wet season, decrease in dry season
Geophysical Fluid Dynamics Laboratory ESM2M	8p5	Decrease in dry season, increase in wet season by 2085

Once the two scenarios were chosen, data were retrieved from the portal of the Inter-Sectoral Impact Model Intercomparison Project" for all mentions. The grid cells of the bias-corrected GCM data have a resolution of 0.5 degrees. The grid covering the Sekong Basin is shown in Figure B.2. Our analysis focused on the future time horizons 2030 and 2090, so there are four climate change scenarios: IPSL 2030, IPSL 2090, GFDL 2030, and GFDL 2090.

Figure B.2: Grid for Application of Conversion Factors for Climate Change Scenarios



[1] SWAT (Soil and Water Assessment Tool), database, https://swat.tamu.edu/.

[2] https://esg.pik-potsdam.de/search/isimip/

For each grid cell, four values were obtained, corresponding to the two climate change scenarios for 2030 and 2090, which resulted in 80 conversion factors being used to convert the present-day rainfall series to the climate change–affected series.

B.1.3 Description of Hydrological Modeling Approach

The first step was to assess the hydrology of the Sekong River and its tributaries, with the main purpose being generation of inflow series for the present and future (climate-change affected) situations. These series formed the basis for reservoir modeling, which in turn formed the basis for hydropower modeling and subsequent assessment of ecological effects.

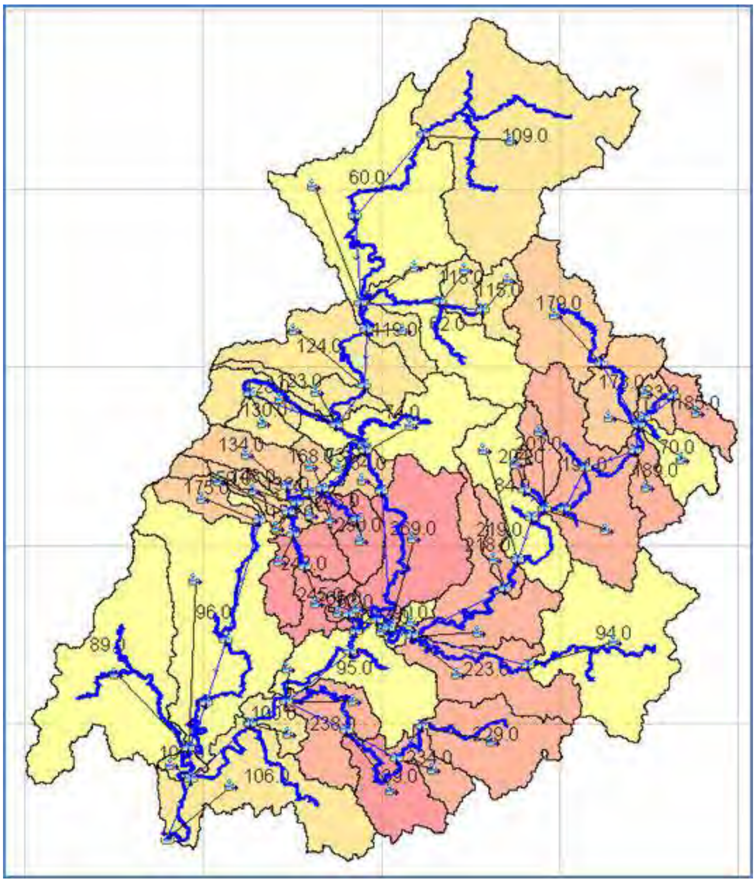
There are several hydrological models for the Sekong Basin. There is a soil and water assessment tool hydrological model coupled with the HEC-ResSIM model, but it focuses more on the sediment balance of the basin. There is also a distributed hydrological model, but it was set up with a main focus on the Sesan River (see Rasanen and Kummu 2013).

For the present study, it was decided to align modeling efforts with the Energy-Water Nexus (EWN) study (World Bank 2018), which a consortium led by CNR Engineering was simultaneously conducting. The core objective of the EWN study was to increase the understanding of the Ministry of Energy and Mines about the principles and processes for integrating water resources management into hydropower planning and management. The EWN study covers the Sekong Basin and uses two hydrological models that the Ministry of Energy and Mines previously developed using open-source software packages:

- HEC-HMS (hydrological and rainfall-runoff model with soil moisture accounting method)
- HEC-ResSIM (reservoir simulation model)

The schematization of the HEC-HMS model of the Sekong Basin is shown in Map B.1.

Map B.1: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System Model of the Sekong Basin



The EWN study developed and updated these models with relevant features of the two basins, particularly the many existing and planned reservoirs. For the EWN study, the accuracy of the model was less important than its use for capacity-building. As a consequence, the HEC-HMS model that EWN updated was based on just five years of gauged rainfall data. This series was considered to be too short for the analysis required for the Sekong CIA, so a longer data series was sought.

In addition to the five years of rainfall data in the EWN HEC-HMS model, the study obtained daily rainfall series (Table B.2) and daily discharge series (Table B.3) from the MRC.

Although some daily rainfall series cover a long period, many values, sometimes many years, are missing. Nevertheless, there are three series with data (up to August 8, 2018) that are useful for comparison with the (fully continuous) daily global rainfall series used as input for the HEC-HMS model in this study.

Daily discharge series were also received from the MRC for several stations (Table B.3).

These discharge data series are of limited utility, being in some cases very short and in some cases not aligned with the 24-year period of global rainfall data the study selected. The daily discharge data also have many gaps (missing records). Of these stations, only the one at Attapeu is considered reliable (Meynell 2014) and so has been used for comparison with the modeling results.

Table B.2: Daily Rainfall

Station		Coordinates (Indian 1960 geodetic datum)		Country	Length of series
Code	Name	Latitude	Longitude		
140603	Siempang	14,115	106,388	Cambodia	01/01/1925–08/31/2018
150602	Saravan	15,717	106,433	Lao PDR	01/01/1929–12/31/2000
140705	Attapeu	14,467	106,833	Lao PDR	01/01/1988–12/31/2008
140704	Kontum	14,347	108,034	Vietnam	01/01/1923–08/31/2018
150607	Nikhom 34	15,183	106,433	Lao PDR	01/01/1998–12/31/2005
150605	Nonghine	14,750	106,217	Lao PDR	01/01/1979–12/31/2000
140715	Dak To	14,650	107,830	Vietnam	01/01/2001–08/31/2018
140505	Pathoumphone	14,767	105,967	Lao PDR	01/01/1979–12/31/2005
150609	Sekong	15,083	106,850	Lao PDR	01/01/1992–12/31/2008

Table B.3: Daily Discharge

Station		River	Coordinates (Indian 1960 geodetic datum)		Country	Length of series
Code	Name		Latitude	Longitude		
390103	Saravanne	Sedone	15,710	106,450	Lao PDR	01/01/1986–12/31/2000
430102	Siempang	Sekong	14,115	106,388	Cambodia	01/01/1965–01/01/1968
430105	M. May (Attopeu)	Sekong	14,807	106,843	Lao PDR	01/01/1989–12/31/2000
440201	Kontum	Dak Bla	14,347	108,034	Vietnam	01/01/1967–12/31/2000

The 24 years of global rainfall data—multi-source weighted-ensemble precipitation (MSWEP)—represent the historical situation (1991–2014). To simulate the effect of climate change on the hydrology, climate change scenarios have been prepared, and the present (daily) rainfall values have been multiplied by a factor representing the climate change scenario for a certain future time horizon.

B.2 Results of Hydrology and Climate Change Assessment

B.2.1 Present Situation

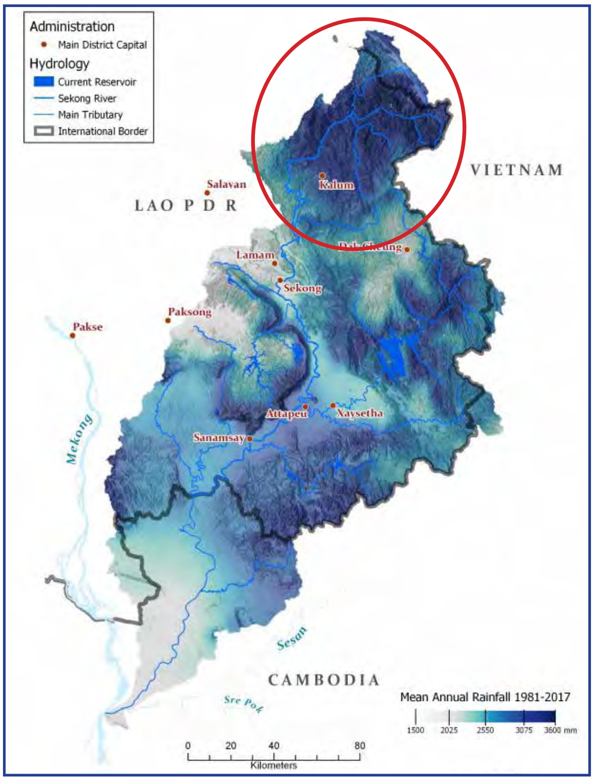
In the present study, the main drawback of the existing hydrological modeling with the HEC-HMS, the short series of just five years (2001–05), has been adjusted by changing to a different data source, as mentioned. In the following paragraphs, the steps that were followed are described in detail.

The original series of precipitation used for the rainfall-runoff modeling with the HEC-HMS model was short for the purpose of the study, with only five years of rainfall data (2001–05). Analysis of the measured data series showed that these series contain frequent gaps and are unequally distributed over the basin, with no stations in the upper northeast corner of the basin, where the highest-intensity rainfall occurs (Map B.2), and that some stations used in the modeling are located far outside the Sekong Basin, so it was decided to use a different source of data. Global data are a good alternative, especially a combination of satellite data and ground measurements (gauge corrected). An important advantage of satellite data over the measured rainfall series is that they are continuous, which allow for long model runs with the HEC-HMS and HEC-ResSim model.[3]

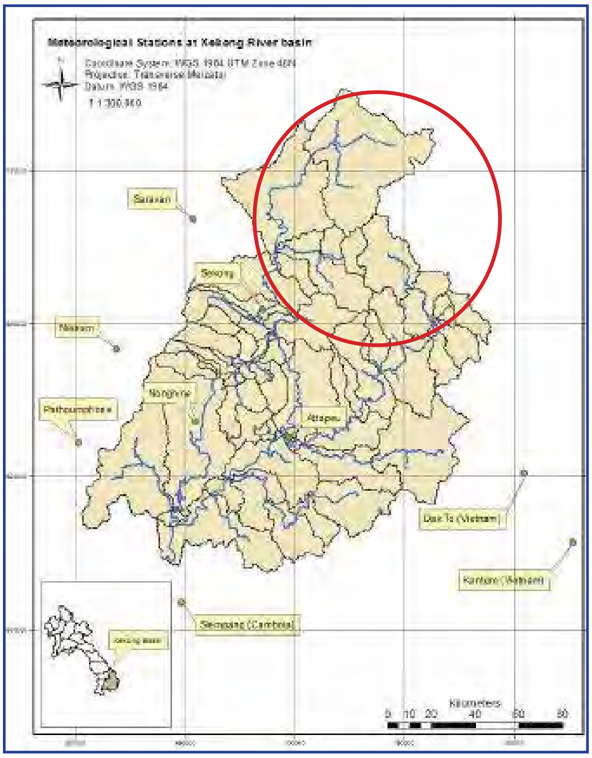
For discharge data, there are no sources other than field measurements, so such data need to be based on data from the MRC.

Map B.2: Rainfall Distribution over the Sekong Basin and Location of Precipitation Stations Used in U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System Modeling

a. Tributary



b. Mainstream



Note: Red circle indicates region with high rainfall without precipitation stations.

[3] HEC-ResSim modeling is described in Appendix D.

For rainfall, a dataset was used that is an optimized combination of satellite precipitation data and in-situ observed precipitation, the MSWEP dataset (Beck et al. 2017), which Deltares and partner hydro-meteorological institutes in the EU FP7 project eartH2Observe developed.[4] This product was judged to be the most reliable gauge-corrected dataset in a recent study of 26 precipitation datasets (Beck et al. 2019). Nevertheless, precipitation estimation is difficult in mountainous areas, where gauge density is low and resolution of satellite products cannot capture the complexity of the topography. In addition, cloud cover during the rainy season hampers satellite rainfall data retrieval, so combining different sources of rainfall observations can lead to better results. Although the MSWEP dataset is available from 1979, the research team decided to retrieve MSWEP data from 1991 to 2014 because a longer series would have led to problems with the size of the data series and calculation times of the two models (HEC-HMS and HEC-ResSim). The series were extracted for all grid cells of 0.25 degrees resolution (approximately 25 x 25 km) in the Sekong Basin (Figure B.3).

MSWEP rainfall data were applied to each of the 53 Sekong sub-basins by overlaying a grid (Figure B.4). Rainfall values from the corresponding 0.25-degree resolution MSWEP dataset were then applied to each of the Sekong sub-basins defined in the HEC-HMS model.

Figure B.3: Application of Multisource Weighted-Ensemble Precipitation Data to the Sekong Sub-Basins in the HEC-HMS

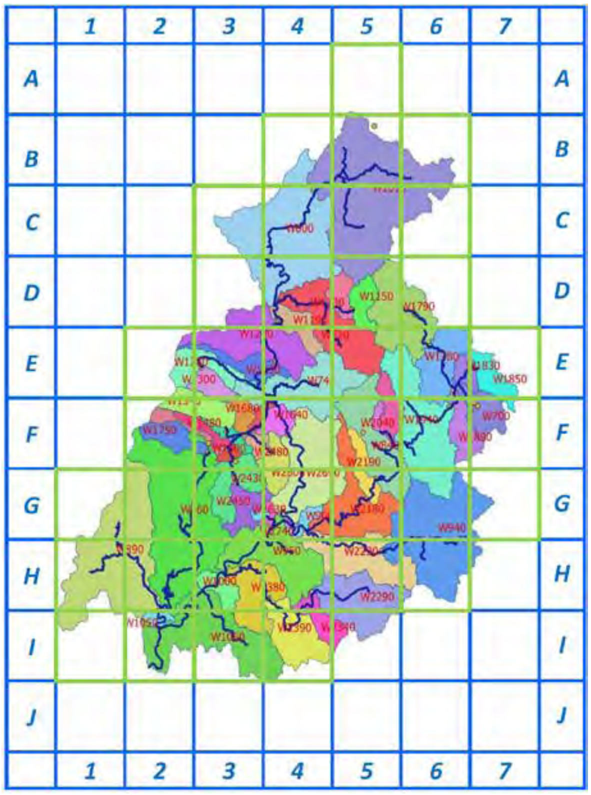
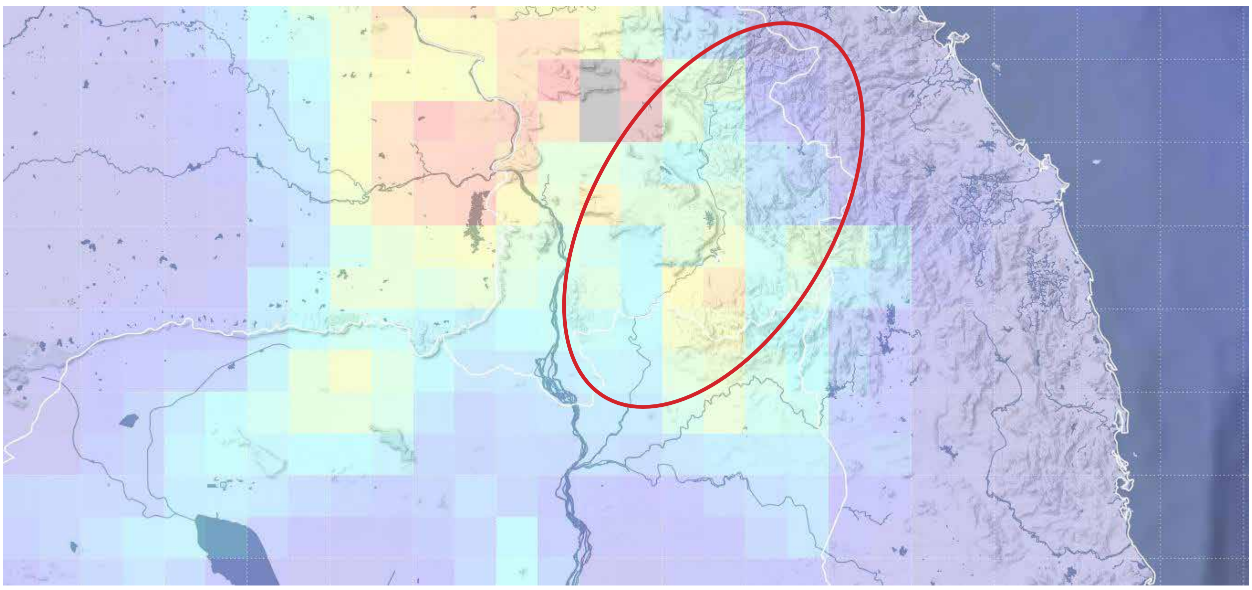


Figure B.4: Modeling Chain for Impact Analysis



Source: Beck et al. 2017.

4 MSWEP is a global, historic precipitation dataset (1979–2016) created by merging a wide range of data from physical monitoring sites (gauges) and satellite records of precipitation to provide reliable precipitation estimates over the entire globe. MSWEP has been validated at global scale using observations from about 70,000 gauges and hydrological modelling for about 9,000 catchments, with daily gauge corrections. More information can be found at the GLOHSO database website, http://www.gloh2o.org/.

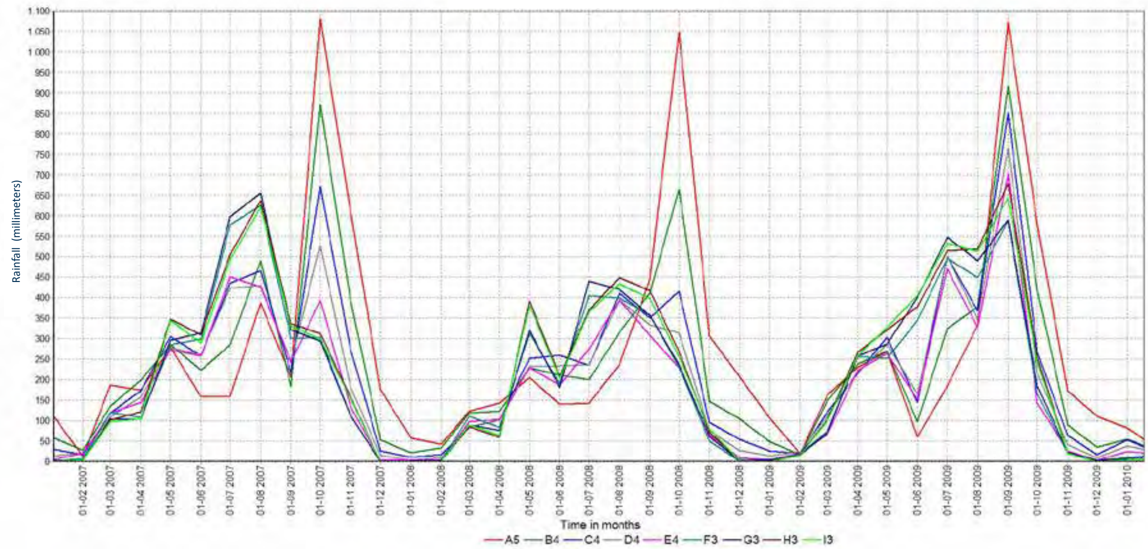
B.2.2 Assessment of MSWEP Dataset for the Sekong Basin

Once the MSWEP data from 1991 to 2014 had been retrieved from the server, they were compared with the series used in the existing HEC-HMS model and with the gauge data obtained from the MRC. Not only are those completely different types of data, but the MSWEP is also an average value over a cell, like the ones shown in Figure B.4, whereas the other data series are point measurements at gauges in the field.

First a comparison was made between the various MSWEP data series themselves for a number of cells (Figure B.5).

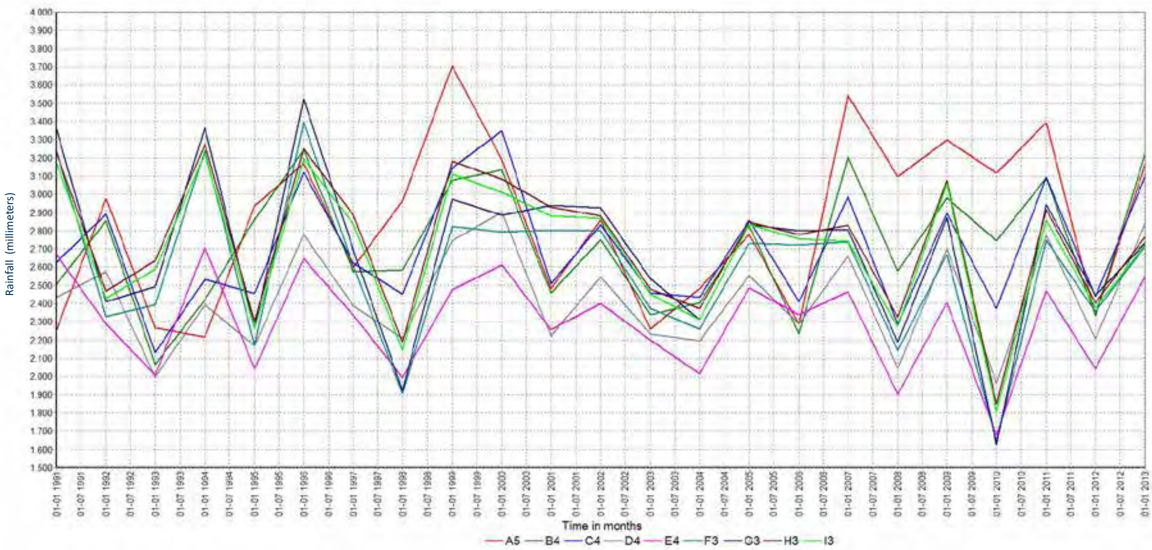
The north of the Sekong Basin has the highest rainfall (Figure B.4; cells A5, B4, C4 in descending order of rainfall depth), in correspondence with the map of annual rainfall over the basin (Map B.2), although this is not always the case, as is evident from a graph of average yearly rainfall for the same grid cells (Figure B.6).

Figure B.5: Comparison of Multisource Weighted-Ensemble Precipitation Monthly Values (North-South Transect of Grid Cells)



Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System, Mekong River Commission Database, and Multisource Weighted-Ensemble Precipitation.

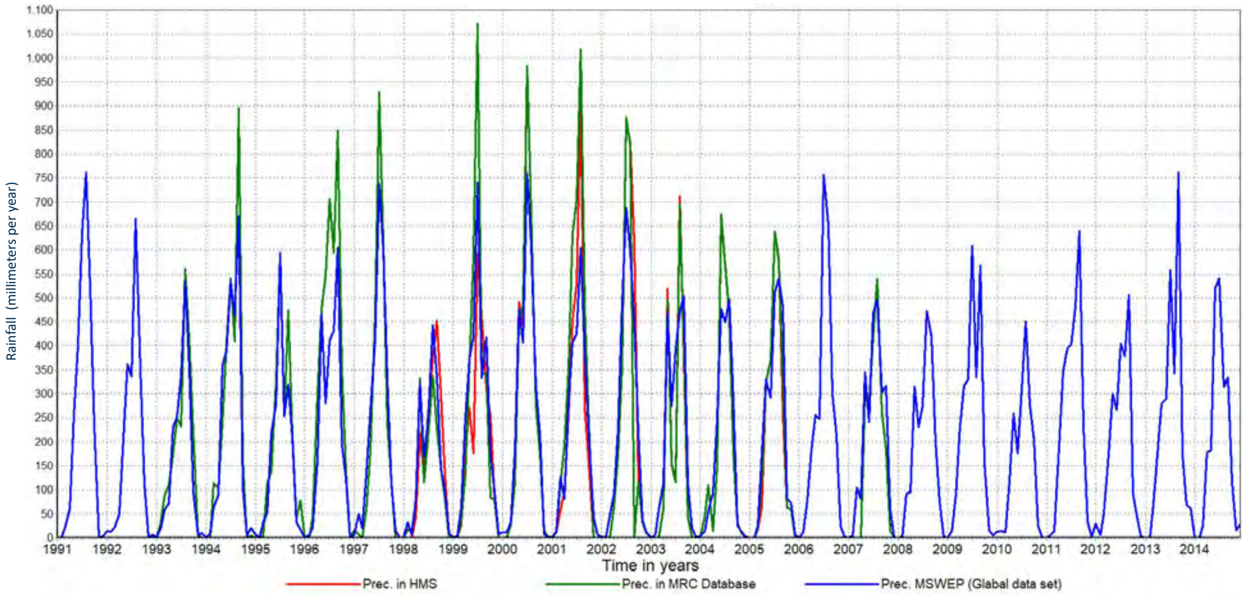
Figure B.6: Comparison of Multisource Weighted-Ensemble Precipitation Yearly Values (North-South Transect of Grid Cells)



Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System, Mekong River Commission Database, and Multisource Weighted-Ensemble Precipitation.

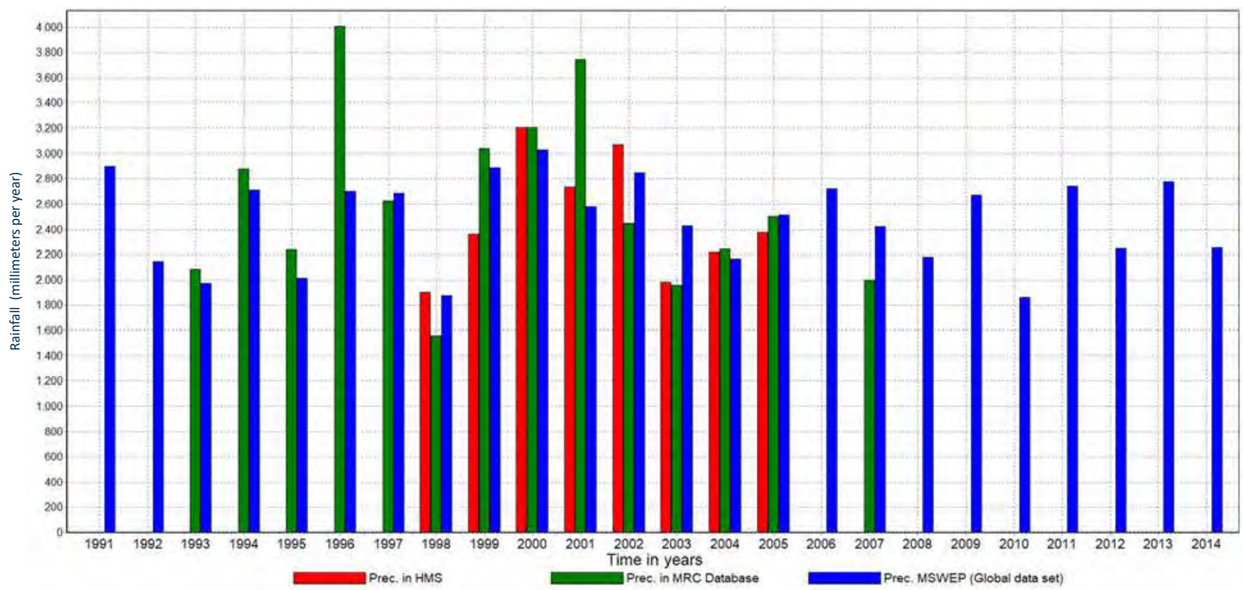
Monthly and yearly average values for the rainfall stations Pathoumphone (Figures B.7 and B.8), Dak To (Figures B.9 and B.10), and Saravan (Figures B.11 and B.12) were compared. For Attapeu, the only rainfall station located within the basin, a comparison is made which covers an overlapping period (original five-year modeling period; Figure B.13) and the new simulation period (Figure B.14).

Figure B.7: Comparison of Monthly Rainfall at Pathoumphone



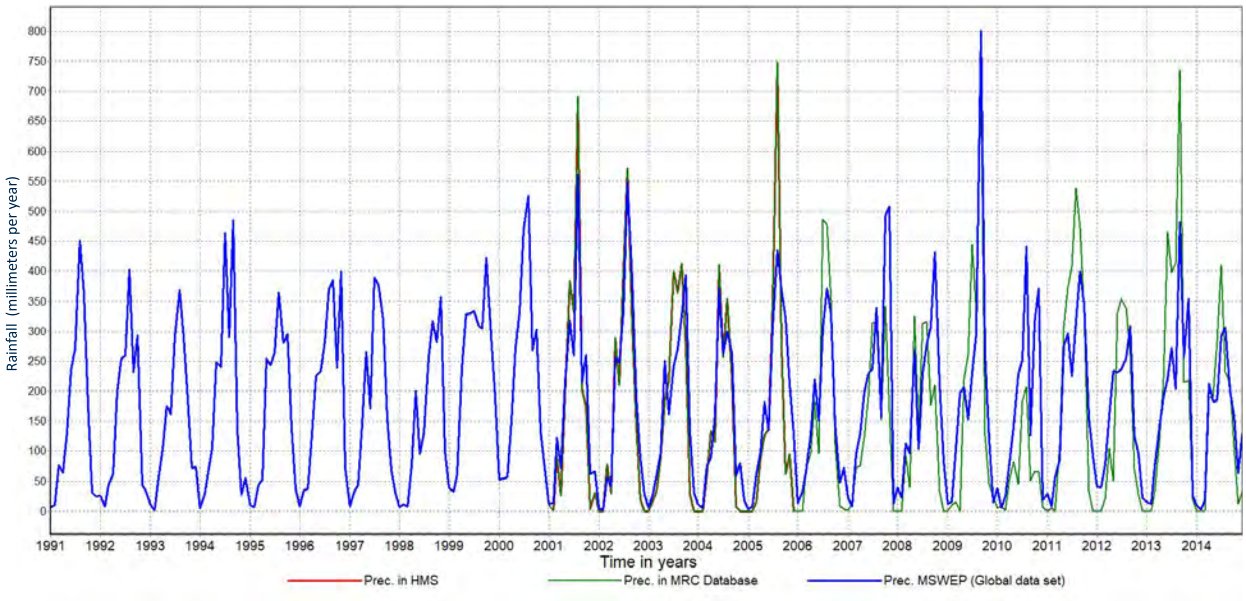
Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

Figure B.8: Comparison of Yearly Rainfall at Pathoumphone



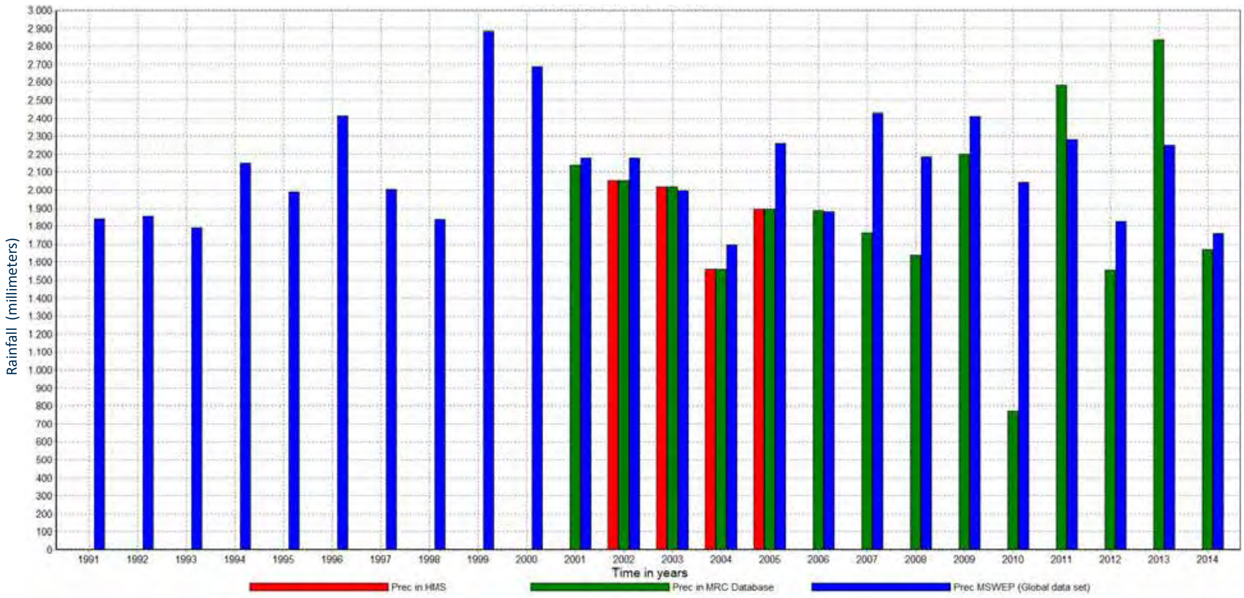
Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

Figure B.9: Comparison of Monthly Rainfall at Dak To



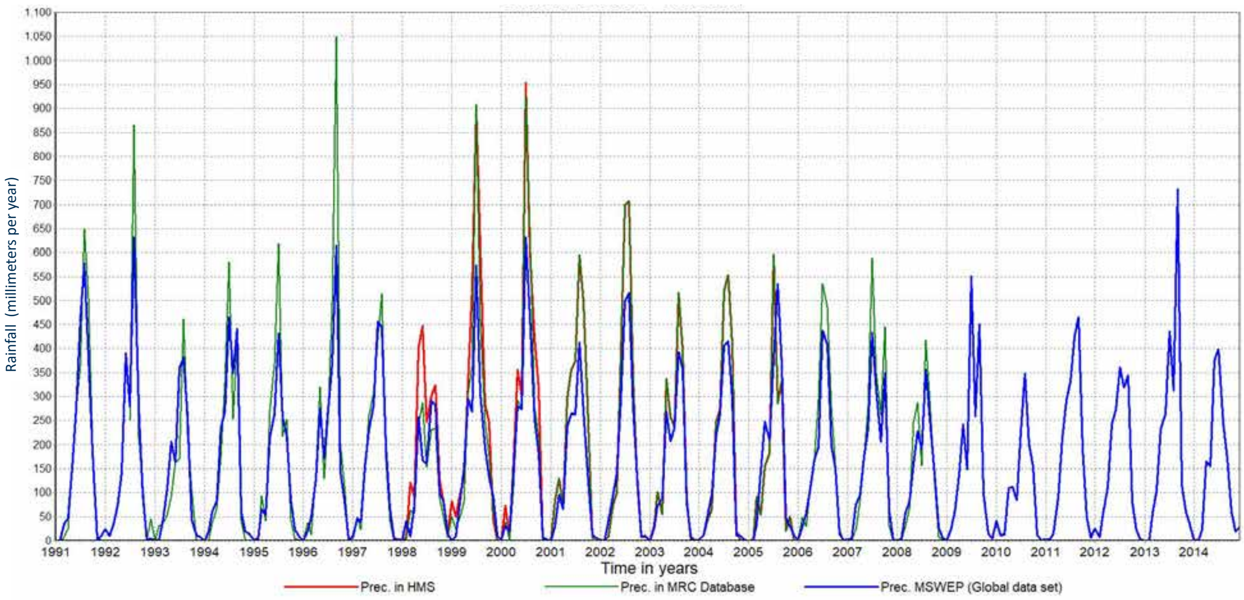
Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

Figure B.10: Comparison of Yearly Rainfall at Dak To



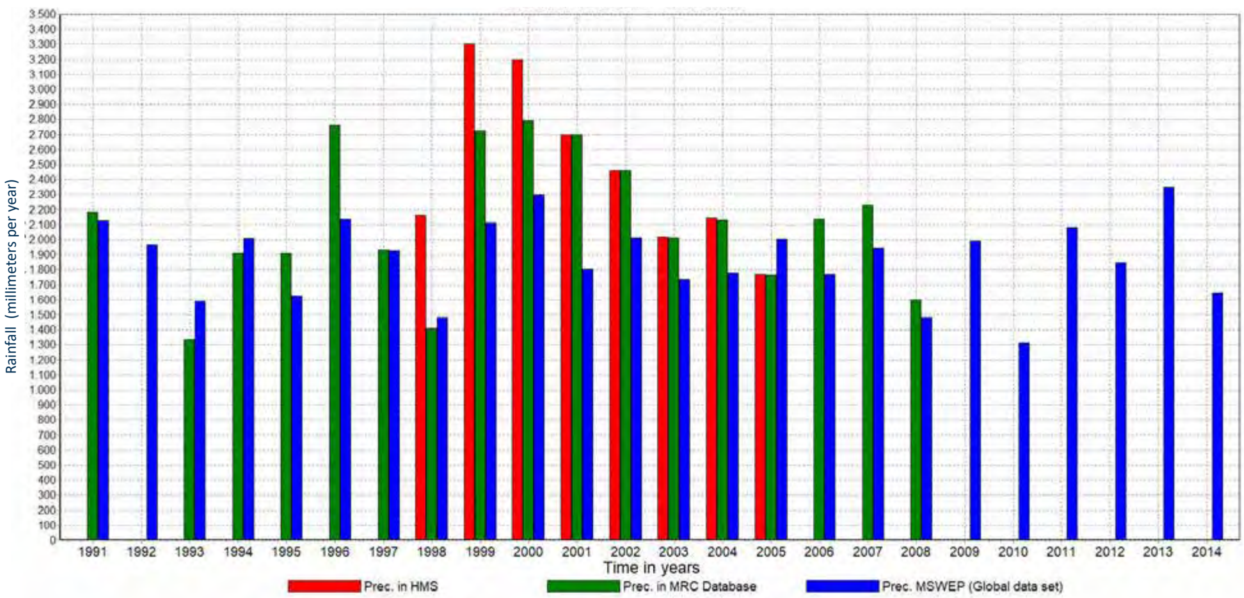
Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

Figure B.11: Comparison of Monthly Rainfall at Saravan



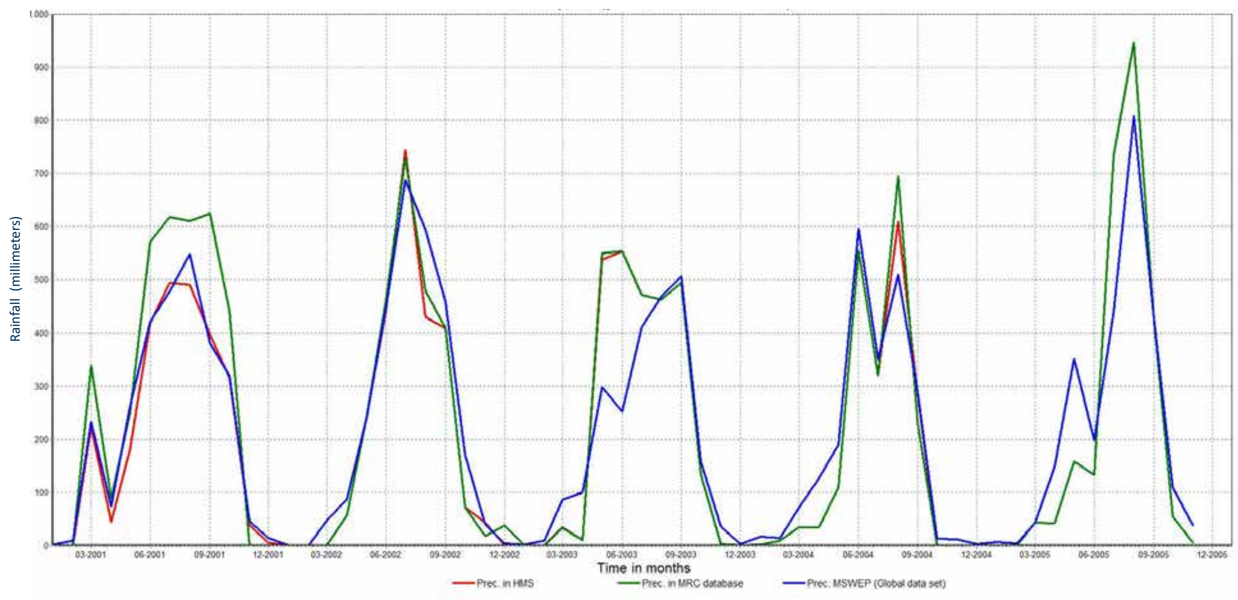
Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

Figure B.12: Comparison of Yearly Rainfall at Saravan



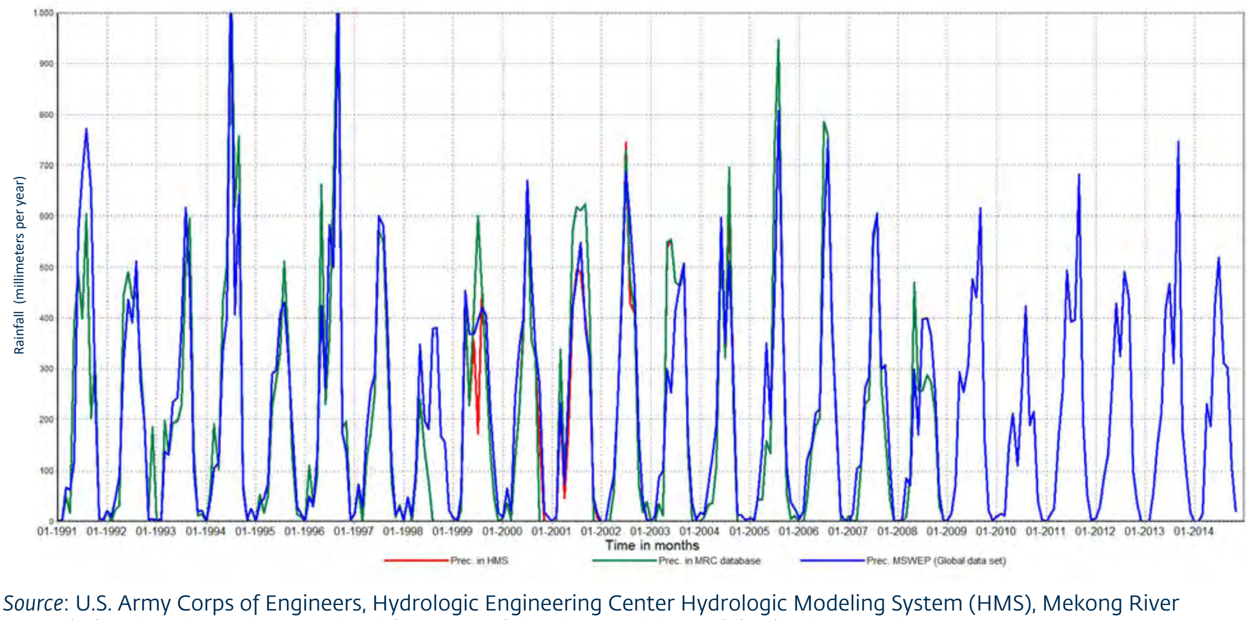
Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

Figure B.13: Comparison of Average Monthly Rainfall at Attapeu (2001–2005)



Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

Figure B.14: Comparison of Average Monthly Rainfall at Attapeu (1991–2014)



Source: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (HMS), Mekong River Commission (MRC) Database, and Multisource Weighted-Ensemble Precipitation (MSWEP).

In each graph, rainfall values from three sources are plotted: those used in the HEC-HMS model, those obtained from the MRC database, and those extracted for that location from the MSWEP database server.

The most remarkable feature of the comparison of the three types of data is that there is often a substantial difference between the values used in the HEC-HMS model and those obtained directly from the MRC database, although for some stations, the data are identical (for example, for Dak To). It is less surprising that there are differences between the measured data (MRC database) and the global MSWEP dataset because the MSWEP data represent average rainfall over a larger area, although in general, average monthly values are similar enough to warrant application of the MSWEP data for simulation of discharges over a longer period (1991–2014) using the HEC-HMS model calibrated for the Sekong Basin.

B.2.3 Preparation of New Input Series for the HEC-HMS Model

To apply the new series of MSWEP daily rainfall values for 1991 to 2014, it was necessary to prepare a new set of daily rainfall values for each of the sub-basins in the HEC-HMS model based on a weighted average of the MSWEP values in the grid cells shown in Figure B.4. In the original HEC-HMS model of EWN with five-year rainfall data, a simple approach was followed: the rainfall station closest to each sub-basin represented the rainfall in that sub-basin, without any weighting. With the MSWEP dataset, which covers the entire Sekong Basin, it was possible to make weighted averages for each sub-basin, depending on which grid cells covered that particular sub-basin. This was achieved by setting up a spreadsheet with all the MSWEP daily rainfall series and assigning one or more of those series with their corresponding weights to each Sekong sub-basin. For most sub-basins, various grid cells cover the sub-basin, although for some of the smaller sub-basins, just one grid cell covered the entire surface (and thus the weighting factor could be set at 1.0) (Figure B.4). Once a matrix was prepared for all the sub-basins and their corresponding MSWEP grid cells with weighting factors, those weighting factors were used to prepare daily rainfall series per sub-basin for the entire period (1991–2014). These series were entered as time series in the HEC-HMS. Once this was prepared, the model could be run again for the present situation, but for 1991 to 2014.

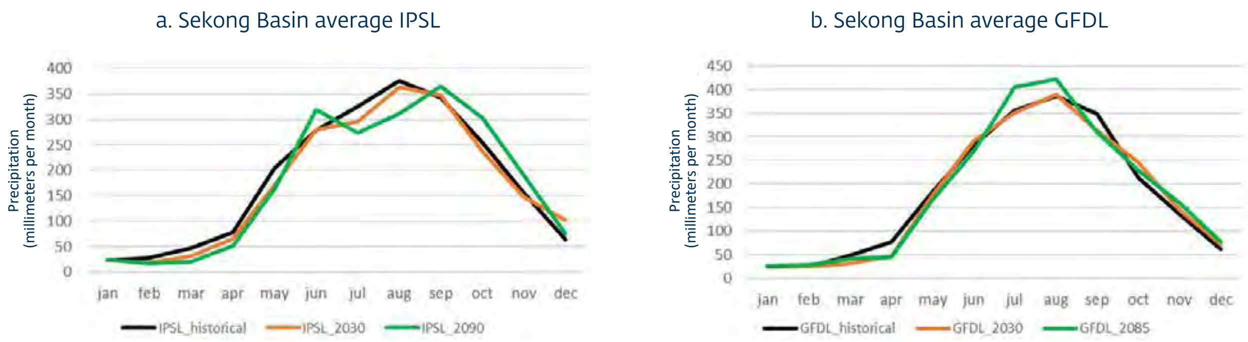
B.2.4 Climate Change Assessment

Figure B.15 displays monthly mean basin precipitation for the historical period (2000), near future (2030), and far future (2090), averaged over a surrounding 20-year period and over the same grid used in the hydrological modeling (Figure B.19, red grid cells). The daily generation circulation model (GCM) precipitation values for each grid, covering the historical period (1991–2010), the near future (2021–40), and the far future (2081–00), were averaged over the basin. Subsequently, the long-term monthly mean values were calculated.

Both selected scenarios indicate a slower onset of rainfall in February, March, and April, which could lead to a longer dry season. According to the Institut Pierre Simon Laplace (IPSL) GCM, by 2090, monthly rainfall would be lower for much of the wet season but higher in June and September, resulting in approximately the same total wet season precipitation. According to the Geophysical Fluid Dynamics Laboratory (GFDL) GCM, by 2090, there would be substantially more rainfall in the wet season, particularly in July and August.

The climate change modeling shows some geographical variation within the Sekong Basin. The monthly precipitation cycle and projected changes are displayed in Figures B.16 and B.17.

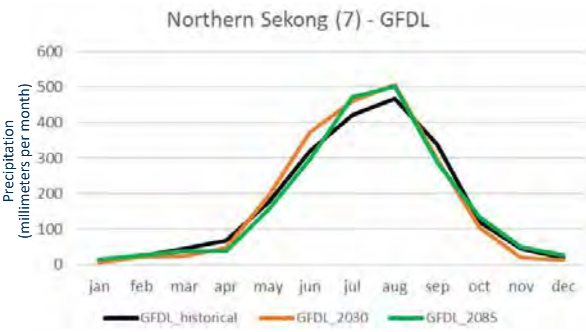
Figure B.15: Long-Term Monthly Mean Precipitation over the Sekong Basin Derived from IPSL and GFDL General Circulation Models for Representative Concentration Pathway 8p5 for Near Future (2030) and Far Future (2090)



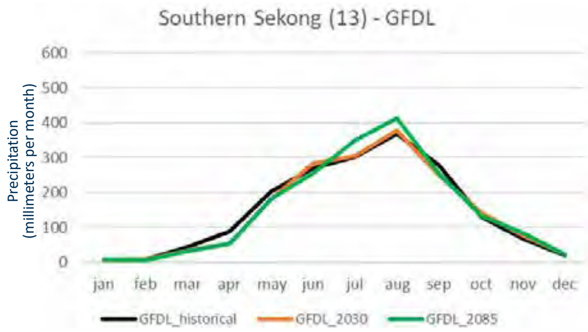
Note: IPSL= Institut Pierre Simon Laplace Model; GFDL = Geophysical Fluid Dynamics Laboratory.

Figure B.16: Long-Term Monthly Mean Precipitation Derived from GFDL General Circulation Model for Representative Concentration Pathway 8p5 for Near Future (2030) and Far Future (2090) for North and South

a. Northern Sekong



b. Southern Sekong



Note: GFDL = Geophysical Fluid Dynamics Laboratory.

The plots with GFDL precipitation (Figure B.16) show that there is more precipitation in the north than in the south. In the north, increased wet season precipitation is projected to be evident by 2030 and be sustained through to 2090, whereas in the south, increased wet season precipitation is projected to occur later. Reduced precipitation during the dry season is projected by 2030 in the north and the south of the basin.

The results for IPSL GCM (Figure B.17) project similar changes in precipitation for the north and south, although absolute amounts are higher in the north.

The effect of climate change on precipitation varies throughout the basin—not only between the north and south, as discussed.

Figure B.18 displays projected monthly changes for 2030 derived for the 20 grid cells. The variation between grid cells is especially large for the dry season. For example, decreases of up to 60 percent are projected for March, but absolute rainfall amounts are only 30 mm, so the absolute decrease is small, which could result in a slightly longer dry season.

The variation is less for the wet season. Because the effect of climate change on precipitation varies in different parts of the Sekong Basin, change factors were derived for all 20 grid cells and applied those to historical precipitation levels instead of using an average conversion factor over the entire basin.

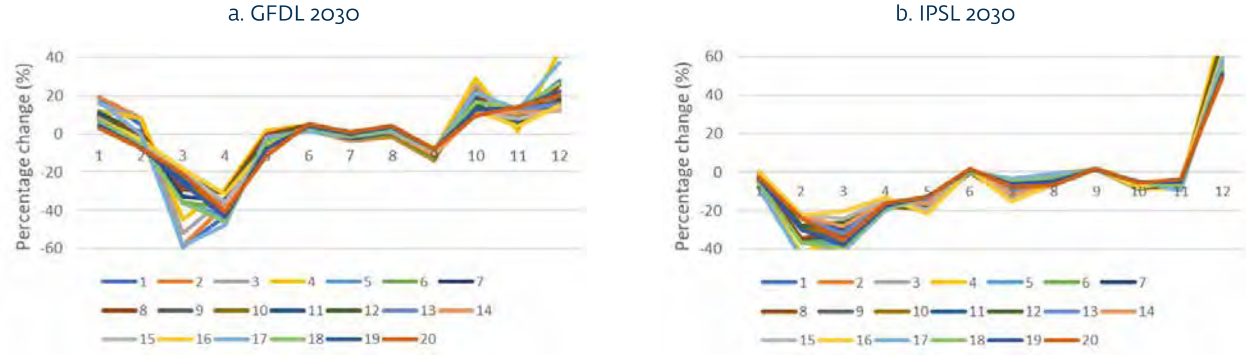
Figure B.17: Long-Term Monthly Mean Precipitation Derived from IPSL General Circulation Model for Representative Concentration Pathway 8p5 for Near Future (2030) and Far Future (2090) for North and South

a. Northern Sekong

b. Southern Sekong

Note: IPSL = Institut Pierre Simon Laplace Model.

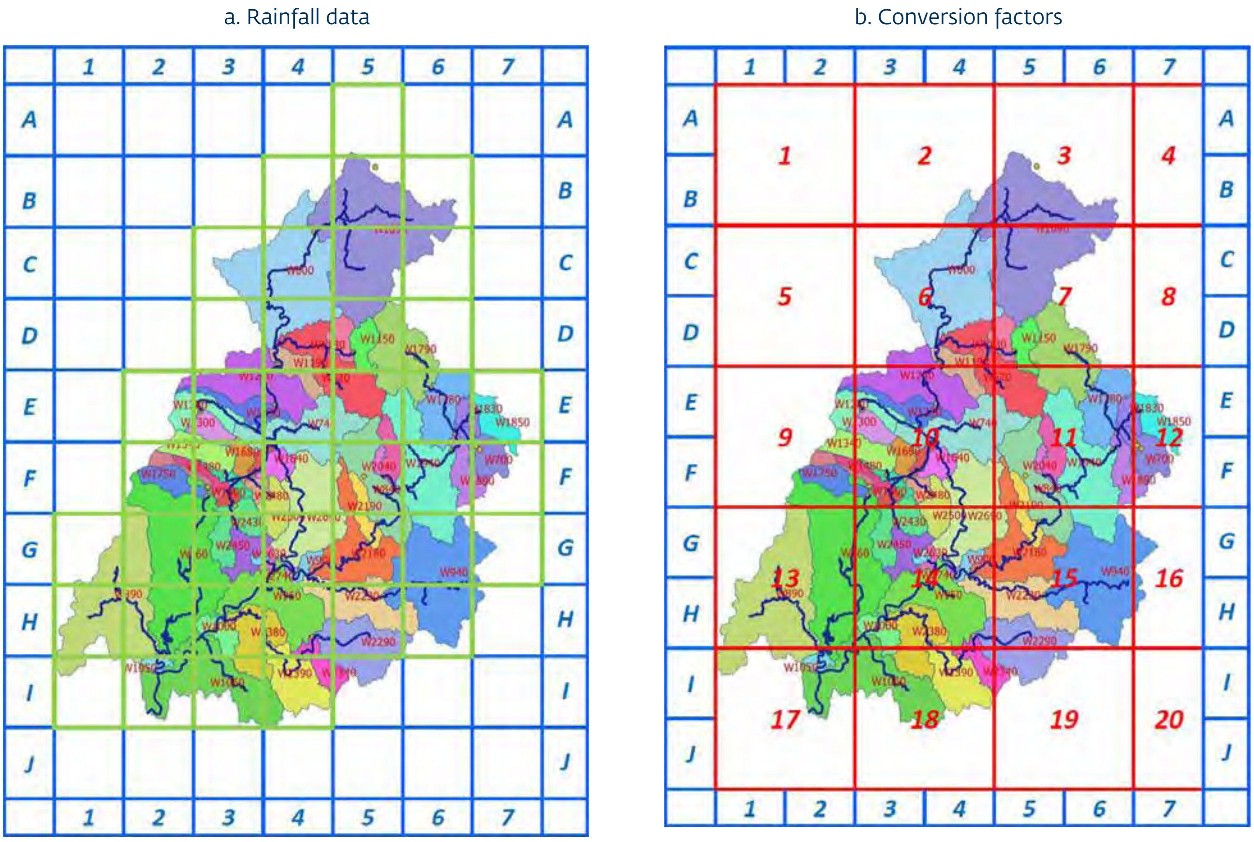
Figure B.18: **Projected Monthly Precipitation Changes (%) for 20 Individual Grid Cells for GFDL and IPSL General Circulation Models for Near Future as Example of Geographic Variation**



Note: Each colored line represents one grid cell. IPSL = Institut Pierre Simon Laplace Model; GFDL = Geophysical Fluid Dynamics Laboratory.

Using the results of the assessment of the effect of climate change on precipitation, these results can be used to convert the rainfall series for the present situation into new series representing the effect of climate change. For this conversion, factors were derived based on the resolution of the bias-corrected GCM grid, similar to that of the MSWEP daily rainfall series but less detailed (Figure B.19a for MSWEP rainfall series, Figure B.19b for climate change conversion factors).

Figure B.19: **Grids Used for MSWEP Rainfall Data Extraction and Application of Conversion Factors for Climate Change Scenarios**



The bias-corrected GCM data have a resolution of 0.5 degrees, whereas the MSWEP data have a resolution of 0.25 degrees. By projecting the GCM changes onto the historical MSWEP data, the HEC-HMS model can be forced with the highest-resolution precipitation data (0.25 degrees) for the future as well. There are four MSWEP grid cells in one climate change grid cell. As an example, for conversion of MSWEP rainfall in grid cell A5, a multiplication factor needs to be applied from climate change grid cell 3.

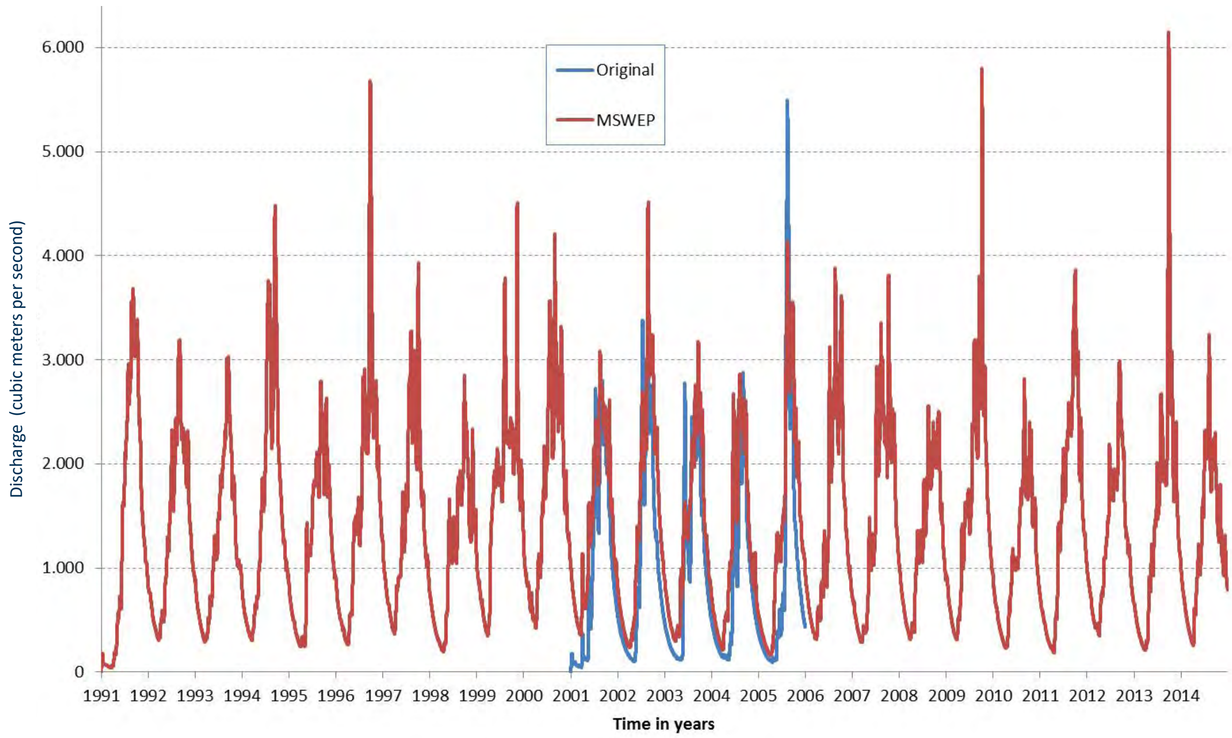
With the results of that assessment, the MSWEP daily rainfall series for the present situation are converted into four series for climate change scenarios: IPSL 2030, IPSL 2090, GFDL 2030, and GFDL 2090. These series have been entered into the HEC-HMS as alternative (climate change) meteorological scenarios.

B.2.5 Recalibration of HEC-HMS Model

The research team used the HEC-HMS model prepared for the EWN study (derived from gauge data) to calibrate the new HEC-HMS model (derived from MSWEP satellite data). Overlaying the two models (Figures B.20 and B.21) shows a good match, although base flow in the MSWEP model is significantly higher, which means a higher volume of total annual flow.

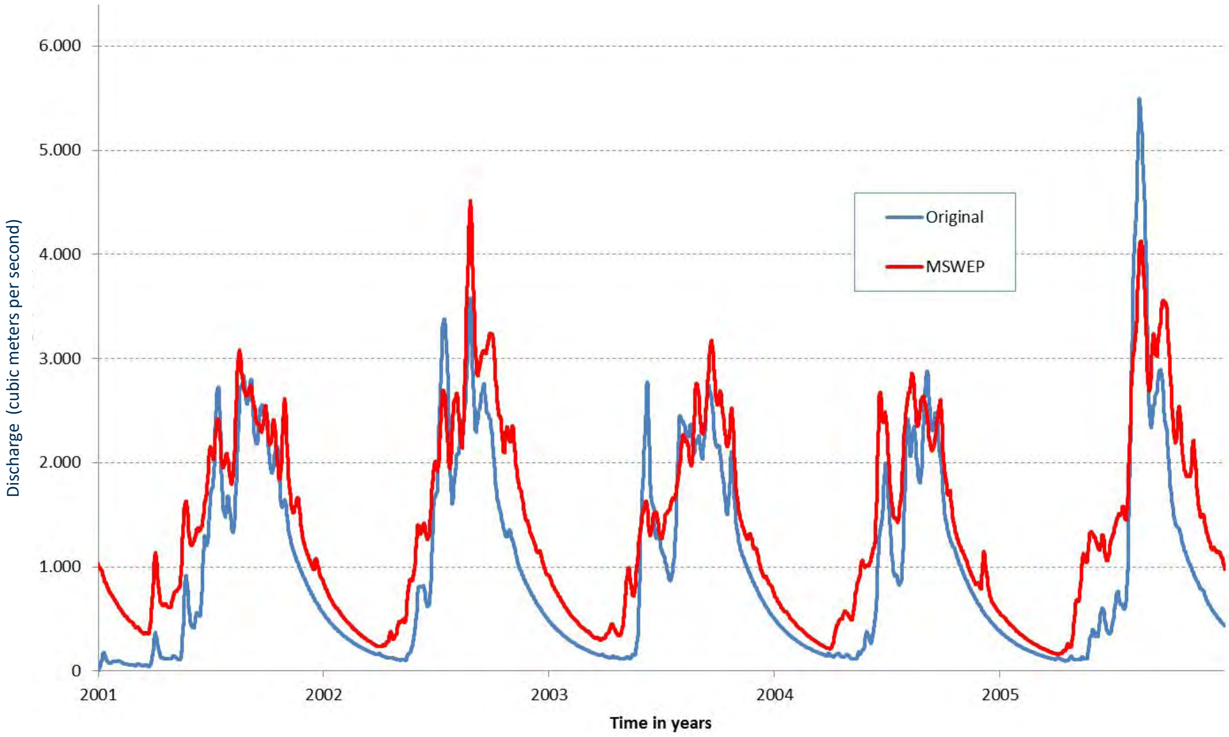
The large difference in the baseflow, which has a major effect on hydropower generation, was a reason to try to recalibrate the HEC-HMS model to have at least the low and medium flows sufficiently similar to measured (gauged) data. The model was recalibrated by adjusting the loss parameters of the soil-moisture accounting module in the HEC-HMS, using the Attapeu gauging station as a reference. This resulted in a much closer match between the simulated and measured hydrographs for the lower and medium flows, but the peak flows continue to be underestimated, probably because the global precipitation data (MSWEP) give an area-averaged value for each grid cell, and therefore flood peaks are difficult to simulate. Although this means that the overall average discharge for the simulated series per simulation period is lower than the measured value, this is probably not a major disadvantage because the high flow peaks will largely cause the storage reservoirs to flow over the spillway and will contribute little to hydropower generation.

Figure B.20: Modeling Results for Present Situation: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (Original EWN and Multisource Weighted-Ensemble Precipitation Input), 1991–2014



Note: MSWEP = multi-source weighted-ensemble precipitation.

Figure B.21: Modeling Results for Present Situation: U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System (Original EWN and Multisource Weighted-Ensemble Precipitation Input), 2001–05



Note: MSWEP = multi-source weighted-ensemble precipitation.

B.2.6 Results of New Simulations with HEC-HMS Model—Present Situation

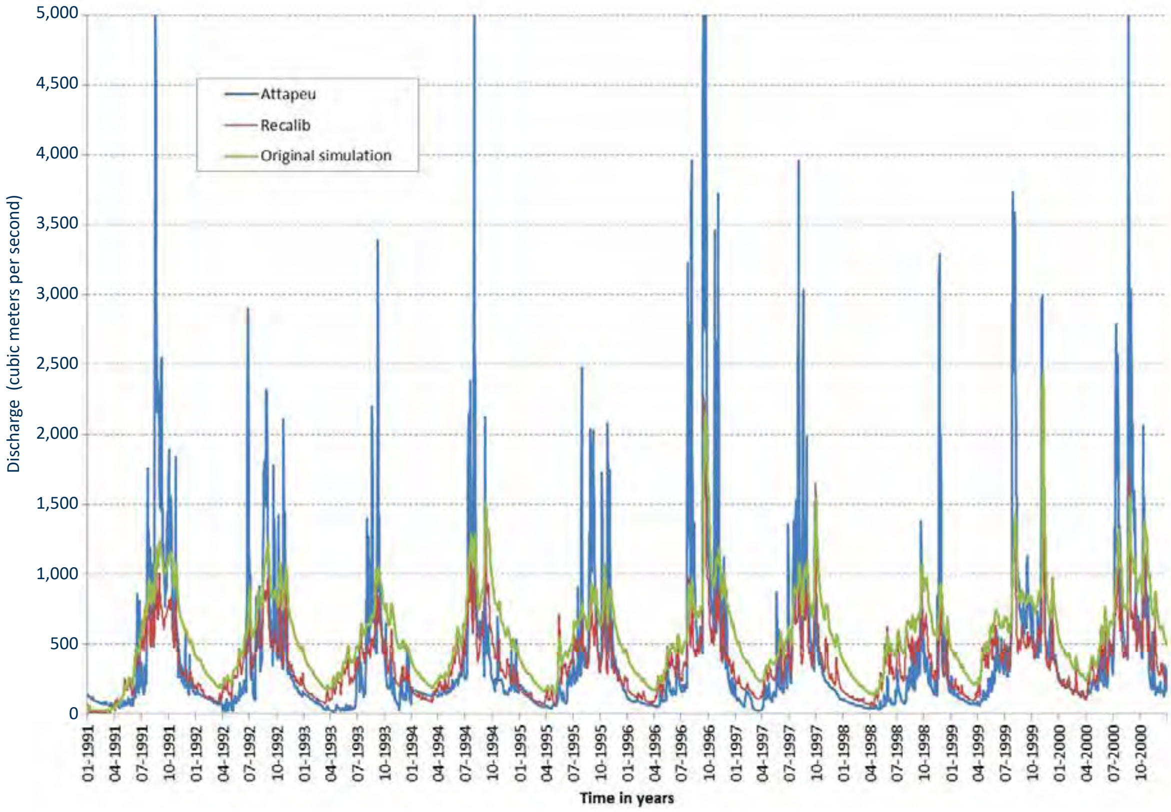
The recalibrated HEC-HMS model was used to simulate flows at the Attapeu gauging station, and the results were compared with measured data collected at the Attapeu gauging station for 1991 to 2000. (Measured data were unavailable beyond 2000.) The full period is shown in Figure B.22 with the maximum discharge cut-off at 5,000 cubic meters per second to show more clearly the differences in low and medium flows between the three hydrographs. The recalibrated model gives more accurate results for lower flow values (closer to measured values at the Attapeu gauging station). Figures B.23 (1994–95) and B.24 (1998–99) show more clearly the improvement in model calibration but also demonstrate that the model only occasionally simulates the higher (flood) values properly.

A closer match between the HEC-HMS model and measured data was obtained for the outlet of the basin. Measurements are available from the Veunkhane gauging station for 2001 to 2005, which allows the original (EWN) simulation results, the new (recalibrated) model, and the Veunkhane gauging station to be compared (Figure B.25).

The results of the two simulations (EWN) and recalibrated model with MSWEP global rainfall data are very similar, and both correspond reasonably well with the measured data at Veunkhane.

The full series of daily flow values for the 53 sub-basins in the HEC-HMS model are stored in the HEC Data Storage System database and were used for subsequent modeling of hydropower generation in the HEC-ResSim model (Appendix D).

Figure B.22: Results of U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System Simulations (1991–2000) for Original and Recalibrated Models and in Attapeu Gauging Station (Cut-Off at 5,000 m³/s)



Note: m³/s = cubic meters per second.

Figure B.23: Detail of Simulation with U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System, 1994–95

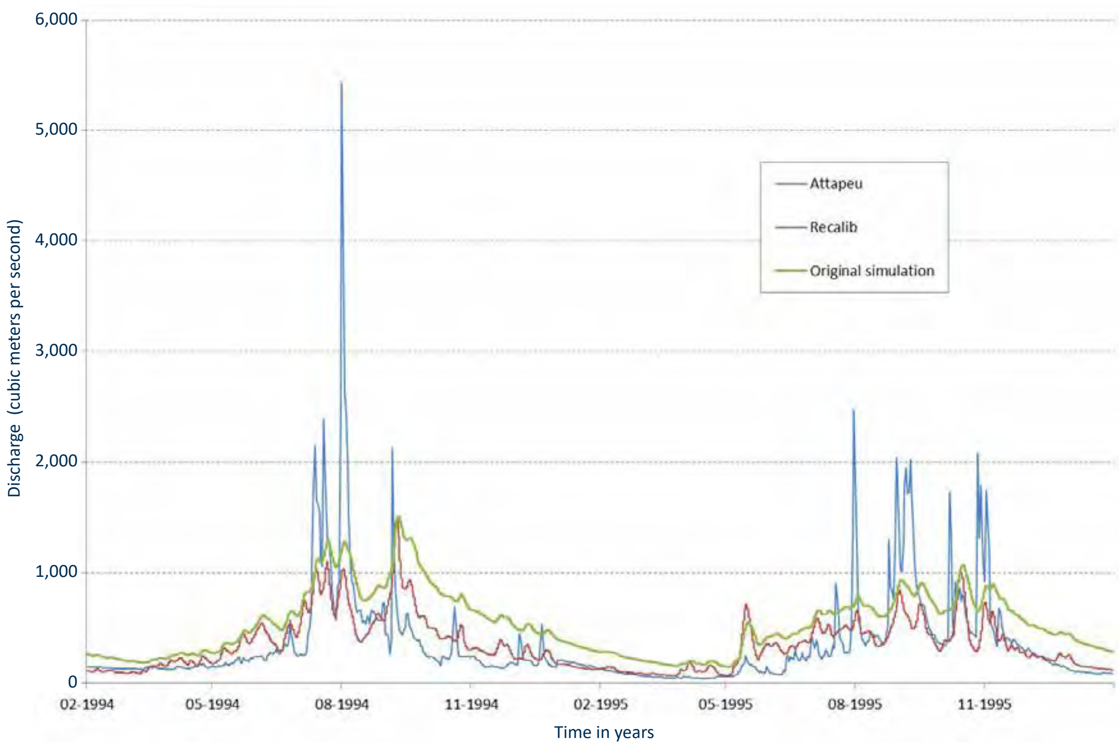


Figure B.24: Detail of Simulation with U.S. Army Corps of Engineers, Hydrologic Engineering Center Hydrologic Modeling System, 1998–99

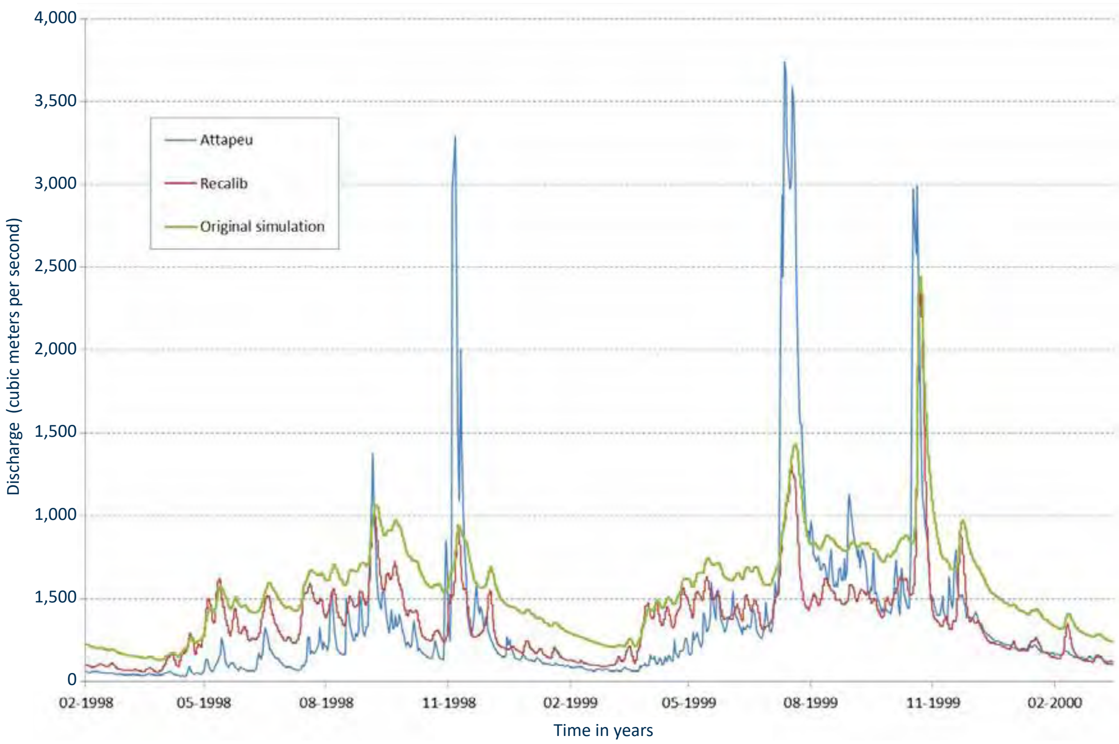
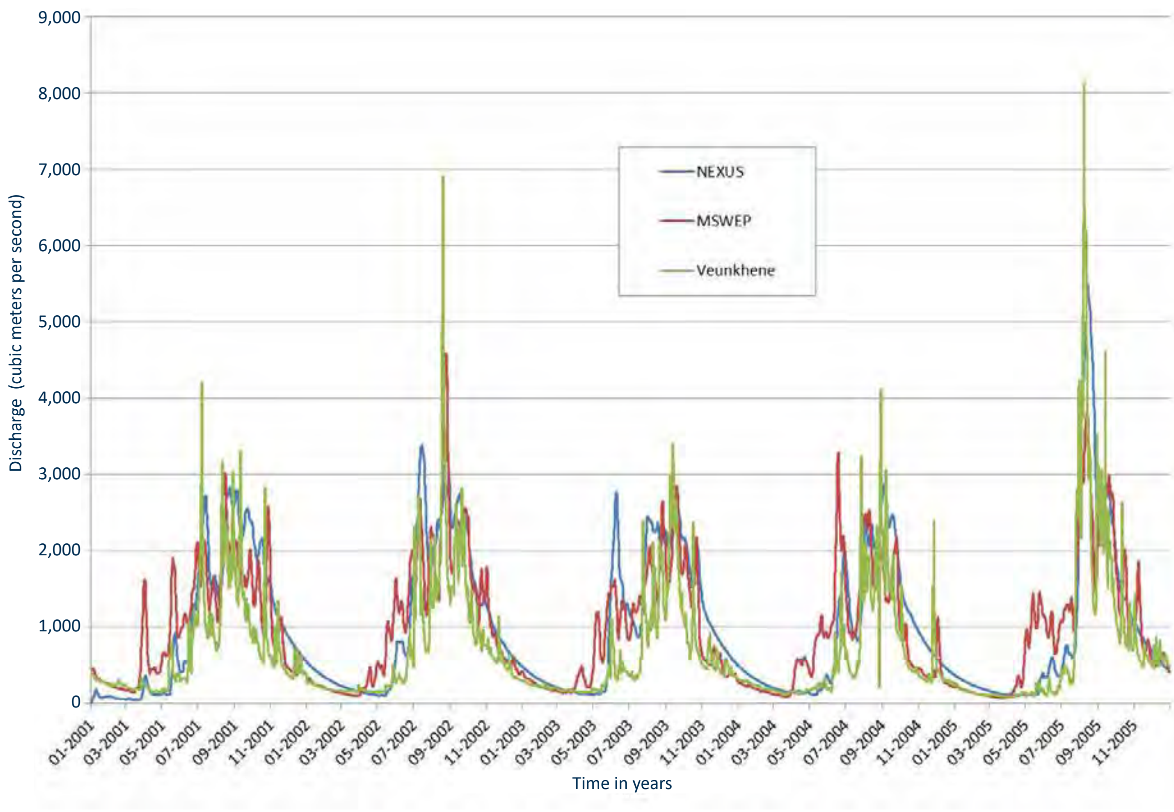


Figure B.25: Results at Sekong Basin Outlet from Energy-Water Nexus Project, Recalibrated Model, and Veunkhane Gauging Station (2001–2005)



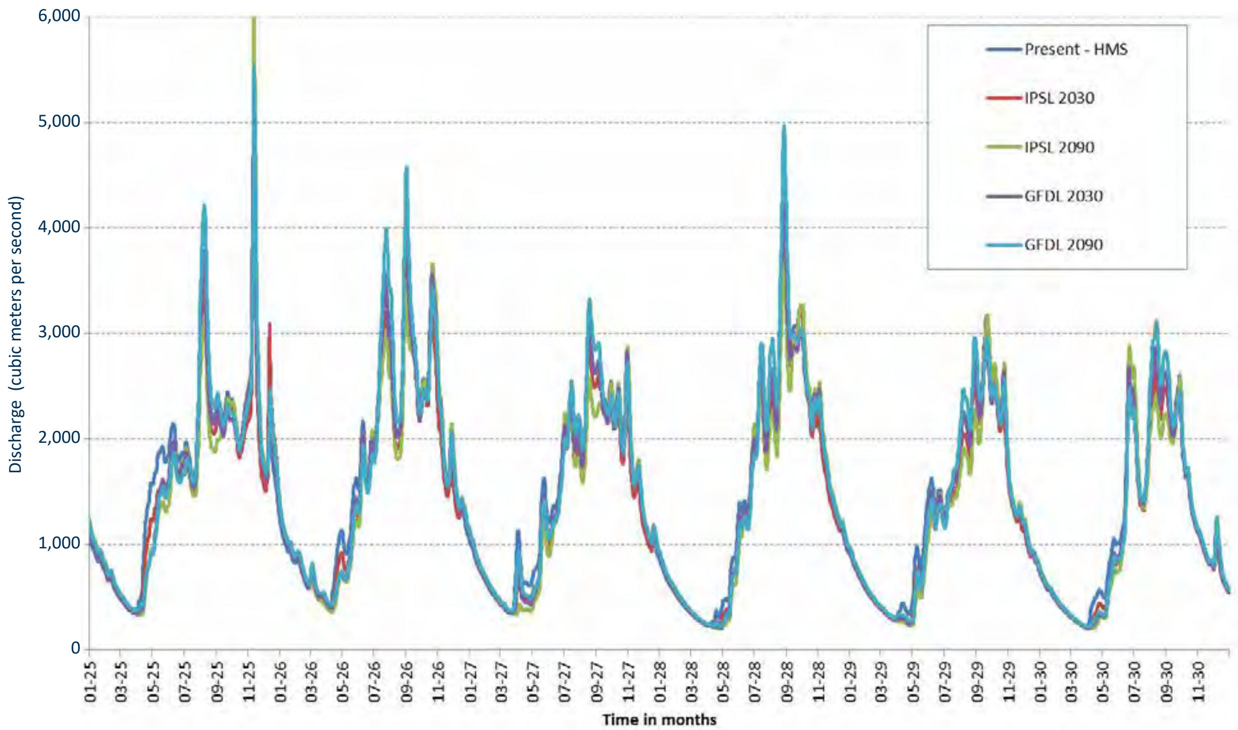
Note: MSWEP = multi-source weighted-ensemble precipitation.

B.2.7 Results of New Simulations Using HEC-HMS Model—Climate Change

Hydrological flows were simulated over a 24-year period for the four climate change scenarios, again with the first four years as a "warm-up" period to exclude the effect of the choice of initial conditions. There was only a very small effect of climate change on the final results. As an example, Figure B.26 illustrates the discharges at the outlet of the Sekong Basin for a five-year period (2025–30). These hydrographs show little variation in flow between the HEC-HMS model (which does not factor in climate change) and adjusted model, taking into account the four climate change models.

The climate change analysis conducted as part of this study was not aimed at studying flood hydrology specifically and therefore gives no indication whether future return intervals for extreme floods are expected to decrease. The current dam safety review should address this question.

Figure B.26: Effect of Climate Change Scenarios on Discharge at the End of the Sekong Basin



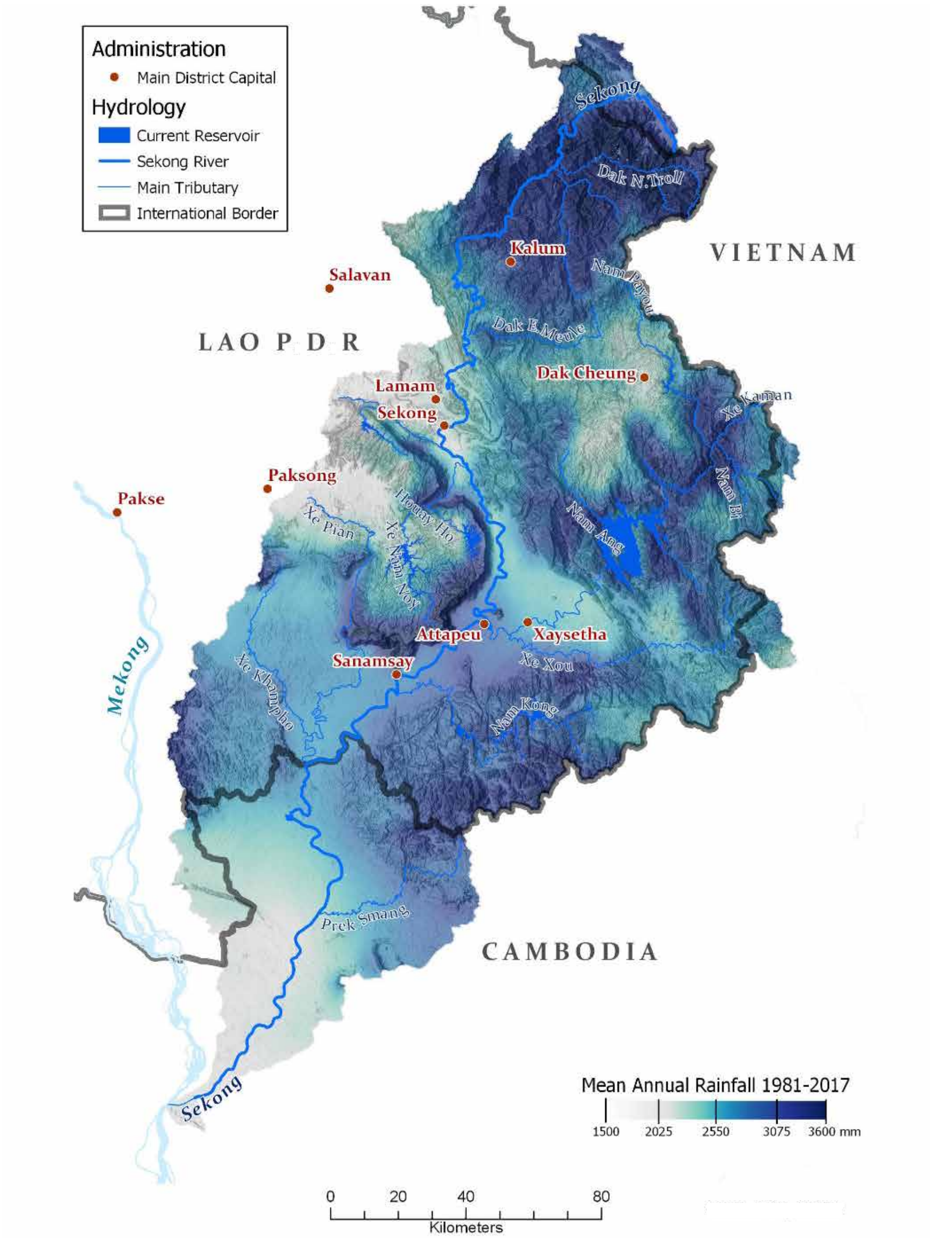
Note: HMS = Hydrologic Modeling System; IPSL = Institut Pierre Simon Laplace Model; GFDL = Geophysical Fluid Dynamics Laboratory.

APPENDIX C
SUPPORTING BASELINE AND SITUATIONAL ANALYSIS

C.1 Hydrology and Water Resources

There are a number of gauging stations in the Sekong Basin, most of them in the lower parts, for example, at Attapeu, and the quality of the data is not known. Some stations measure only gauge height and thus do not provide data relevant to the present study. Meynell (2014) states that the records from Attapeu are the most comprehensive dataset of flows in the Sekong. There are also a number of meteorological stations, but most of the series are intermittent, with many missing values.

Map C.1: Mean Annual Precipitation



Mean annual rainfall of the Sekong Basin ranges from 1,400 mm to 2,900 mm (Meynell 2014). Nearly 60 percent of the basin receives 1,700 mm to 1,900 mm per year, and 23 percent receives 2,300 mm to 2,700 mm. Mean annual temperature of the Sekong Basin is 21°C to 28°C. Temperatures in 56 percent of the basin are 21°C to 22°C, but approximately 33 percent of the area experiences much higher temperatures. Distribution of mean annual rainfall over the basin is shown in Map C.1 and temperature in Map C.2.

Map C.2: Mean Annual Temperature

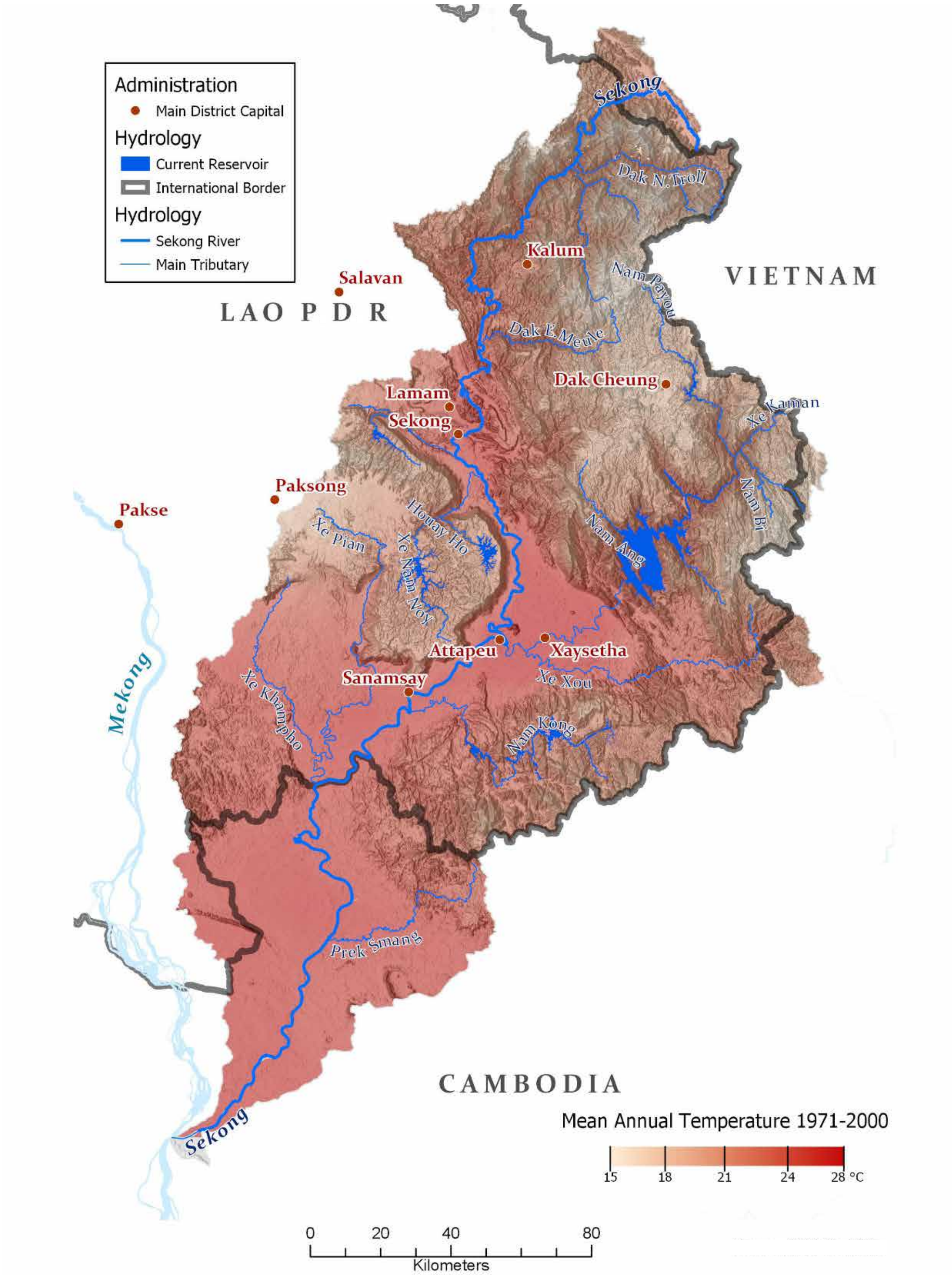
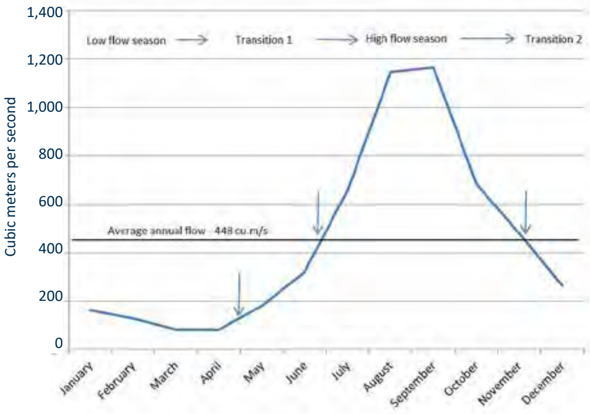
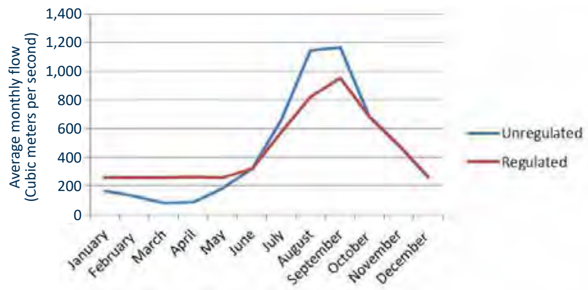


Figure C.1: Mean Monthly Flow Distribution for the Sekong River at Attapeu—Transitions from Low- to High-Flow Phases and Effect of Regulation due to Hydropower Reservoirs in Basin

a. Average monthly flows in Sekong at Attapeu (1989–2005)



b. Comparison of average monthly flows in a fully regulated Sekong



Source: Meynell 2014.

Figure C.1 shows how the Sekong River flow changes during the year in response to monsoonal rainfall patterns. Transitions from low- to high-flow phases are indicated in panel a. The effect of regulation due to hydropower reservoirs in the basin is illustrated in panel b.

C.2 Fish Diversity

Fish and other aquatic resources from the Sekong River are important for the population's livelihood, second only to agriculture as a source of income (IUCN, n.d.). Fisheries contribute 35 percent to 40 percent of annual household income through trade or sale and provide 80 percent of the protein consumed in the basin. In the Lao PDR part of the basin, mean annual consumption of fish has been estimated at nearly 50 kg per person.

As the last major free-flowing tributary to the Mekong River, the Sekong River provides unobstructed passage for migratory fish between the headwaters and the South China Sea, via the Mekong mainstream, the Tonle Sap Great Lake, and the Vietnam Delta. As such, the Sekong River contains a high level of fish diversity and endemism, with many species spawning only in its unique habitats. Estimates of numbers of fish species in the Sekong River vary from 175 to 265, with approximately two-thirds of these being migratory.[1] Geographic data from the International Union for Conservation of Nature (IUCN) between 2007 and 2013 suggest that 21 endangered and critically endangered fish species are present in the basin (Table C.1) (IUCN 2017). Some of the IUCN distribution data are old, however, and several species have a very small overlap with the Sekong Basin, which could indicate that there are actually fewer endangered fish species in the Sekong Basin.

Thirty-one of 62 fish conservation zones[2] in Lao PDR are within the Sekong Basin (Map 3.2)—half the national total. There are four national protected areas (NPAs) and one Ramsar site in the Sekong Basin (Map 3.3). The Ramsar site is the Beung Kiat Ngong Wetland, which is 2,360 hectares of swamps, lakes, and marshes that are important for spawning fish, turtles, and birds. It contains more than 350 species of medicinal plants and is the only place in Lao PDR where peatland is found.[3]

During provincial and village consultations, it was reported that fish diversity and abundance have declined drastically in the last 15 years in Champasak, Sekong, and Attapeu provinces. This was attributed to the combined pressures of overfishing, industry, mining, agriculture, and hydropower development on the tributaries. Extremely high rates of decline in total fish abundance were noted, including important food fish species such as *Poropuntius*, *Schistura*, and *Sewillia*.

[1] Meynell (2014) reports 213 species on the Sekong, of which 64 are identified as migratory.

[2] Fish conservation zones are legally defined protected areas where fishing is prohibited to help restore fish stock. This is a community co-management framework in which locals actively help enforce the regulations. http://www.wwf.org.la/projects/comfish/

[3] https://rsis.ramsar.org/ris/1941

Table C.1: Endangered and Critically Endangered Fish Species Where Geographic Ranges Overlap the Sekong Basin

Scientific name	English name	International Union for Conservation of Nature Red List status	Status consultations
Aaptosyax grypus	Mekong giant salmon carp	Critically endangered	Very rare
Catlocarpio siamensis	Giant carp	Critically endangered	Reported in the Sekong River and main tributaries
Datnioides pulcher	Siamese tiger perch	Critically endangered	Reported in Pak Kayong area
Hemitrygon laosensis	Mekong freshwater stingray	Critically endangered	Reported in the Sekong River and main tributaries
Laubuca caeruleostigmata	Flying minnow	Critically endangered	Reported in Pak Kayong area
Pangasianodon gigas	Mekong giant catfish	Endangered	Potentially gone
Pangasianodon hypophthalmus	Striped catfish	Endangered	Reported in Pak Kayong area
Pangasius sanitwongsei	Giant pangasius	Endangered	Reported in the Sekong River
Poropuntius bolovenensis	n.a.	Endangered	Reported in Pak Kayong and Nong Kheuang Yai areas
Poropuntius consternans	n.a.	Endangered	Reported in Pak Kayong, Nong Kheuang Yai, and Phaosamphan areas
Poropuntius deauratus	n.a.	Endangered	Reported in Nong and Kheuang Yai areas
Poropuntius lobocheiloides	n.a.	Endangered	Reported in Pak Kayong area
Poropuntius solitus	n.a.	Endangered	Reported in Pak Kayong area
Pristis pristis	Large-tooth sawfish	Endangered	Very rare
Probarbus jullieni	Julien's golden carp	Endangered	Reported in the Sekong River and main tributaries
Probarbus labeamajor	Thick-lipped barb	Endangered	Reported in Nang Yong and Nong Kheuang Yai areas
Schistura bairdi	n.a.	Endangered	No information
Schistura bolavenensis	n.a.	Endangered	Reported in small upstream streams
Schistura spilotera	n.a.	Endangered	Reported in Nang Yong area
Sewillia breviventralis	Butterfly loach	Critically endangered	Reported in Nong Kheuang Yai area
Urogymnus polylepis		Endangered	No recent sightings

Note: n.a. = not applicable.

C.3 Ecosystems and Natural Resources

The IUCN (2017) Red List indicates that there are many flora and fauna species in the Sekong Basin, and some are threatened (Table C.2). According to the Integrated Biodiversity Assessment Tool, there are approximately 89 globally threatened vertebrate species, of which 21 are critically endangered, 32 endangered, and 36 vulnerable. The species list contains 18 birds, 28 mammals, eight reptiles, 31 fishes, and two amphibians.

Many of the reported globally threatened species have small population numbers and are threatened across the Sekong Basin because of overfishing, hunting, habitat loss, land use change, and deforestation, but there are areas across the basin that function as refuge areas for threatened species, such as the Xe Pian NPA. The basin's wildlife zones are as follows:

- *Montane forest in upper Sekong (Kaleum)*. Forest condition remains good in the Xe Sap NPA at the Sekong headwaters and along the Lao–Vietnamese border, which is designated as a biodiversity corridor area. The lower area of the upper Sekong is more degraded and has been transformed into secondary forest and fallow and hill rice agricultural land.

- *Pine forest (Dak Cheung)*. Pine forest condition remains good in the northeast of Dak Cheung of Sekong Province along the Lao PDR–Vietnamese border as part of the biodiversity conservation corridor and to the south along the Phou Kathong National Protection Forest and biodiversity conservation corridor. Few endangered species reside here, but there are some gibbon and douc langur. Along the road from the Sekong provincial capital to Dak Cheung, the pine forest is highly degraded.

- *Mixed evergreen forests*. Forest condition remains good in the Dong Ampham NPA and along the Lao PDR–Vietnamese border, which is designated as a biodiversity corridor area. Various large mammals are reported in this sub-ecosystem zone, such as Asian elephants, banteng, gaur, gibbons, and douc langur.

- *Mixed deciduous forest (Nam Kong)*. Forest condition remains good in the upper hills, on the border with Cambodia from Ban Phou Nyang on the east of Phouvong District and to the western part of Phouvong District. The number of large mammals here is similar to that of the Dong Ampham NPA. The forest in the lower foothills and along the access road to Nam Kong 1, 2, and 3 hydropower plants (HPPs) is degraded, and secondary forest and hill rice cultivation prevail. Large rubber tree plantations are situated along the road from Phouvong District to Nam Kong 1 HPP.

- *Bolaven upper evergreen forest (Paksong)*. Forest condition is fairly good in Xe Khampho area, Houy Ho watershed, upper Xe Pian–Xe Namnoy, and upper Xe Katam. Various large mammals such as Asian elephants, tiger, gaur, and gibbons have been reported in this area. Parts of this subzone, especially along the roads, have been converted into cash crop plantations, especially coffee plantations.

- *Floodplain*. Wetland and riparian ecosystems with dry dipterocarp forest (the Xe Pian NPA) prevail here, and forest condition remains good. Various large mammals are reported here, such as tiger, banteng, gaur, gibbon, and douc langur. This area contains wetland and seasonal wetland complexes with dry dipterocarp forest landscapes. Some of the wetland areas have been exploited and are thus degraded.

Table C.2: Globally Threatened Fauna (Vertebrate) Species in the Sekong Basin

Taxon	Critically endangered	Endangered	Vulnerable	Total
Birds	7	5	6	18
Mammals	5	10	13	28
Reptiles	2	2	4	8
Amphibians	0	2	0	2
Fish	7	13	13	31
Total	**21**	**32**	**36**	**89**

Source: IUCN 2017. https://www.iucnredlist.org/.

C.4 Supporting Analysis on Terrestrial Ecology

C.4.1 Selection of Indicator Species

A list of terrestrial species in the Sekong Basin that were critically endangered and endangered was derived from the IUCN Red List with the Sekong Basin boundaries and from the Integrated Biodiversity Assessment Tool (IBAT) database (IUCN 2017 and IUCN n.d.). See Table C.3.

Table C.3: Globally Threatened Fauna Species According to IBAT and Zone

Scientific name	Common name	Conservation status	Upper Sekong		Dak Cheung		Dong Ampham		Nam Kong		Pak Song		Lower Sekong	
			IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present
Amphibian														
Leptobrachium xanthops	Giant frog	Endangered	X		X		X		X					
Leptolalax melicus	Musical leaf-litter toad	Endangered			X		X		X					
Bird														
Asarcornis scutulata	White-winged duck	Endangered					X		X				X	X
Ciconia episcopus	Woolly-neck stork	Vulnerable	X		X		X	X	X				X	X
Clanga	Greater spotted eagle	Vulnerable	X		X		X	X	X		X		X	
Emberiza aureola	Yellow-breasted bunting	Critically endangered									X		X	
Garrulax konkakinhensis	Chestnut-eared laughing thrush	Vulnerable	X		X		X		X					
Gracula robusta	Nias hill myna	Critically endangered	X		X		X		X		X		X	
Gracula venerata	Tenggara hill myna	Endangered	X		X		X		X		X		X	
Gyps bengalensis	White-rumped vulture	Critically endangered	X		X		X	X	X	X	X		X	X

Scientific name	Common name	Conserva-tion status	Upper Sekong		Dak Cheung		Dong Ampham		Nam Kong		Pak Song		Lower Sekong	
			IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present
Gyps tenuirostris	Slender-billed vulture	Critically endangered	X		X		X		X		X		X	
Mulleripicus pulverulentus	Great slaty woodpecker	Vulnerable	X	X	X		X	X	X		X		X	X
Pavo muticus	Green peafowl	Endangered	X		X		X	X	X	X	X		X	X
Sarcogyps calvus	Red-headed vulture	Critically endangered	X		X		X		X		X		X	X
Leptoptilos javanicus	Lesser adjutant	Vulnerable					X	X			X		X	X
Heliopais personatus	Masked finfoot	Endangered			X		x						X	
Sterna acuticauda	Black-bellied tern	Endangered			X		X		X		X		X	
Pseudibis davisoni	White-shouldered ibis	Critically endangered											X	X
Pseudibis gigantean	Giant ibis	Critically endangered											X	X
Grus antigone	Sarus crane	Vulnerable											X	X
Fish														
Bangana behri		Vulnerable	X		X		X		X				X	
Hypsibarbus lagleri		Vulnerable											x	
Labeo pierrei		Vulnerable	X		X									
Pangasius sanitwongsei	Giant pangasius	Critically endangered	X				X		X				X	X
Aaptosyax grypus	Mekong giant salmon carp	Critically endangered							X				X	X
Catlocarpio siamensis	Giant carp	Critically endangered											X	X
Cirrhinus microlepis	Small-scaled mud carp	Vulnerable											X	
Epalzeorhynchos munense	Red fin shark	Vulnerable							X				X	
Datnioides pulcher	Siamese tiger perch	Critically endangered									X		X	X
Datnioides undecimradiatus		Vulnerable											X	

Scientific name	Common name	Conservation status	Upper Sekong		Dak Cheung		Dong Ampham		Nam Kong		Pak Song		Lower Sekong	
			IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present
Laubuca caeruleostigmata	Flying minnow	Endangered											X	X
Osphronemus exodon	Elephant ear gourami	Vulnerable							X				X	
Hemitrygon laosensis	Mekong freshwater stingray	Endangered											X	X
Pangasianodon hypophthalmus	Striped catfish	Endangered											X	
Pangasius krempfi		Vulnerable											X	
Poropuntius bolovenensis		Endangered	X		X									
Poropuntius consternans		Endangered	X		X									
Poropuntius deauratus	Yellow tail brook barb	Endangered	X		X									
Poropuntius lobocheiloides		Endangered	X		X									
Poropuntius solitus		Endangered	X		X									
Pristis	Large tooth sawfish	Critically endangered	X											
Probarbus jullieni	Jullien's golden carp	Endangered											X	X
Schistura spiloptera													X	
Pangasianodon gigas	Mekong giant catfish	Critically endangered											X	
Probarbus labeamajor	Thick-lipped barb	Endangered											X	
Tenualosa thibaudeaui	Mekong herring	Vulnerable											X	
Urogymnus polylepis		Endangered											X	
Scaphognathops bandanensis		Vulnerable											X	
Pseudohemiculter dispar		Vulnerable	X		X		X		X					
Schistura bolavenensis		Endangered	X		X									
Yasuhikotakia nigrolineata	Black-lined loach	Vulnerable	X		X								X	

Scientific name	Common name	Conservation status	Upper Sekong		Dak Cheung		Dong Ampham		Nam Kong		Pak Song		Lower Sekong	
			IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present
Schistura kontumensis		Vulnerable					X		X					
Sewellia breviventralis	Butterfly loach	Critically endangered					X		X					
Mammal														
Orcaella brevirostris	Irrawaddy dolphin	Vulnerable							X				X	
Rucervus eldii	Eld's deer	Endangered											X	
Aonyx cinereus	Asian small-clawed otter	Endangered											X	
Arctictis binturong	Binturong	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X
Arctonyx collaris	Greater hog badger	Vulnerable	X	X	X		X	X	X	X	X	X	X	X
Bos gaurus	Gaur	Vulnerable	X	X	X		X	X	X	X	X	X	X	X
Bos javanicus	Banteng	Endangered					X	X					X	X
Bos sauveli	Kouprey	Critically endangered					X		X		X		X	
Cuon alpinus	Dhole	Endangered		X		X	X	X	X	X	X	X	X	X
Chrotogale owstoni	Owston's civet	Endangered	X	X	X		X	X	X					
Elephas maximus	Asian elephant	Endangered	X		X		X	X	X	X	X		X	
Lutrogale perspicillata	Smooth-coated otter	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X
Macaca arctoides	Stump-tailed macaque	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X
Macaca leonina	Northern pig-tailed macaque	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X
Manis javanica	Sunda pangolin	Critically endangered	X	X	X	X	X	X	X	X	X	X	X	X
Manis pentadactyla	Chinese pangolin	Critically endangered	X	x	X		X		X		X			
Muntiacus vuquangensis	Large-antlered muntjac	Critically endangered	X	X	X		X		X					
Neofelis nebulosa	Clouded leopard	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X

Scientific name	Common name	Conservation status	Upper Sekong		Dak Cheung		Dong Ampham		Nam Kong		Pak Song		Lower Sekong	
			IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present	IBAT data	Present
Nomascus gabriellae	Buff-cheeked gibbon	Endangered	X	X	X	X	X	X	X	X		X	X	X
Nycticebus bengalensis	Bengal slow loris	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X
Nycticebus pygmaeus	Pygmy slow loris	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X
Panthera tigris	Tiger	Endangered	X	X	X		X	X	X	X	X	X	X	X
Pseudoryx nghetinhensis	Saola	Critically endangered	X	X										
Pygathrix nemaeus	Red-shanked douc langur	Endangered	X	X	X		X	X	X	X	X	X		
Rusa unicolor	Sambar	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X
Trachypithecus germaini	Indochinese lutung	Endangered	X	X	X	X	X	X	X	X	X	X	X	X
Ursus thibetanus	Asiatic black bear	Vulnerable	X	X	X	X	X		X	X	X	X	X	X
Viverra megaspila	Large-spotted civet	Endangered	X	X	X		X		X		X		X	
Reptile														
Bungarus slowinskii	Red river krait	Vulnerable	X		X		X		X					
Crocodylus siamensis	Siamese crocodile	Critically endangered	X		X		X		X				X	X
Cuora bourreti	Bourret's box turtle	Critically endangered	X		X		X	X	X					
Cuora mouhotii	Keeled box turtle	Endangered	X		X		X		X					
Naja siamensis	Black and white spitting cobra	Vulnerable	X		X		X		X		X		X	
Ophiophagus hannah	King cobra	Vulnerable	X	X	X	X	X	X	X	X	X		X	X
Protobothrops sieversorum	Three-horned scaled pit viper	Endangered	X		X		X		X					
Python bivittatus	Burmese python	Vulnerable	X	X	X	X	X	X	X	X	X	X	X	X

Note: Some super-endemic fish species that are not globally threatened were excluded. IBAT = Integrated Biodiversity Assessment Tool.

The species from the list were discussed with regard to their presence and estimated population size during the stakeholder consultations in the field with local communities and at the district level with relevant officers in September 2018. Then the criteria for short-list selection of species was applied. The selection criteria considered not only conservation status of globally threatened species but also species' uniqueness, sensitivity, connectivity, and importance for food, beliefs, economic value, and the like. A score from 0 to 3 was given for each criterion. See Table C.4.

Terrestrial species with a total score of 6 points or higher were selected for the short list (Table C.5).

Table C.4: Criteria for Selection of Short List for Terrestrial Species

Characteristic	Points
Unique, super-endemic species with limited distribution and requiring specific habitats	2
Species requiring large areas for ranging and sensitive to decreased habitat connectivity	3
Species particularly sensitive to habitat disturbance	2
Identified by species stakeholders as important for food and livelihoods	1
Species assessed as important for conservation by environmental specialists	3
Species with importance for cultural values and belief systems	2
Critically endangered species	2
Endangered species	1
Vulnerable species	0.5

Table C.5: Short List of Selected Terrestrial Species for Detailed Valued Environmental Component Analysis

Scientific name	English name	Conservation status
Nomascus anamensis	Buff-cheeked gibbon	Endangered
Pygathrix nemaeus	Red-shanked douc langur	Endangered
Elephas maximus	Asian elephant	Endangered
Crocodylus siamensis	Siamese crocodile	Critically endangered
Pavo muticus	Green peafowl	Endangered
Bos javanicus	Banteng	Endangered
Pseudibis davisoni	White-shouldered ibis	Critically endangered
Sterna acuticauda	Black-bellied tern	Endangered

Source: IUCN 2017.

C.4.2 Assessing Effects on Terrestrial Fauna and Valued Sekong Basin Habitats

Habitat loss or inundation from hydropower reservoirs is a direct effect, but habitat fragmentation can also create indirect habitat pressure by blocking movement of various terrestrial species. Associated access roads may also increase chances for hunting and harvesting of forest resources.

Effects on terrestrial biodiversity have been estimated based on area of habitat loss of protected areas and calculated as follows for the different pathways:

Habitat loss = Total reservoir area / Total protected area affected

Degree of habitat loss, calculated in percentage of total protected area, can be categorized or ranked (Table C.6).

Table C.6: Habitat Loss

Habitat loss (percentage take of protected area)	Score	Degree of habitat loss (modification)
≥ 20	4	Severe
15–20	3	High
5–10	2	Moderate
> 5	1	Slight

Transmission lines. The zone of influence of a transmission line is wider than the strip of land that the transmission line takes, covering the indirect effects on biodiversity in the conservation area (for example, from greater poacher access for hunting, wildlife trade, collection of forest products, and simple disturbance by people using the transmission line corridor and its access roads). It is calculated by taking a one-kilometer zone of influence on each side of the transmission line as it traverses the conservation area. The calculation of zone of influence is as follows:

$$ZoI = \sum[\text{width} + 2(1\text{km}) \times \text{length}]$$

A *degree of fragmentation* refers to the effects of separating wildlife populations from each other within a conservation area. Many species cannot or do not (because they are frightened) cross open spaces such as those that transmission lines create because they require unbroken, undisturbed habitat. As a result, the areas of continuous habitat become smaller and have smaller carrying capacities for the species than the original, undisturbed area. This may result in the decline or local extinction of some species; existing transmission lines and roads may already have fragmented some conservation areas under the present situation (2020). New reservoirs, transmission lines, and access roads will increase fragmentation for the different pathways by 2030. Degree of fragmentation was ranked (Table C.7).

Table C.7: Fragmentation

Degree of fragmentation	Number of fragments	Size of largest fragment as percentage of original protected area
Total	6	25–49
Partial	4	50–79
Minimal	2	80–99
None	0	100

The degree of fragmentation indicator was used to estimate the number of conservation areas that transmission lines, reservoirs, and access roads would fragment under each pathway.

Project location and threatened species.
The location of each project, especially reservoirs and transmission lines, will affect the degree of threat to biodiversity. If renewable energy projects, dams, or reservoirs are located entirely or mainly inside a protected area, the threat is considered severe (Table C.8).

Table C.8: Threat to Biodiversity

Location	Score	Threat to biodiversity
Wholly or mainly inside protected area	4	Severe
1 kilometer from protected area	3	High
5 kilometers from protected area	2	Moderate
> 5 kilometers from protected area	1	Slight

The protected areas also have differences in importance based on the number of globally threatened (critically endangered, endangered, and vulnerable) species in them. With more globally threatened species, risks to biodiversity are assumed to be higher. The number of globally threatened species in each protected area was based on the Integrated Biodiversity Assessment Tool website.

Globally threatened terrestrial species were categorized as shown in Table C.9.

Table C.9: Globally Threatened Species in Protected Areas

Number of globally threatened species present in protected areas	Score	Importance of protected areas for biodiversity
≥ 30	4	Very high
20–29	3	High
10–19	2	Medium
< 10	1	Low

A final composite assessment (scored from 0 to 4, in line with the general valued environmental component assessment) of protected areas affected by renewable energy projects and their transmission lines was calculated. The composite scoring considered level of habitat loss, location of energy projects with regard to protected areas, level of fragmentation, and number of globally threatened species within a protected area affected by an energy project.

C.4.3 Cumulative Impact Assessment Analysis and Results

Impacts on selected indicator species (Table C.5) were assessed with regard to changes in forest habitat and key conservation areas for the present situation and the three future pathways. Several of the other valued environmental components depend on forest habitat for sustainable use or conservation, including hardwood timber, non-timber forest products (assessed under Chapter 3 in Main Report), valued terrestrial fauna, and protected areas and key biodiversity areas. Forest loss, including of conservation forest, is discussed in Chapter 3.

Forest areas are under pressure in the Sekong Basin, and the resource base has declined in recent decades. Hydropower development is likely to contribute to this continued decline because it will inundate additional forested areas. The estimated loss of forest types under the different pathways is presented in Table C.10.

Hydropower development is only one cause of forest loss in the Sekong River Basin, with logging and conversion of forest to mining and plantation land also playing significant roles. Mining has placed as much or more pressure on forest land than hydropower, and if new concessions in the basin are granted, this pressure is likely to increase.

Table C.10: Summary of Inundated Forest Areas Under Each Pathway

Development pathway	Production forest (hectares)	Conservation forest and/or national protected areas (hectares)	Protection forest (hectares)	Regeneration forest (hectares)	Total forest loss (hectares)
Present situation	422	3,408	12,924	118	16,872
Full	5,843	2,324	860	1,743	11,196
Intermediate	651	2,192	500	1,928	5,271
Conservative	651	625	86	1,928	3,290

C.4.4 Key Conservation Areas

The status of conservation areas important for terrestrial fauna under the present situation was compared with that under the full development pathway (Table C.11). Several of the selected indicator species are found in these key conservation areas. In the present situation, the Dong Ampham National Protected Area (NPA) has lost 1.86 percent (3,641 hectares), and the Nam Kong National Protected Forest (NPF) has lost 0.46 percent (937 hectares). Specifically, the Xe Khaman 1 and Nam Kong 3 projects have caused habitat fragmentation of these conservation areas. Transmission lines from the Nam Kong 2 and 3 dams to the main grid have also fragmented these conservation areas.

Under present conditions, the cumulative effect on the Dong Ampham NPA is of high concern (with an average cumulative impact score of 3.00, large); that of the Nam Kong and Bolaven Upstream NPFs is slightly less but still moderate to large (score of 2.25 for both). The effect on the Dong Ampham NPA is slightly higher for the full development pathway (score 3.25, large). For the Nam Kong and Bolaven Upstream NPFs, there will be minor differences, whereas the effect on the Xe Pian and Xe Sap NPAs is greater (Table C.11).

Two thousand hectares less will be affected in key conservation areas under the conservative development pathway (with no Sekong mainstream dams) than under the full development pathway. This is specifically related to no development of Sekong 5 in the Xe Sap NPA and Sekong Downstream A in the Nam Kong NPF. The conservation value of the Xe Sap NPA will be maintained because no area will be taken, and there will be no fragmentation related to hydropower plant development.
For the intermediate pathway, Sekong 5 will affect the Xe Sap NPA. Sekong 4B is not associated with any important conservation areas.

Table C.11: Estimated Cumulative Impacts of Key Conservation Areas

Key conservation area	Number of projects	Project footprint (hectares)	Impact score according to category				Cumulative impact score
			Level of habitat loss	Number of projects interacting	Degree of fragmentation	Globally threatened species	
Present situation							
Dong Ampham NPA	2	3,641	2	4	2	4	3.00
Nam Kong NPF	3	937	1	4	2	4	2.75
Xe Pian NPA	1	10	1	2	0	4	1.75
Xe Sap NPA	0	0	0	0	0	4	1.0
Boloven NPF	9	12,706	3	3	2	3	2.75
Full development pathway							
Dong Ampham NPA	8	4,266	3	4	2	4	3.25
Nam Kong NPF	5	1,048	1	4	2	4	2.75
Xe Pian NPA	1	10	1	4	0	4	2.25
Xe Sap NPA	1	1,567	1	4	1	4	2.50
Boloven NPF	13	13,204	3	3	2	3	2.75

Note: NPA = National Protcted Area; NPF = National Protected Forest.

C.4.5 Indicator Species

Development of renewable energy projects in the Sekong Basin will threaten Asian elephants most under the present situation and gibbons as well under the full development pathway. This is not only because of development of renewable energy projects but also because of additional stressors and drivers such as mining, road development, plantations, hunting, and population increase in general. Human conflict with Asian elephants in the Sekong Basin has been reported at Ban Houy in Xanxay District due to the construction of the Xe Khaman 1. Also, greater road access as part of the renewable energy development projects may lead to more hunting and habitat disturbance, which could also threaten gibbons, banteng, red-shanked douc langurs, white-shouldered ibis, green peafowl, and Siamese crocodiles. The development pathways are not the greatest pressure on wildlife species, and there will be marginal differences between them.

The full development pathway will affect forest habitats, key conservation areas, and terrestrial fauna moderately, and the conservative and intermediate pathways will affect them slightly to moderately. Other factors such as mining, plantations, transmission line and road development, hunting, and forest resource extraction will cumulatively exacerbate the effect of all pathways.

C.5 Renewables

Other than hydropower, there are currently no renewable energy projects in the Sekong Basin, although investors are exploring a number of possible solar and wind projects. These plans are outlined below.

C.5.1 Solar Photovoltaic Energy

Solar photovoltaic investments are expanding rapidly throughout the world because of falling costs of panels and large-scale project development. Recent tenders indicate that solar will soon become economical without subsidies wherever sunlight is plentiful and land is inexpensive (near the tropics and in non-forested areas not used for agriculture or other purposes). The potential for solar is high in Lao PDR but not necessarily in remote regions and forested areas.

Solar power and hydropower can be integrated in pump storage design whereby solar energy is used to pump water into hydropower reservoirs during the day when the sun is shining and used for hydropower generation at night.

In the Sekong Basin, nine proposals for large-scale, ground-mounted solar photovoltaic plants with the potential to provide up to 5 terawatt-hours (TWh) of energy per year have been identified. The aggregate land take of these projects will be more than six square kilometers, mostly in Attapeu Province, although only three projects have memoranda of understanding, and there will be challenges with integrating such large projects into the existing weak transmission grid and balancing rapid fluctuations in solar output.

Large-scale solar projects in the Sekong Basin will presumably be designed for export because existing hydropower already satisfies energy demand from Lao consumers on the southern grid. Access to long-distance transmission lines will be required, but even large-scale solar projects may not be able to finance dedicated transmission lines because they generally have a low plant utilization factor (15–20 percent). Solar projects will therefore be more feasible where transmission capacity already exists, for example, where hydropower projects are exporting to Vietnam and Thailand.

C.5.2 Floating Solar Photovoltaic

The owner of Xe Kaman 1 reservoir, the Viet-Lao Joint Stock Company, in partnership with Convalt Energy has proposed floating solar power as an addition to the HPP at Xe Kaman 1 reservoir. A press release from June 2018 indicates that 250 megawatts (MW) of ground-mounted solar and 280 MW of floating solar will be developed. This presumably can be exported to Vietnam through existing transmission lines.

By 2017, the largest floating solar plant in the world[4] had reached 40 MW, and larger ones are being planned, so it is conceivable that a 280-MW plant could be realized within the planning horizon of 2030 at an energy price of $0.07 to $0.1 per kilowatt-hour (levelized cost of energy). Annual energy production is expected to be approximately 400 gigawatt-hours (GWh) from a 280-MW plant, mainly outside the monsoon season, which supplements maximum hydropower production in the wet season.

[4] The largest plant is in Huainan, in China's eastern Anhui Province. See WEC (2017).

Nevertheless, it is unlikely that maximum output in megawatts from the Xe Kaman 1 HPP will change from the current capacity of the grid connection to Vietnam until the first phase of solar photovoltaic projects has been tested and proven successful and economical. Some additional investments may be needed in reactive compensation to maintain voltage stability. The Vietnam power system uses hydropower for daily peaking operations, and as such, the floating solar project cannot provide additional peaking power capacity to Vietnam and will not increase export capacity of guaranteed power.

Because of variable weather conditions, delivery of solar power at the time of peak demand cannot be guaranteed. Solar energy is, therefore, usually regarded as a supplement to firm power and so is likely to attract a lower price than hydropower, which delivers reliable power during peak demand.

In principle, similar floating solar plants could be introduced on other larger hydropower reservoirs in the Sekong Basin, and the technology is rapidly being introduced on an increasingly larger scale around Asia (including China and the Greater Mekong subregion).[5] The main advantage over ground- and roof-mounted arrangements is that floating plants avoid loss of land.

There is little published research on the environmental effect of floating solar because the technology is new. On nutrient-rich water it can be expected that the reduction in light caused by the surface floats would reduce local primary production of phytoplankton and so reduce risk of eutrophication. The shade could also provide refuge for fish normally subject to predation from surface or airborne predators. Conversely, a reduction in phytoplankton could cause a reduction in zooplankton and thus a decline in fishery productivity. There are likely to be some positive and some negative environmental effects, but in cases in which floating solar alleviates the need for new dam developments and regulation of river systems, the overall effect is likely to be positive.

Solar photovoltaic on a hydropower reservoir surface can provide renewable energy that involves minimal environmental and social conflict provided other reservoir users (for example, boatmen and fishermen) are involved in siting decisions. If the technology takes off by 2030, it should be viewed as a provider of additional renewable energy, not of reliable peak power. No other floating solar investments have, therefore, been incorporated into the base-case scenario, although they might be studied in the other pathways.

An assumption of 1,000 GWh of additional energy from 600 MW of ground-mounted and floating solar photovoltaic seems reasonable for future developments, but one can assume no peak power transfer in addition to what the hydropower projects can provide to fulfill export agreements.

C.5.3 Wind Power

A Thai investor group has proposed the first wind power project in Lao PDR. The 600-MW Monsoon Wind Power project will occupy 68,000 hectares in Sekong and Attapeu Provinces roughly where indicated in Map C.3. This location was chosen not only because of its promising sources of wind energy but also because of limited conflicting land use. The new transmission line for the project requires less than 40 kilometers to connect to the 220-kilovolt (kV) Électricité du Vietnam (EVN) grid in Vietnam, and export of power to Vietnam seems likely, although the Thai project sponsors are exploring options for exporting to Thailand. The investors have conducted public consultations with nearby villages; no resettlement of local communities is envisaged.

In this part of Lao PDR, average monthly wind speed is highest from October to January, when hydropower output from run-of-river plants is receding. The wind energy would therefore supplement hydropower, and it is quite likely that the project can be financed and commissioned by 2030, especially if the planned 220-kV transmission connector to Vietnam is also constructed. It is not known how much energy the plant could provide, but a reasonable estimate would be 1.5 TWh to 2.0 TWh annually. This exceeds domestic demand forecasts, and therefore it is assumed that it will become part of the planned export quota for Thailand or Vietnam, although as with floating solar photovoltaic, the output is unreliable and not suited to peak power exports.

[5] The Greater Mekong Subregion is a natural economic area bound together by the Mekong River and covering 2.6 million square kilometers with a combined population of approximately 326 million. It includes Cambodia, the People's Republic of China (specifically, Yunnan Province and Guangxi Zhuang Autonomous Region), Lao PDR, Myanmar, Thailand, and Vietnam. See Asian Development Bank, "Greater Mekong Subregion," https://www.adb.org/countries/gms/main.

Map C.3: Location of Proposed Monsoon Wind Park and Various Solar Farms

In the Sekong Basin, the largest environmental and social effects of large wind farms are likely to be from land take, new access roads and transmission lines, and the possible effect on local bird life. Installation of modern land-based wind power requires long, straight access roads to transport the more than 60-meter-long blades from the nearest port. Although the International Energy Agency has quoted a need for a land area of 60 square kilometers, only a small percentage of this land will be directly affected for access roads, foundations, and crane stand areas. The area is unlikely to include primary forest with high tree canopy because such a site would be unsuitable for wind power. It is not known how visible the turbines would be from any nearby sites of tourist interest.

C.6 Grid Expansion and Other Infrastructure

C.6.1 Transmission Lines in the Sekong Basin

The Electricité du Laos (EDL) transmission system in the Sekong Basin currently operates at 115 kV, with the main supply from the Xeset HPPs to the north of the basin and Houay Lamphan in the west on the Bolevan Plateau.

There are 230-kV transmission lines for export from Xe Kaman Sanxay going east into Vietnam and collecting power from other projects in the Xe Kaman tributary basin. Similarly, there is an export line from the Houay Ho project to Thailand and a separate export line from the Xe Pian–Xe Namnoy project to be commissioned in 2020.

C.6.2 International Grid Integration Plans

The Lao PDR Ministry of Energy and Mines, with support from international development partners, is exploring the possibility of connecting the separate power grids in Vietnam and Lao PDR. This will enable a considerable increase in ability to extract power from the Sekong region. The location and layout of the cross-border interconnection will determine the pace and pattern of development of many of the hydropower projects planned in the Sekong Basin.

The Lao PDR–Vietnam Power Interconnection Project includes extension of the 230-kV network already connected to Vietnam and run synchronously with the Vietnamese system. Three hundred and twenty-two MW from the Xe Kaman 1 and Xe Kaman Sanxay projects are already connected to Pleiku in Vietnam. The Nam Kong cascade of three power plants will add a further 270 MW when operational. There are also possibilities to connect the Sekong 3A and 3B projects and some small and medium HPPs to the same 230-kV system through 115-kV extensions from the Xe Kaman 1 substation. The design of this interconnector is expected to enable a maximum export load of 942 MW to Pleiku.

The Xe Kaman 3 project (250 MW) is connected to the EVN system at a substation at Thanhmy, north of Pleiku. The Nam Emoun project and Xe Kaman 4 would add a further 199 MW when they were completed in 2020. Up to five small hydropower projects with a total capacity of approximately 100 MW could also be connected, giving a maximum export capacity of 548 MW through this interconnector.

Both cross-border 230-kV connections will facilitate at least 1,500 MW of export to Vietnam. Alternative routes and configurations are being analyzed, with a major new switching station being planned at Hatxan near Sekong. The Lao PDR–Vietnam Power Interconnection project will fulfill the ambitions of both countries to increase power trade to 3,000 MW by 2025 and 5,000 MW by 2030. On this basis, it is likely that all of the hydro capacity proposed for the Sekong Basin can be exported to Vietnam or locally to the Lao PDR distribution system.

A long-term plan includes raising the transmission voltage to 500 kV, enabling large capacities to be exported while the grid systems of Lao PDR and Vietnam continue to operate as separate synchronous systems. Most of the Sekong mainstream projects (except Sekong 3A and 3B) must find alternative connection lines for export, including Sekong Downstream A and B, Sekong 4A and 4B, and Sekong 5.[6] The full development pathway would require export capacity for all these projects, but no information is available on how these projects will connect to Thailand or Vietnam.

C.7 Power Demand and Hydropower Operation and Dispatch

C.7.1 Institutional Set-Up

The power sector in Lao PDR is organized under the Ministry of Energy and Mines and the government-owned utility EDL. Pertinent features of the Lao PDR power system are summarized below:

- State-owned transmission and distribution network managed by a central electricity authority (EDL)
- Total electrical energy consumption in 2017 of 5,000 GWh
- Ninety-five percent electrification ratio but low per capita consumption of 600 kilowatt-hours per year
- High transmission and distribution losses
- Network connections with Thailand, China, and Vietnam
- Independent power producers owning most generation capacity
- Most independent power producer generation (>4,000 MW) exported to Thailand and Vietnam
- EDL transmission grid comprising three weakly connected power systems

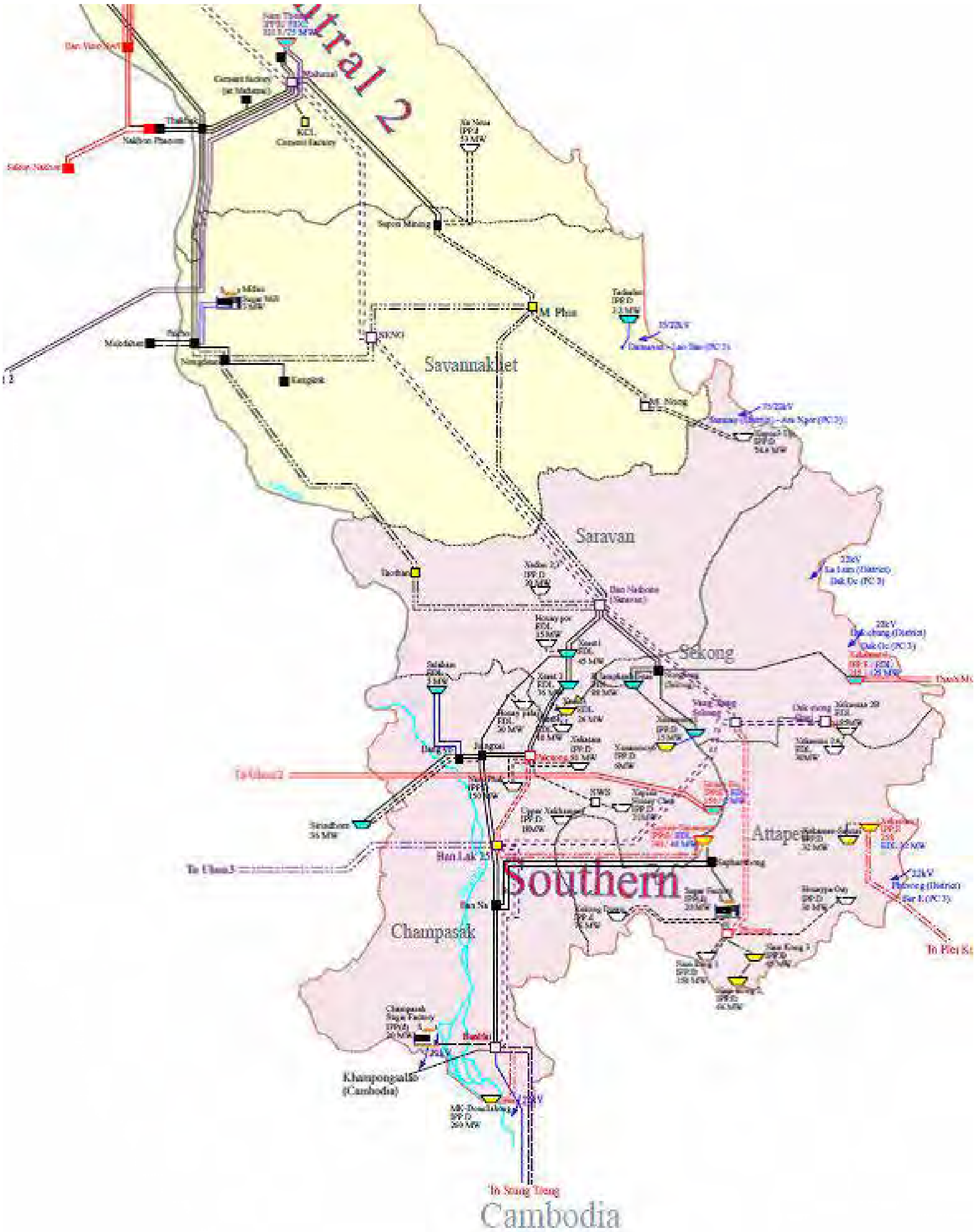
For the Sekong cumulative impact assessment study, it is relevant to focus on the southern power grid and the transmission interconnections with Thailand and Vietnam. Although it is likely that the separate EDL power grids will be strengthened and operating under a single EDL dispatch center

[6] The power destination is Lao PDR for Sekong Downstream A and B and Thailand for Sekong 4A, 4B, and 5.

by 2030, the EDL grid development has little relevance for the power sector base-case pathway definition. Because additional domestic electricity demand in Lao PDR is minimal, projects exporting peak power to Thailand and Vietnam will dominate hydropower development in the Sekong River Basin. This report therefore describes the expected power sector scenario for the basin in terms of each of the three countries: Lao PDR, Thailand, and Vietnam. Cambodia is expected to continue using domestic power resources rather than depend heavily on import from Lao PDR and is therefore not discussed here.

The southern EDL grid is at 115 kV and supplies only to the western part of the Sekong Basin (Map C.4). The eastern part is supplied from Vietnam and is therefore controlled from the Vietnamese dispatch center.

Map C.4: Power System (115 kV) of the Lao People's Democratic Republic, 2017



Note: Red lines are 230-kV lines for export.

C.7.2 Power Supply and Demand in Lao PDR

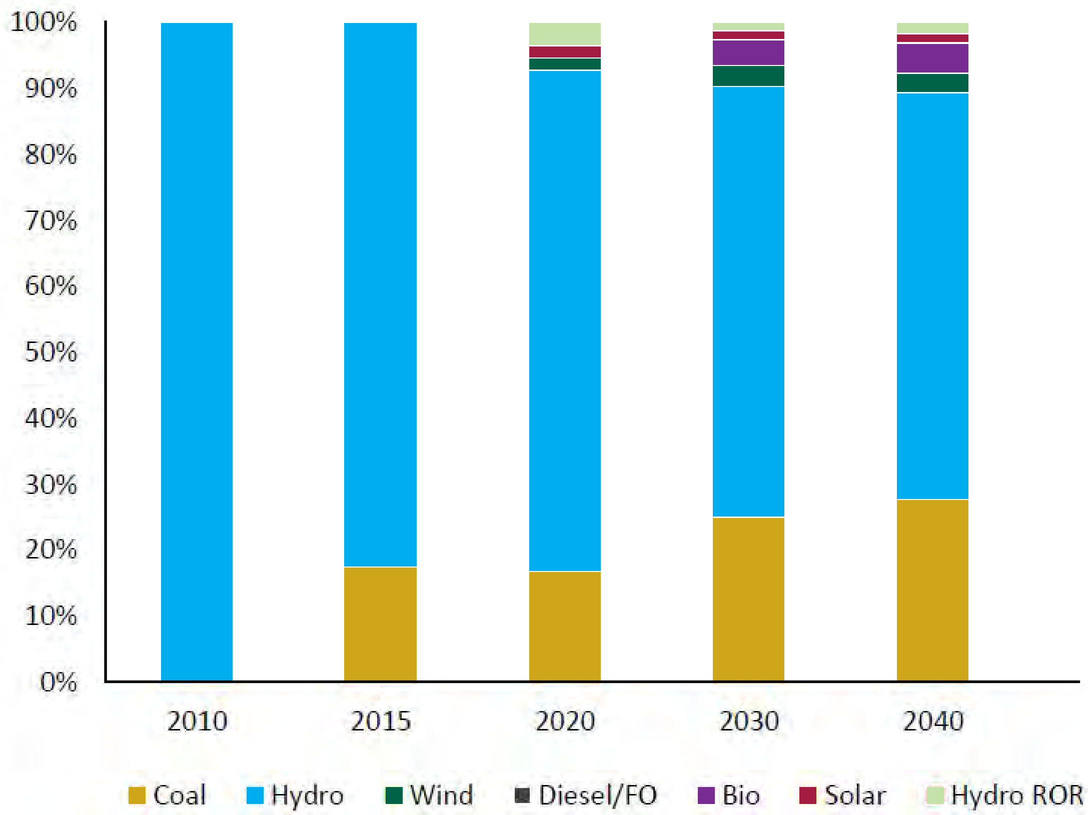
Until 2015, hydropower, predominantly from the Nam Ngum plant, which has a large reservoir and can therefore provide a reliable year-round supply, entirely supplied the Lao PDR power system. There will be a gradual reduction in dependence on hydropower to 65 percent by 2030, with the remainder being met from coal-fired thermal plants and some solar photovoltaic and wind farms. The 1,878-MW Hong Sa coal-fired plant in northwestern Lao PDR already provides some power to EDL and exports the remainder to Thailand. Figure C.2 presents Lao PDR's anticipated power generation mix.

Annual growth in energy demand has been in double digits since 2012 but from a low base. Growth in energy demand slowed to 6.5 percent from 2016 to 2017, and because electrification of rural areas nationwide is nearly complete, annual rate of growth to 2030 is not expected to exceed that. Demand from the southern regions of Lao PDR is expected to grow in the coming years but not as fast as from the central region, where demand will increase from Vientiane, Luang Prabang, and tourist centers in the north. How fast demand in the south grows will depend largely on the pace of investment in the numerous mining concessions awarded. Assuming 6 percent annual growth on average, national demand will be approximately 10 TWh in 2030 but still with only a minor portion in the south. All proposed larger hydropower projects in the Sekong Basin are expected to seek export power purchase agreements with the Electricity Generating Authority of Thailand or EVN.

The 115-kV EDL system extends south to Stung Treng in Cambodia near the confluence of the Sekong and Sesan rivers. This provides for some export potential to Cambodia, but that may not continue once the lower Sesan hydropower project in Cambodia is commissioned.

The potential for large-scale export from Lao PDR to Cambodia is not likely to be significant until the 500-kV regional interconnector system is in place after 2030.

Figure C.2: Anticipated Power Generation Mix for Lao PDR (Until 2040)



Source: IES and MKE 2016.

Note: FO = fuel oil; ROR = run-of-river.

C.7.3 Power System in Thailand

The latest available data on the Thai power system are from 2017, when peak demand was close to 28,578 MW. The power forecast released in 2015 indicated that this would rise to more than 44,400 MW by 2030, but this might need to be revised downward because gross domestic product has slowed, and power demand stagnated from 2016 to 2017.

Nonetheless, based on the latest official power forecast, there are many plans for adding capacity to the Thai power system. To offset retirement of older plants, more than 57,400 MW of new capacity is needed by 2036, of which some 23,700 MW is expected to come from renewables, including hydropower, meaning that the need for new thermal capacity is therefore nearly 34,000 MW.

Thailand has only 2,952 MW of hydropower capacity, and its remaining unexploited hydropower resources are limited. Therefore, imports from HPPs in neighboring countries are required, particularly to provide a fast response to variations in peak demand. In 2017, nearly 20 independent power producer HPPs (>15 MW) were operating in Lao PDR, supplying approximately 3,500 MW of power to Thailand during peak demand periods. Of these, only the Houay Ho project (152 MW) lies in the Sekong Basin; the others are in central Lao PDR. The 1,285-MW Xayaburi project north of Vientiane will come online soon, and 1,225 MW is to be exported from it to Thailand. The 410-MW Xe Pian–Xe Namnoy project will also come online soon. There are 1,800 MW of export capability from the Hongsa coal-fired plant in the north. Thailand has agreed to import 9,000 MW from Lao PDR by 2030, but only 2,000 MW of the agreed-upon 9,000 MW is not yet allocated to specific projects, so the new Sekong projects (after Xe Pian–Xe Namnoy) are hoping to fill this 2,000 MW. The receiving power utilities in neighboring countries will decide how much power they need, and when they need it, as is the case for many of the existing hydropower projects in Lao PDR.

C.7.4 Power System in Vietnam

The latest available data on the EVN power system are from 2017, when annual energy demand was approximately 186 TWh. Peak power demand was close to 20,000 MW in 2013 and was probably approaching 30,000 MW in 2017. Energy demand seems to be growing steadily at 10 to 15 percent annually based on annual gross domestic product growth of approximately 7 percent.

Total hydropower and pumped storage capacity was approximately 16,000 MW in 2017 in more than 30 different large hydropower projects. Despite plans to introduce an additional 5,000 MW of new hydropower by 2030, the share of hydropower and pumped storage will fall from 30 percent to near 15 percent by 2030 because of ambitious plans for 6,000 MW of new wind power and 12,000 MW of solar power.

There are many undeveloped hydropower sites in Vietnam, but there is a trend to develop multi-purpose reservoirs where flood control as well as hydropower is an important benefit. The latest power development plan indicates a need for close to 500 TWh of annual energy and 127,000 MW of capacity by 2030, almost triple current capacity. The main supply of Vietnamese power is from coal- and gas-fired thermal plants, accounting for 63 percent of energy supplied at present, increasing to 70 percent by 2030. Normally, renewables provide less energy than thermal power plants, having plant utilization factors of 15 to 40 percent. Thermal energy will remain the backbone of Vietnam's power system and the provider of base load power.

Available reports do not indicate how much of the new hydropower capacity is expected to come from imports from Lao PDR, but hydropower projects will retain their role as suppliers of reliable peak power to the Vietnamese power system while thermal plants provide the base load.

Much of this imported power (around 900 MW) is expected to come from the Xe Kaman tributary to the Sekong River, where 570 MW is being supplied from three already operating power plants. There are plans for a further 200 MW in three new HPPs on the Xe Kaman and a new cascade on the Nam Bi tributary, including 130 MW in three separate power stations.

All of these plants are expected to be synchronized with the south Vietnamese grid, and decisions about power generation (dispatch) is effectively made from Vietnam. This situation is expected to continue beyond 2030, meaning that there will be two separate power systems serving power plants and substations in the Sekong Basin: one run by EDL and one by EVN. It is expected that the EVN system will require short-term variability in output from its HPP generators, meaning that flows below EVN-connected hydropower stations will vary rapidly as the EVN dispatch center ramps the units up and down.

Table C.12: Power Demand in Lao People's Democratic Republic, Thailand, and Vietnam, 2017

Demand	Lao PDR	Thailand	Vietnam	Lao PDR % of total
Megawatt peak	928	28,578	(29,500)	1.5
Annual terawatt-hours	5	189	186	1.3
Megawatt hydropower installed	4,700	2,952	(16,000)	20.0
Hydro annual terawatt-hours	22	4	(60)	25.6

Note: Values extrapolated from older data.

Some import agreements already require a wheeling of power through Vietnam to supply towns and rural centers elsewhere in Lao PDR. This situation will prevail for a few years until construction of the Lao PDR–Vietnam transmission interconnector described.

C.7.5 Power Export to Vietnam and Thailand

Current power demand in all three countries is compared in Table C.12. Lao PDR accounts for less than 2 percent of aggregate demand from all three countries and 20 to 26 percent of hydropower capacity. Base load production is from coal- and gas-fired thermal power plants, with hydropower providing flexibility to cover peak demand during weekday and evening peak load periods. This in turn means that output from Lao PDR HPPs for export to Thailand and Vietnam varies greatly from hour to hour.

Export and import intentions from each country's power development plan are summarized in Table C.13. Lao PDR plans to export 11,700 MW of power to Thailand and 841 MW to Vietnam by 2040. In contrast, the power development plan for the Electricity Generating Authority of Thailand shows only a little more than 4,200 MW imported from Lao PDR—a mismatch of approximately 7,500 MW.

Vietnam plans to import more than 1,500 MW of power from Lao PDR by 2040, which could be met from hydropower projects in the Sekong Basin, including on the Xe Kaman and Nam Bi tributaries.

If the mismatch in Thailand is confirmed, there will be approximately 7,500 MW of hydropower projects not likely to reach a power purchase agreement to export to Thailand, and many of these may be in the Sekong River Basin.

C.7.6 Xe Kong Kalum Thermal Power Plant for Export to Vietnam and Associated Coal Mining

There are plans to develop a large-scale coal-fired power plant for export to Vietnam, based on anthracite found in the Sekong Basin. Concession agreements for mining coal have been granted and extend over large parts of Kalum District. If developed, there could be up to 1,800 MW installed, although there is doubt whether proven resources will be sufficient for more than 900 MW. The Kalum project is mainly for export to Vietnam through a dedicated interconnector or through the stage 2 network upgraded to 500 kV. Because the exact location and size of the power plant is unknown, this power plant is not included in the study.

Table C.13: National Power Development Import Plans in the Mekong Region

NATIONAL PDP IMPORT PLANS

Planned					
MW	From				
To	Cambodia	Laos	Thailand	Vietnam	
Cambodia	1,620	-	-	-	1,620
Laos	-	7,602	-	-	7,602
Thailand	-	4,274	745	-	5,019
Vietnam	-	1,554	-	2,607	4,161
	1,620	13,430	745	2,607	18,402

Difference from Current Plans pathway - 2040					
MW	From				
To	Cambodia	Laos	Thailand	Vietnam	
Cambodia	-	(85)	-	-	(85)
Laos	-	-	-	-	-
Thailand	-	(7,465)	-	-	(7,465)
Vietnam	(3,150)	713	-	-	(2,437)
	(3,150)	(6,838)	-	-	(9,988)

Source: MRC 2018.

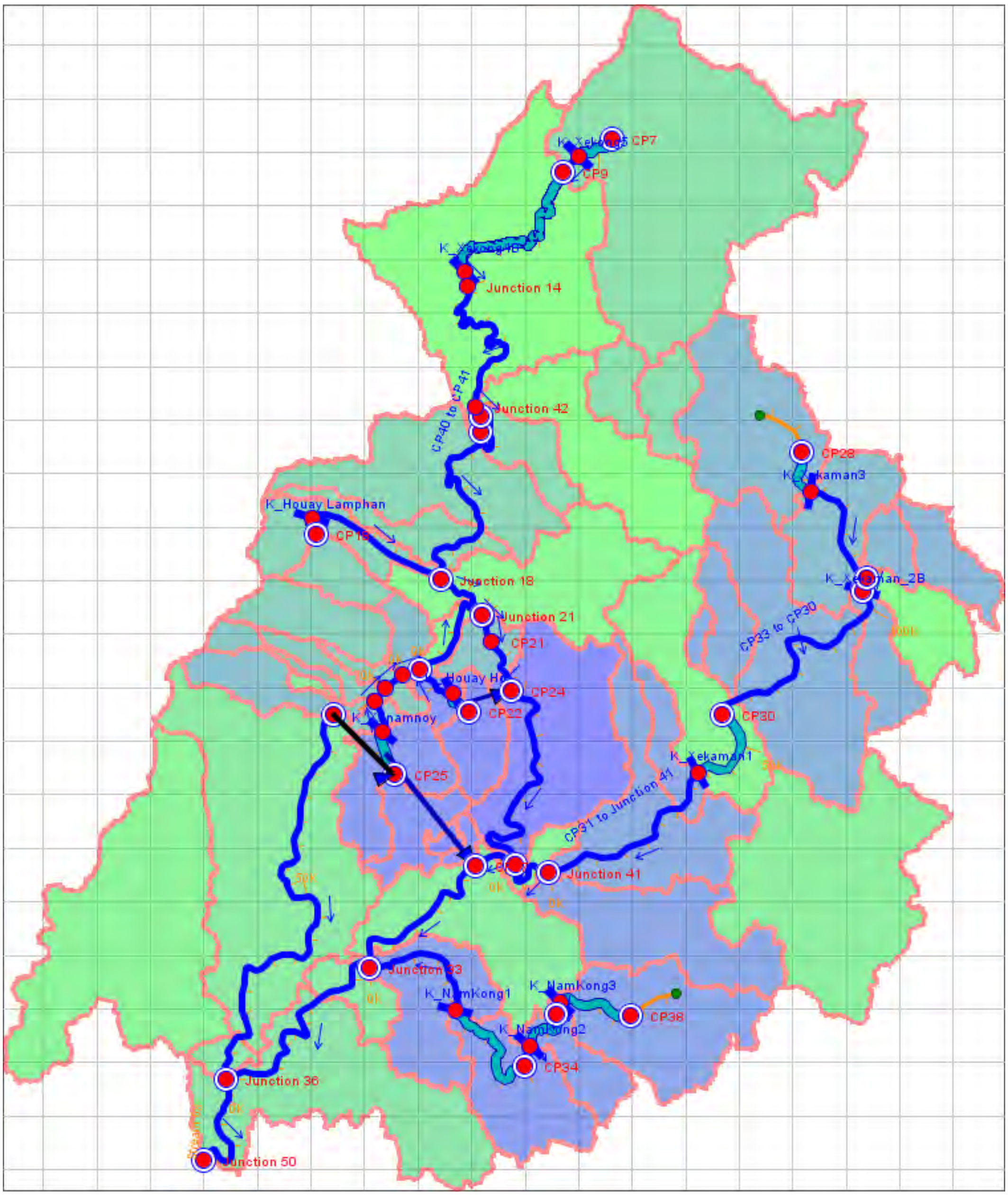
Note: PDP = Power Development Plan

APPENDIX D
WATER BALANCE MODELING

D.1 Model Set-Up

Reservoirs have been modeled using the U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) water balance modeling software. A HEC-ResSim model was created using up-to-date information on existing and planned hydropower projects in the Sekong Basin (Appendix B). Map D.1 shows the new model configuration.

Map D.1: Screenshot of Model in U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center Reservoir System Simulation



The aim of the modeling is to ascertain seasonal flow variation caused by storage reservoirs. Only the 12 largest reservoirs are included in the model. Smaller reservoirs are expected to operate as run-of-river or daily peaking reservoirs and do not affect daily mean flows significantly. The 12 reservoirs included in the model are shown in Table D.1.

The model is run with hourly time steps, but output is exported as daily time steps. There is no river routing in the model, so the exact timing of some flood peaks may be a day or so earlier than in the field.

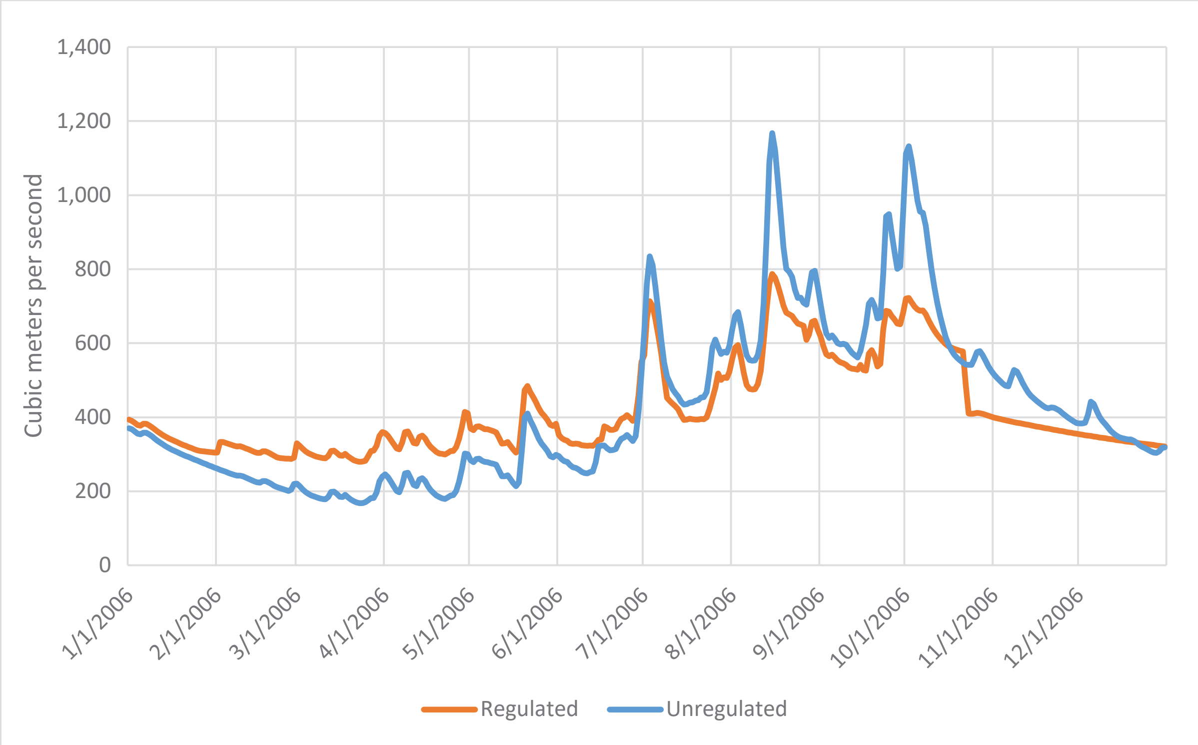
Real-life operation of hydropower plants and reservoirs depends on details of power purchase agreements, which are project specific. We decided to model reservoir operations to make the flow as even as possible because this is understood to be a standard requirement; see, for example, the publicly available Xe Pian–Xe Namnoy power purchase agreement. The power station release cannot exceed maximum station outflow and has been selected never to empty the reservoir completely. This is expected to give close to optimal firm energy production, which is the goal of developers exporting to Thailand and Vietnam. An example of this is shown in Figure D.2.

Table D.1: Reservoirs Included in the HEC-ResSim Model

Name	Full supply level (meters above sea level)	Minimum operating level (meters above sea level)	Active reservoir volume (m^3)	Active reservoir (% of annual inflow)
Houay Lamphan Gnai	820	795	141	34
Nam Kong 1	320	287	505	38
Nam Kong 2	427	420	29	3
Nam Kong 3	542	521	471	52
Xe Kaman 1	230	218	1,683	36
Xe Kaman 2B	370	340	217	10
Xe Kaman 3	960	925	109	12
Houay Ho	883	861	527	176
Xe Pian–Xe Namnoy	787	745	908	71
Sekong 4A	200	180	460	6
Sekong 4B	291	277	180	4
Sekong 5	485	440	1,145	29

Note: m^3 = cubic meters.

Figure D.2: **Flow into and out of Xe Kaman 1 Reservoir in Average Year**



D.2 Water Balance Assessment and Results

Four pathways have been modeled: present situation, full development pathway, intermediate development pathway, and conservative development pathway. In addition, HEC-ResSim models natural (unregulated) flow. We also modeled for climate change 2090 using two different climate models for the full development pathway. (See Map 5.1, Chapter 5, for a visual representation of the full development pathway.) These results are presented in terms of major tributary rivers and the Sekong mainstream at various points of interest.

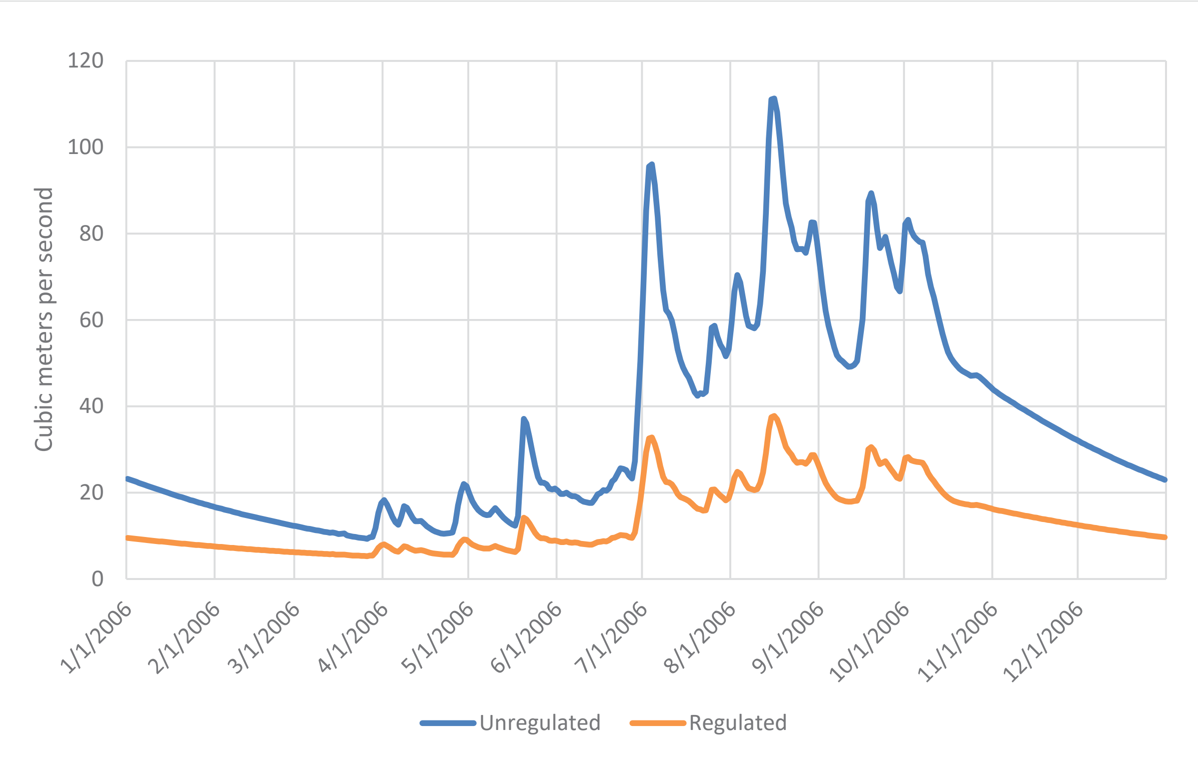
The assessment of cumulative effects is summarized in terms of degree of hydrological modifications caused by all reservoirs, river diversions, and hydropower plants included in each of the pathways. Degrees of modification have been assigned for each stretch of river or tributary based on alteration of flood regime and of low flows.

D.2.1 Xe Namnoy, Xe Pian, Xe Katam, and Houay Ho Tributary Rivers

These tributaries are the subject of extensive hydropower development, but the greatest single hydrological effect comes from the large seasonal Xe Pian–Xe Namnoy reservoir, which captures and diverts much of the flow in the headwaters (Figure D.3).

A significant reduction in flow will be observable in the Xe Pian River downstream of the dam. The residual Xe Namnoy flow at the confluence with the Xe Katam will be more than halved and flood peaks reduced to approximately 35 percent of their natural values. Despite inflows from the Xe Katam reservoir, there will be an overall reduction in flow in the Sekong River below the confluence with the Xe Namnoy. Further downstream, at the outlet from the Xe Pian–Xe Namnoy power plant, the flow in the Sekong River will again increase.

Figure D.3: Regulation of Flows in the Xe Namnoy River as a Result of the Xe Pian–Xe Namnoy Reservoir (from 2020 in All Pathways)



D.2.2 Xe Kaman, Nam Bi, and Nam Ang Tributary Rivers

The large Xe Kaman 1 reservoir has a substantial seasonal regulating effect on the Xe Kaman River below the Xe Kaman Sanxai power plant (Figure D.4). This reservoir dominates regulation of the river and is large enough to capture most of the monsoon floods except in very wet years. Depending on how the reservoir is being operated, there will be a two- to four-month delay in flood water moving downstream. Floods will be much smaller and later, even in wet years. In dry years, no flood rise may occur at all. Low-flow situations will be changed substantially, with minimum flows being as much as five times as great.

One new seasonal storage reservoir, the Xe Kaman 2B, upstream of the Xe Kaman 1 reservoir, will have a small additional effect that reinforces the changes described above, but the effect of the Xe Kaman 1 reservoir will overshadow that. There are six other projects planned upstream, but all will have minimal reservoir storage for hourly peaking operation. Because of the limited additional cumulative effect on flow regulation, the seven planned projects located upstream of the Xe Kaman 1 reservoir have been included in all development pathways.

The Xe Xou tributary enters the Xe Kaman just before its confluence with the Sekong mainstream. The Xe Xou has much of its catchment in the Dong Amphan National Protected Area and is assumed to be unregulated in all development pathways. It contributes significantly to volatility in the lower Xe Kaman during the wet season (June–October, Figure D.5). Although the regulating effect of dams in the Xe Kaman catchment suppresses flood peaks, the Xe Xou (if unregulated) will have an important role in providing flood pulses and sediment transport within the lower Sekong Basin.

Figure D.4: Flows Downstream of the Xe Kaman Sanxai Power Plant

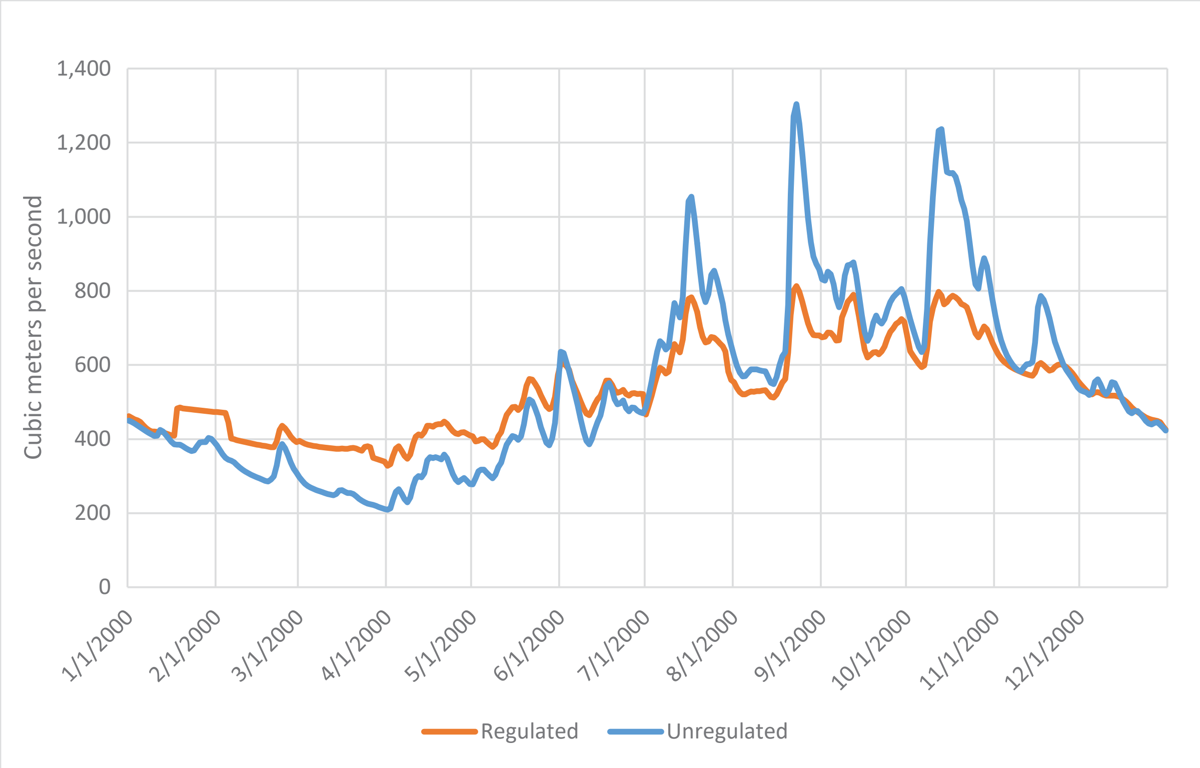
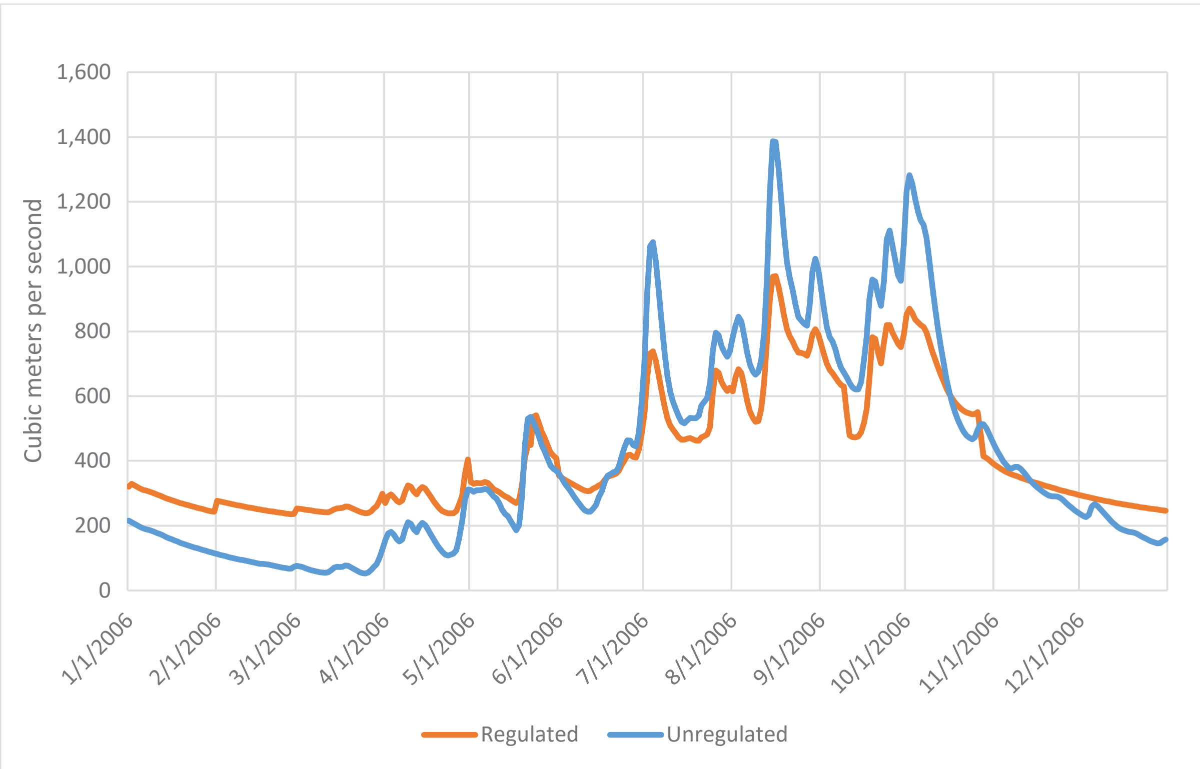


Figure D.5: Effect of Existing Reservoirs on Flows in the Xe Kaman Below Confluence with Xe Xou



D.2.3 Upper Sekong

The Upper Sekong has only one diversion reservoir on the Vietnamese side of the border. This A Luoi project regulates the upper reaches of the Sekong and transfers water to the Vietnamese rivers flowing eastward to the Vietnamese coast. It is not known what releases are being made to the Sekong River from the dam, but for illustration purposes, we assumed in the model that no flow is being released down the Sekong. The catchment for A Luoi is not included in the Hydrologic Engineering Center, Hydrologic Modeling System (HEC-HMS) or HEC-ResSim models.

The present situation (2020) shows close to natural flow variability along the upstream Sekong. Major changes in flow regime occur if the Upper Sekong portfolio (Sekong 5 and 4B) is built as in the full development and intermediate pathways. These reservoirs are much larger than the inflow and will be able to almost completely regulate Upper Sekong flows, removing flood events in almost all years.

Even in wet years, arrival of the flood peak will be delayed until both reservoirs have been refilled, and some flood spill may occur as late as December in very wet years. The typical flow regulation in the full and intermediate development pathways is shown in Figure D.6.

D.2.4 Nam Emoun Tributary River

The Nam Emoun tributary drains a catchment area of 462 square kilometers at the confluence where the Nam Emoun project is under construction. There is no large seasonal reservoir planned on this tributary, so there will be no observable changes in the flow regime along the Nam Emoun except for the effect of peaking operation on hourly flow variations immediately below the new power plant.

The planned Sekong 4A project will collect and regulate runoff from the Upper Sekong and the Nam Emoun; the result below this dam is shown in Figure D.7.

If we consider the flow regime of the mainstream Sekong north of Attapeu above the confluence with the Xe Kaman, we observe contributions from unregulated tributaries, but several other factors influence the flow regime (Figure D.8). First, the power plant has diverted regulated inflow from the Xe Pian tributary that is delivered into the Sekong downstream of Attapeu and the confluence with Xe Kaman and Xe Xou. We assume this flow is relatively constant all year round. Second, the effect of regulating reservoirs in the full development pathway is still visible in delaying flood peaks by two months and reducing their magnitude.

Figure D.6: Effect of Upper Sekong Portfolio on Flows Above Confluence with Nam Emoun

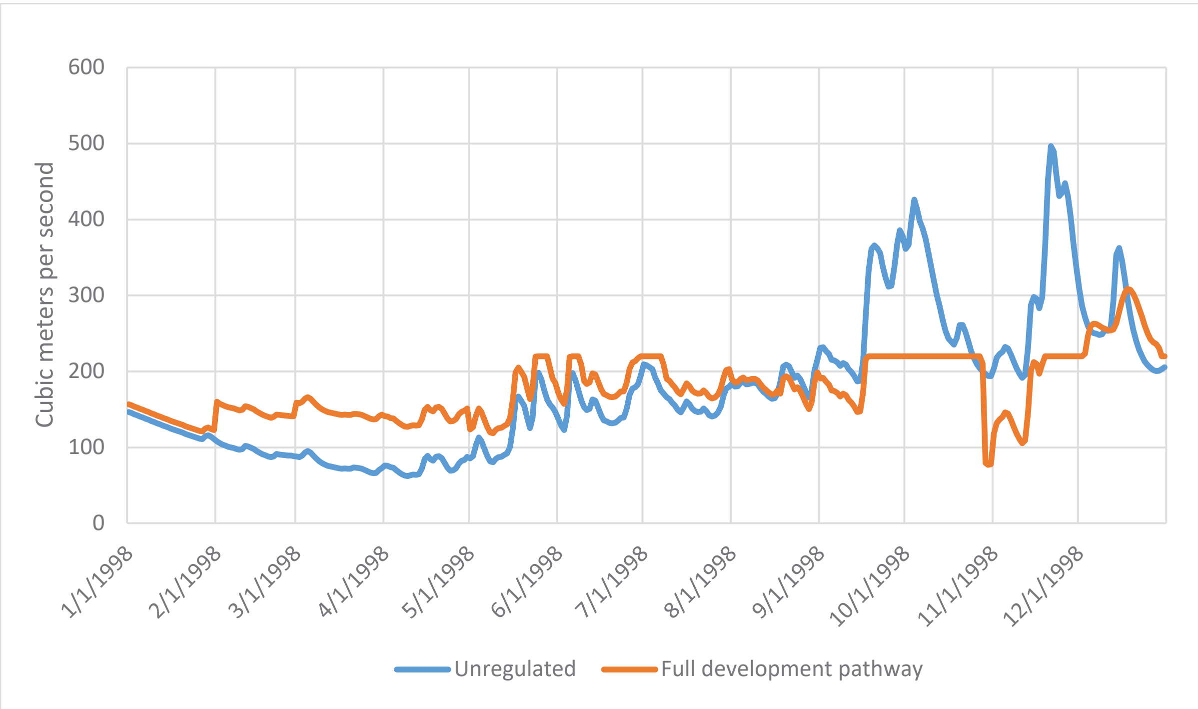
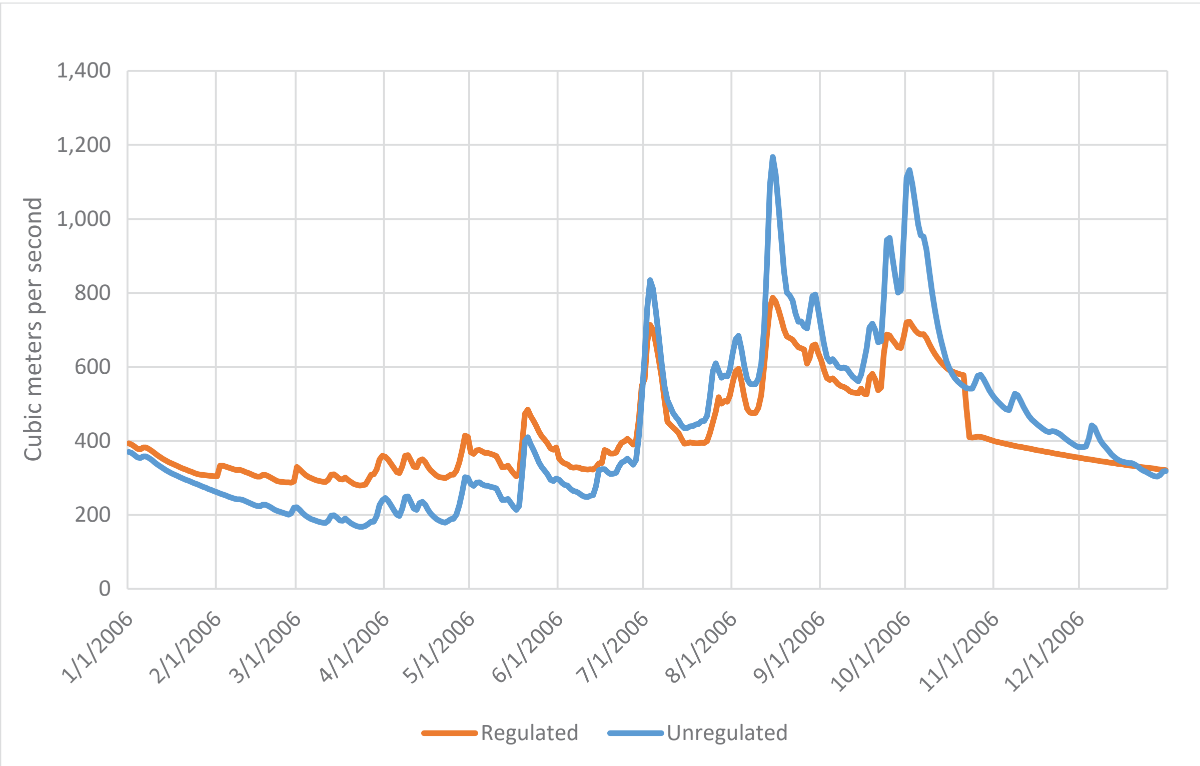


Figure D.7: **Flow Regulation Below Sekong 4A**

Figure D.8: **Flows in Sekong North of Attapeu Above Xe Kaman Confluence, Regulated and Unregulated**



D.2.5 Nam Kong Tributary

The large Nam Kong 3 reservoir already substantially regulates the Nam Kong tributary, which will be even more regulated after the impoundment of another large reservoir, Nam Kong 1, the furthest downstream of the cascade of three dams.

Figure D.9 shows the substantial effect these reservoirs have on the flow regime in the downstream Nam Kong. Assuming the reservoirs are operated as seasonal regulating reservoirs, they will capture flood runoff in all normal and dry years, with only occasional late spills of flood waters in October if the reservoirs have all been filled. The frequency and magnitude of flood peaks will be greatly reduced, as will sediment transport past the dams. The river geomorphology below these dams will experience some of the largest changes anywhere in the Sekong Basin, with steady flows all year round and rare flood peaks occurring three to four months later than before.

D.2.6 Lower Sekong

In the lower Sekong River below the confluence with the Nam Kong, the low-flow situation changes considerably as a result of flow regulation from the Xe Pian–Xe Namnoy power plant and from the heavily regulated tributaries of Xe Kaman and Nam Kong. Under the full development pathway, in which seasonal reservoirs regulate all upstream tributaries and the Sekong mainstream, the only tributary providing sediment and some flow variation is the Xe Xou.

To illustrate the effect of flow regulation that hydropower reservoirs provide, an average hydrological year has been simulated (Figure D.10) for three scenarios: unregulated, moderately regulated, and highly regulated flow. Moderately regulated takes into account the hydrological effect of three large tributary hydropower projects: Xe Kaman 1, Xe Pian-Namnoy, and Nam Kong 3. Highly regulated adds the proposed Sekong mainstream hydropower projects.

Figure D.9: **Flows Below Nam Kong 1 Power Plant After Completion**

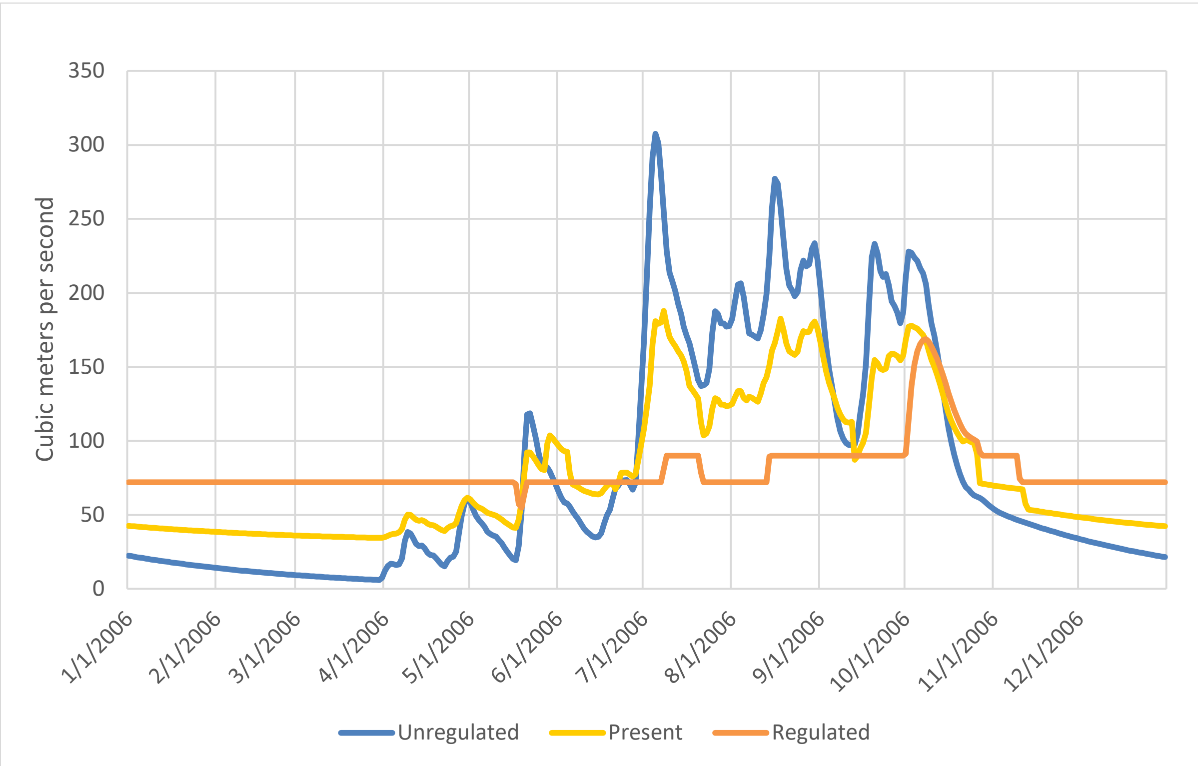
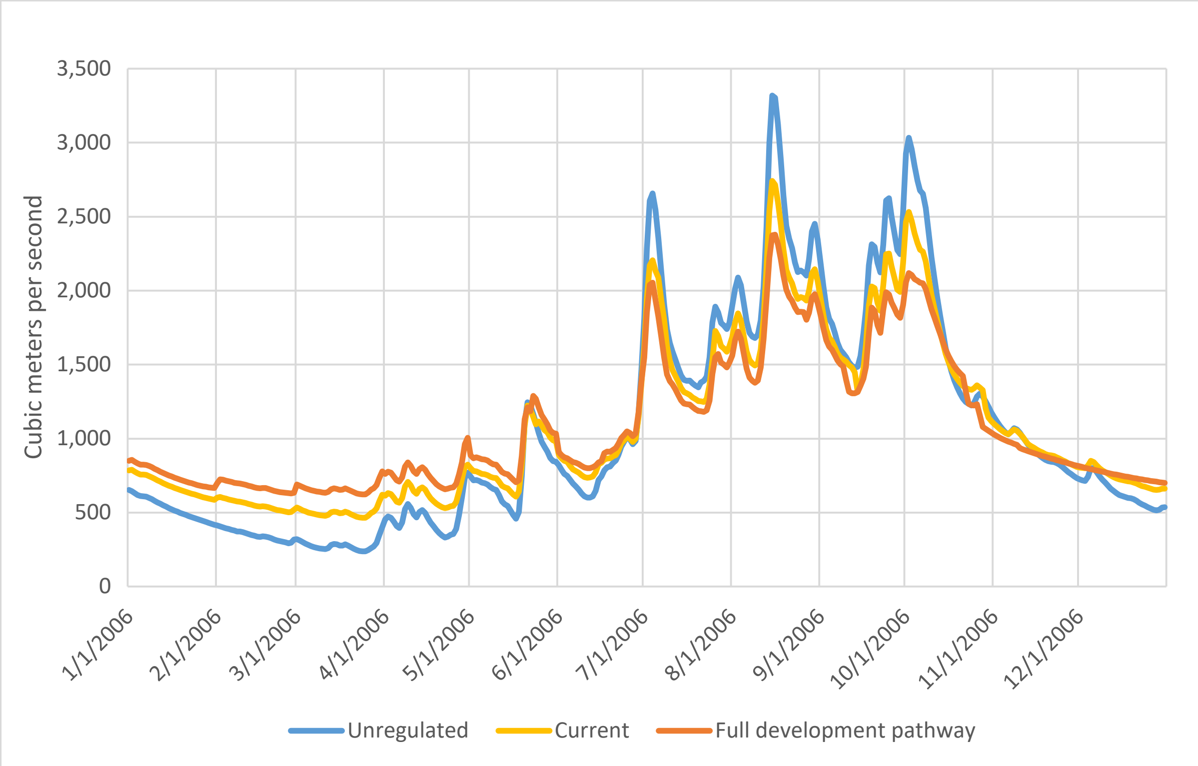


Figure D.10: Flow Regimes Below Nam Kong Confluence in Average Year

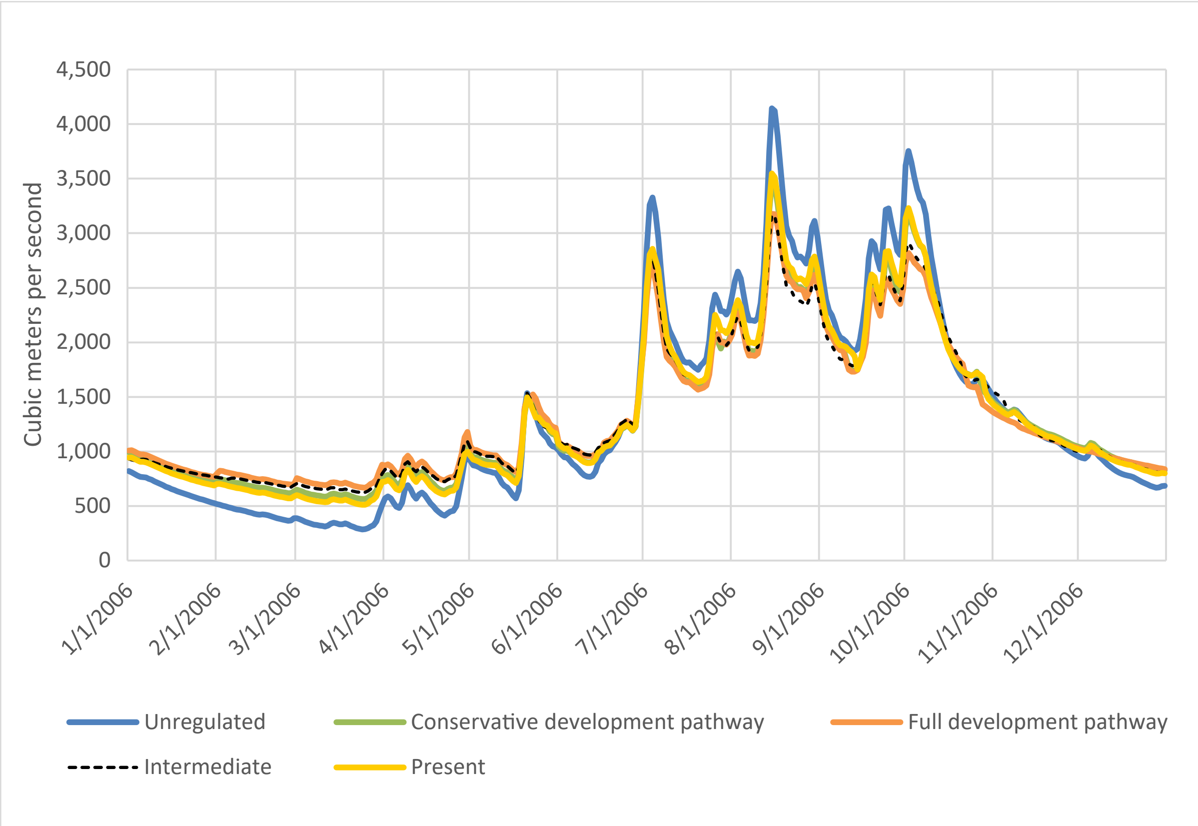


D.2.7 Lower Sekong After Entering Cambodia

After the confluence with the Xe Pian and Xe Khampho rivers, the Sekong leaves the Lao PDR and becomes a Cambodian river, where the aggregated effect of various development pathways can be seen (Figure D.11). The largest observable change is the low-flow month of March, when low-flow values nearly double. Peak flood levels are approximately 500 to 1,000 cubic meters per second lower, but this is less than 20 percent less than today's flood peaks. There is little indication of significant delays in arrival of the rising flood or the flood peak because the large tributaries of the Nam Emoun, Xe Xou, Nam Kamphon, and the lower part of the Xe Pian River still contribute as free-flowing rivers.

A slight difference is observed in how the Sekong 5 and 4B reservoirs regulate flows under the full and intermediate but not the conservative development pathway. The flow volatility of the free-flowing tributaries mentioned above remains dominant over the seasonal regulating effect of these two upstream regulating reservoirs.

Figure D.11: **Flow Regimes Below Border with Cambodia Under Various Pathways, Showing Effect of Upper Sekong Regulating Reservoirs**



APPENDIX E
SEDIMENT MODELING AND ASSESSMENT

E.1 Model Set-Up

E.1.1 Brune's Curves

Multiconsult's Seditrans-Brune model is a nodal model for reservoir sedimentation based on Brune (1953) curves for sediment transport.

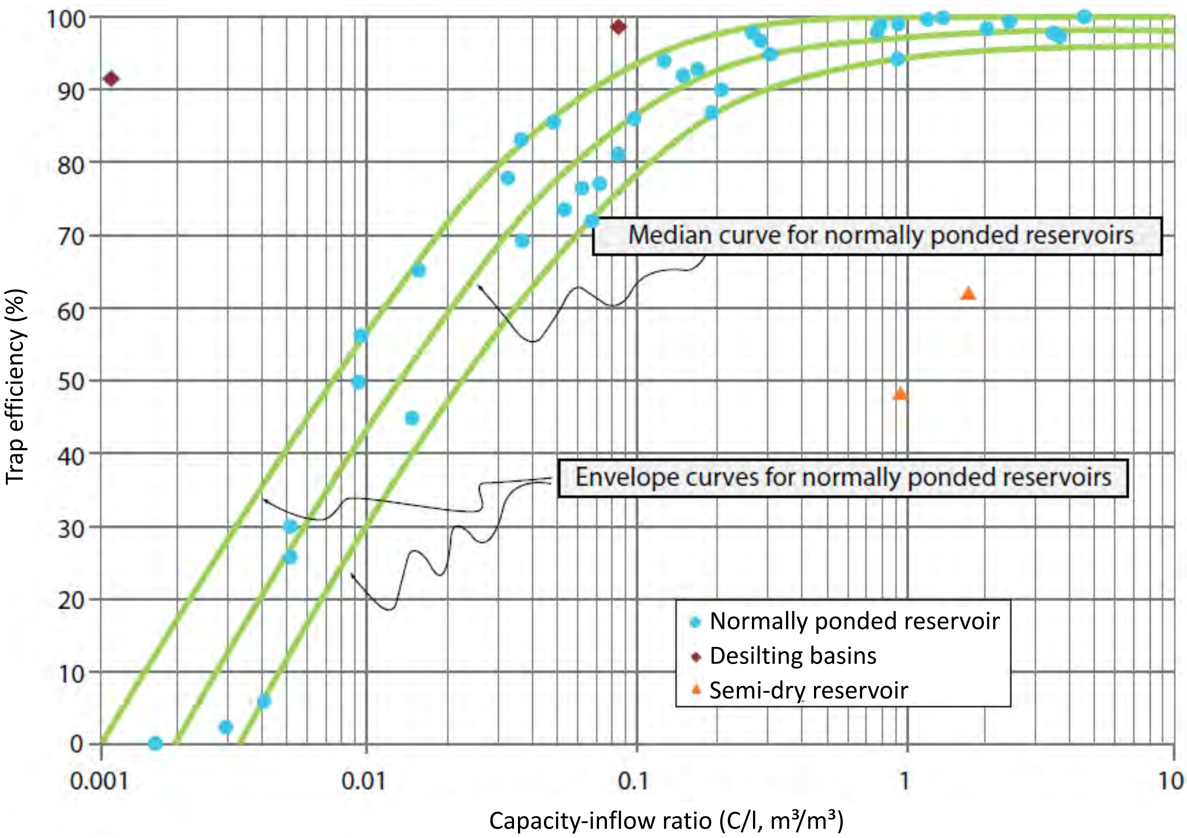
Brune's curves are widely used in estimating sedimentation of reservoirs. Brune developed curves relating trap efficiency to the ratio of reservoir volume to annual average inflow (Figure E.1). Trap efficiency depends on sediment grain size. The trap efficiency of coarse sediments (sand and gravel) is greater than the trap efficiency of fine sediments (silt and clay). Brune's curves include curves for coarse and fine sediments and a median curve.

Under the full development pathway, sediment grain size was assumed to follow the median curve in the Brune trap efficiency curves. Additional models were run with curves for fine and coarse sediments.

Initial reservoir volume determines initial trap efficiency. When the reservoir is filled with sediment, reservoir volume decreases, which decreases trap efficiency.

The model has annual time steps to take into account that trap efficiency decreases as reservoirs fill with sediment. Thus, it tracks the gradual build-up of sediment in each reservoir over its design lifetime (normally 100 years) based on the following simplified generalized assumptions:

Figure E.1: Brune's Curve for Trap Efficiency of Normally Ponded Reservoirs



Source: Brune 1953 in Efthymiou et al. 2017.

Note: C/I = capacity/inflow; m³/m³ = capacity and inflow use of same units , cubic meters.

Table E.1: Source of Bulk Density Assumptions for Sekong Sediment Transport Mode

Operational condition	Initial weight (kilograms per cubic meter)		
	W_C	W_M	W_S
Continuosly submerged	416	1,120	1,554
Periodic drawdown	561	1,140	1,554
Normally empty reservoir	641	1,150	1,554
Riverbed sediment	961	1,170	1,554

Source: Annandale et al. 2016.
Note: W_C = weight of clay; W_M = weight of silt; W_S = weight of sand

- The entire catchment has an assumed constant and homogeneous sediment yield of 280 tons per square kilometer per year, as predicted for the Kon Tum massif (Kondolf, Rubin and Minear 2014).
- An average bulk density of 1.5 tons per cubic meter was used to convert incoming load to sediment volumes, based on a predominance of sand being trapped (Table E.1).
- Different curves for fine, coarse, and mixed sediment fractions can be applied in the model, as Brune documented, and the volume of sediment trapped is subtracted from the available free water volume of the reservoir for the following year.
- All reservoirs were assumed to be at highest regulated water level when most of the sediments arrive in the monsoon season. A sensitivity test reducing the reservoir level of the largest five reservoirs to the lowest regulating water level showed negligible change in sediment accumulation and transport downstream.
- In the full development case, no flushing of sediments was assumed, so Brune's curves were applied with no modifications. In a mitigation analysis, the effect of applying sediment management by flushing through bottom outlets was studied.
- A compaction factor of 1.0 was applied in the full development case for coarse sediments (no compaction assumed), but a compaction factor of 0.8 was applied for very fine sediments to represent the long-term compaction of finer sediment normally experienced in deeper reservoirs. Sensitivity tests demonstrated that this had negligible effect on the transport downstream.

E.1.2 Model Overview

The model includes 17 reservoirs. Figure E.2 shows a schematic overview of the reservoirs and the relationship between them.

E.1.3 Key Data for Reservoirs

Key data used for the model include total reservoir volume (dead and active volumes), catchment area, and annual inflow. Data used are shown in Table E.2.

Figure E.2: Schematic Overview of Reservoirs Included in Model

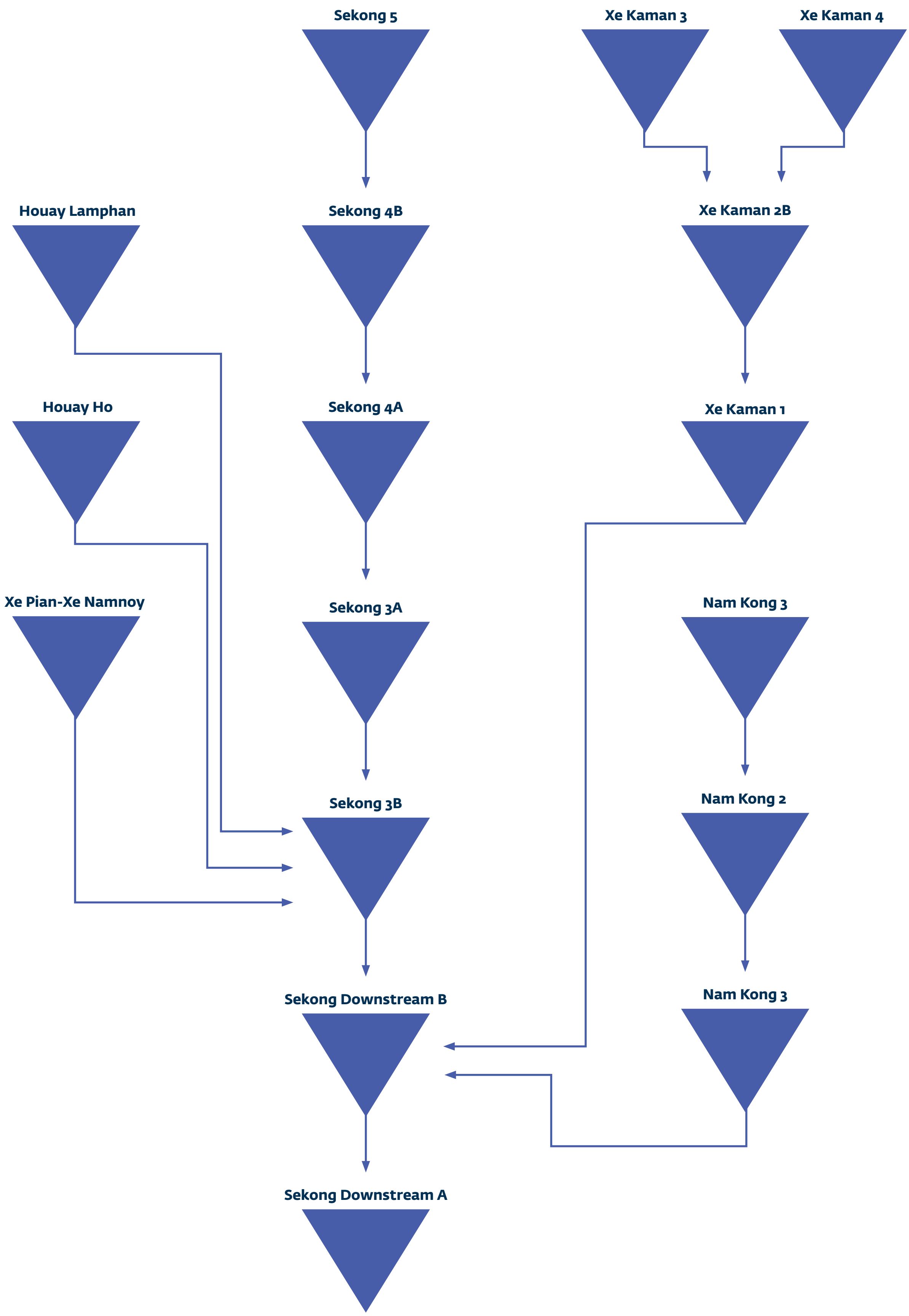


Table E.2: Key Data for Reservoirs Used in Sediment Simulations

Name	Catchment area (km²)	Mean annual inflow (m^3/s)	Total reservoir volume (m^3)	Capacity-inflow ratio (%)
Houay Lamphan Gnai	237	11	481	134
Houay Ho	192	10	674	225
Xe Pian–Xe Namnoy	820	43	1,072	80
Sekong 5	2,518	125	3,300	84
Sekong 4B	2,758	132	634	15
Sekong 4A	5,182	227	655	9
Sekong 3A	5,800	209	187	3
Sekong 3B	8,733	316	168	2
Sekong Downstream B	9,594	399	105	1
Sekong Downstream A	18,800	796	92	0
Xe Kaman 3	712	30	142	15
Xe Kaman 4	216	10	19	6
Xe Kaman 2B	1,740	68	349	16
Xe Kaman 1	3,580	149	4,804	102
Nam Kong 3	646	29	500	55
Nam Kong 2	861	37	71	6
Nam Kong 1	1,250	42	679	51

Note: Reservoir volume is total (active reservoir plus dead storage) initial reservoir volume for each hydropower plant. km2 = square kilometers; m^3/s = cubic meters per second; m^3 = cubic meters.

E.2 Summary of Results

E.2.1 Sediment Inflow and Outflow for Each Reservoir

Modeled sediment transport for each reservoir for the full development pathway with medium-size sediments can be seen in Table E.3. The last column shows reduction in sediment transport downstream of the reservoir.

E.2.2 Sediment Transport per Pathway

Reduction in sediment transport from each reservoir in the three development pathways is summarized in Table E.4.

There is a very slight increase after 2030 as reservoirs gradually fill with sediment, the free water volume is reduced, and trap efficiency declines slightly.

Table E.3: Sediment Transport (1,000 Tons per Year) for Each Reservoir in Natural Condition (1998) and After Full Development (2030)

Name	1998 In/out	2025		Reduction %
		In	Out	
Houay Lamphan Gnai	66	66	-	100
Houay Ho	54	54	-	100
Xe Pian–Xe Namnoy	207	207	-	100
Sekong 5	705	705	-	100
Sekong 4B	772	67	6	99
Sekong 4A	1,451	685	94	94
Sekong 3A	1,624	267	90	94
Sekong 3B	2,445	584	267	89
Sekong Downstream B	2,686	508	317	88
Sekong Downstream A	5,264	1,545	992	81
Xe Kaman 3	199	199	19	90
Xe Kaman 4	60	60	11	81
Xe Kaman 2B	487	258	22	95
Xe Kaman 1	1,002	538	-	100
Nam Kong 3	181	181	3	98
Nam Kong 2	241	64	18	93
Nam Kong 1	350	127	3	99
Sekong at Lao PDR–Cambodia border	**6,415**	**2,143**		**67**

Note: "-" means no sediment outflow from respective reservoirs.

Table E.4: Reduction in Sediment Transport per Reservoir per Pathway

Name	Full development	Present	Conservative development	Intermediate development
	% reduction			
Houay Lamphan Gnai	100	100	100	100
Houay Ho	100	100	100	100
Xe Pian–Xe Namnoy	100	100	100	100
Sekong 5	100	0	0	100
Sekong 4B	99	0	0	99
Sekong 4A	94	0	0	53
Sekong 3A	94	0	0	47
Sekong 3B	89	13	13	45
Sekong Downstream B	88	12	12	41
Sekong Downstream A	81	29	32	46
Xe Kaman 3	90	90	90	90
Xe Kaman 4	81	0	81	81
Xe Kaman 2B	95	37	95	95
Xe Kaman 1	100	100	100	100
Nam Kong 3	98	98	98	98
Nam Kong 2	93	93	93	93
Nam Kong 1	99	64	99	99
Sekong at Lao–Cambodia border	**67**	**24**	**26**	**38**

E.2.3 Sensitivity Analysis

E.2.3.1 Coarse and Fine Sediments

Brune's curves include envelope curves for fine and coarse sediments. The study assumed that most sediments in the Sekong Basin are of medium grain size, but if fine sediments were to predominate (silt and clay), more sediment would be transported, whereas if there were more coarse sediments (sand), less would be transported. The difference in sediment transport per reservoir is summarized in Table E.5. Compared to a modeling based on medium sediments, the variation is greater for fine sediments than for coarse sediments.

E.2.3.2 Compaction Factor

A smaller compaction factor means that a reservoir fills up faster and thus reaches equilibrium sooner. The study conducted a simulation with a compaction factor of 0.8 that had little effect on sediment transport, because many reservoirs are very large. The sediment transport in the furthest downstream reservoir would increase by a negligible 0.7 percent in 2100.

E.2.3.3 Reservoir Water Level

In the initial simulations, all reservoirs were assumed to be at full supply level. The study conducted additional simulations with the five largest reservoirs at minimum operational water levels. In theory, lower reservoir water levels should transport more sediment, but the model showed only a small increase of 2.7 percent in the furthest downstream reservoir. In any case, assuming full supply level is much more realistic because most reservoirs will be full when the heaviest sediment load arrives.

Table E.5: Sediment Transport Downstream from Each Reservoir as Percentage of Natural Condition Using Brune's Curves for Fine and Coarse Sediments

Name	Fine sediments (%)	Coarse sediments (%)
Houay Lamphan Gnai	96	100
Houay Ho	96	100
Xe Pian–Xe Namnoy	95	100
Sekong 5	95	100
Sekong 4B	98	100
Sekong 4A	87	96
Sekong 3A	89	96
Sekong 3B	82	93
Sekong Downstream B	78	92
Sekong Downstream A	69	86
Xe Kaman 3	81	96
Xe Kaman 4	70	88
Xe Kaman 2B	90	98
Xe Kaman 1	98	100
Nam Kong 3	94	100
Nam Kong 2	87	95
Nam Kong 1	97	100
Sekong at Lao–Cambodia border	**56**	**71**

APPENDIX F
SUPPORTING CUMULATIVE IMPACT ASSESSMENT ANALYSIS OF AQUATIC ECOLOGY AND FISH

F.1 Approach and Methodology

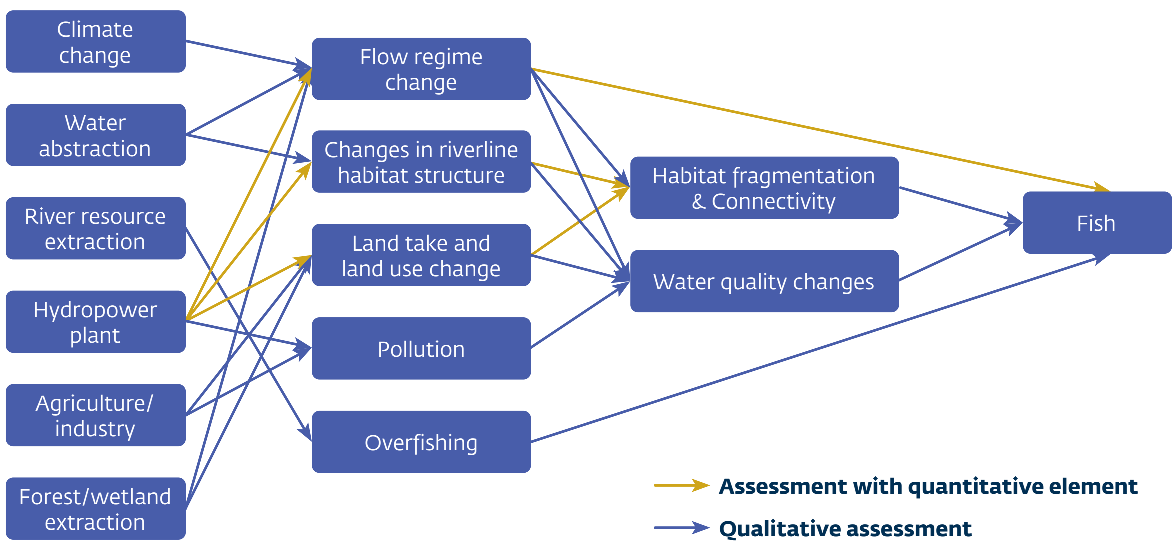
Figure F.1 illustrates the impact pathway network for fish. Part of the impact assessment was analyzed quantitatively using geographic information system (GIS) data and results from hydrological modeling. The yellow arrows in Figure F.1 indicate which parts of the impact pathway use this quantitative method. The method for the quantitative analysis is described in Sections F.1.1 to F.1.4.

F.1.1 Selection of Indicator Species

An initial list of fish species in the Sekong Basin was derived by creating a geographic overlap of reported species ranges from the International Union for Conservation of Nature (IUCN) with the Sekong Basin boundaries. This was done in ArcGIS (a geographic information system for working with maps and geographic information), in which IUCN species ranges were overlaid on the Sekong Basin. The result was an ArcGIS attribute table in which all fish species with ranges in the Sekong Basin were recorded. These data were subsequently supplemented with data from the Integrated Biodiversity Assessment Tool database.[1] Then a list was created of species that were critically endangered and endangered according to the IUCN Red List status (IUCN 2017). The list was supplemented with the 15 super-endemic species reported by Meynell (2014) and served as the basis for the district consultations.

The final fish species to be included in the cumulative impact assessment were selected by assigning points to each species according to characteristics that are important ecologically (super-endemic, IUCN status, and conservation) and socio-economically (important food fish and conservation) as well as sensitive to the proposed developments (migratory behavior) (Table F.1). These criteria were presented to stakeholders during the interim workshop on October 30 and 31, 2018. After the workshop, the method and list of fish species were discussed and agreed upon with the Champassak Provincial Agriculture and Forestry Office and Sekong Provincial Ministry of Natural Resources and the Environment.

Figure F.1: Impact Pathway Network for Fish



[1] IBAT Alliance (http://www.ibat-alliance.org).

Table F.1: Scoring Criteria for Selection of Fish Species

Characteristic	Points	Reasoning
Critically endangered	2.0	Important for conservation
Endangered	1.0	Important for conservation but not critical
No data or other status	0.5	Because they occur in the basin, but their condition is unclear
Super-endemic	2.0	Highly important for conservation
Migratory	1.0	Sensitive to decreased connectivity
Importance for stakeholders	2.0	Important for food, livelihoods, and cultural reasons

The final score for each fish species was calculated by summing scores for each characteristic (Table F.2). For instance, a fish species that was critically endangered (two points), migratory (one point), and important to local communities for food (two points) received five points. Fish species with three points or more were added to the final list, resulting in a list of 12 species. The list was then shortened because several species had a very small distribution overlap with the Sekong Basin—in the far southern tip only.

To be able to conduct a quantitative analysis of the effect of flow alteration and habitat fragmentation, species ranges need to be in the range of the hydrological model and in the range where potential developments take place. Giant salmon carp (*Aaptosyax grypus*), Julien's golden carp (*Probarbus jullieni*), Mekong giant catfish (*Pangasianodon gigas*), Mekong freshwater stingray (*Hemitrygon laosensis*), and *Schistura bairdi* were therefore eliminated from the shortlist.

Discussions with stakeholders revealed that *Probarbus jullieni* was still observed in the middle and lower ranges of the Sekong Basin, indicating that the IUCN ranges do not appear to reflect the current range of this species, but because available data on the specific range details are limited, a quantitative analysis was not possible for this species.

The final list now includes seven fish species (Figure F.2) with distinct characteristics such as IUCN status, importance for local food or conservation, and being migratory or super-endemic (Table F.3).

Table F.2: Scoring for Selection of Fish Species

Scientific name	Common name	IUCN Red List status	Super-endemic	Importance for stakeholders	Migratory	Sum of points
Aaptosyax grypus	**Mekong giant salmon carp**	**2.0**			**1**	**3.0**
Catlocarpio siamensis	**Giant carp**	**2.0**		**1**	**1**	**4.0**
Datnioides pulcher	Siamese tiger perch	2.0				2.0
Devario salmonata		0.5	2			2.5
Hemitrygon laosensis	**Mekong freshwater stingray**	**1.0**		**1**	**1**	**3.0**
Laubuca caeruleostigmata	Flying minnow	1.0				1.0

Scientific name	Common name	IUCN Red List status	Super-endemic	Importance for stakeholders	Migratory	Sum of points
Pangasianodon gigas	**Mekong giant catfish**	**2.0**		**1**	**1**	**4.0**
Pangasianodon hypophthalmus	**Striped catfish**	**1.0**		**1**	**1**	**3.0**
Pangasius sanitwongsei	**Giant pangasius**	**2.0**		**1**	**1**	**4.0**
Poropuntius bolovenensis		1.0			1	2.0
Poropuntius consternans		**1.0**		**2**		**3.0**
Poropuntius deauratus	Yellow tail brook barb	1.0				1.0
Poropuntius lobocheiloides		1.0				1.0
Poropuntius solitus		1.0				1.0
Pristis	**Large tooth Sawfish**	**2.0**			**1**	**3.0**
Probarbus jullieni	**Jullien's golden carp**	**1.0**		**1**	**1**	**3.0**
Probarbus labeamajor	Thick-lipped barb	1.0			1	2.0
Schistura bairdi		**1.0**	**2**			**3.0**
Schistura bolavenensis		**1.0**	**2**	**2**		**5.0**
Schistura clatrata		0.5	2			2.5
Schistura fusinotata		0.5	2			2.5
Schistura imitator		0.5	2			2.5
Schistura khamtanhi		0.5	2			2.5
Schistura nomi		0.5	2			2.5
Schistura rikiki		0.5	2			2.5
Schistura spiloptera		1.0				1.0
Schistura tizardi		0.5				0.5
Serpenticobitis octozona		0.5				0.5
Sewellia breviventralis	Butterfly loach	2.0				2.0
Sewillia diardi		0.5	2			2.5
Sewillia elongata		0.5	2			2.5
Sewillia speciosa		0.5	2			2.5
Urogymnus polylepis		1.0		1		2.0

Note: Selected species in bold.

Figure F.2: International Union for Conservation of Nature–Reported Ranges of Selected Fish Species in the Sekong Basin

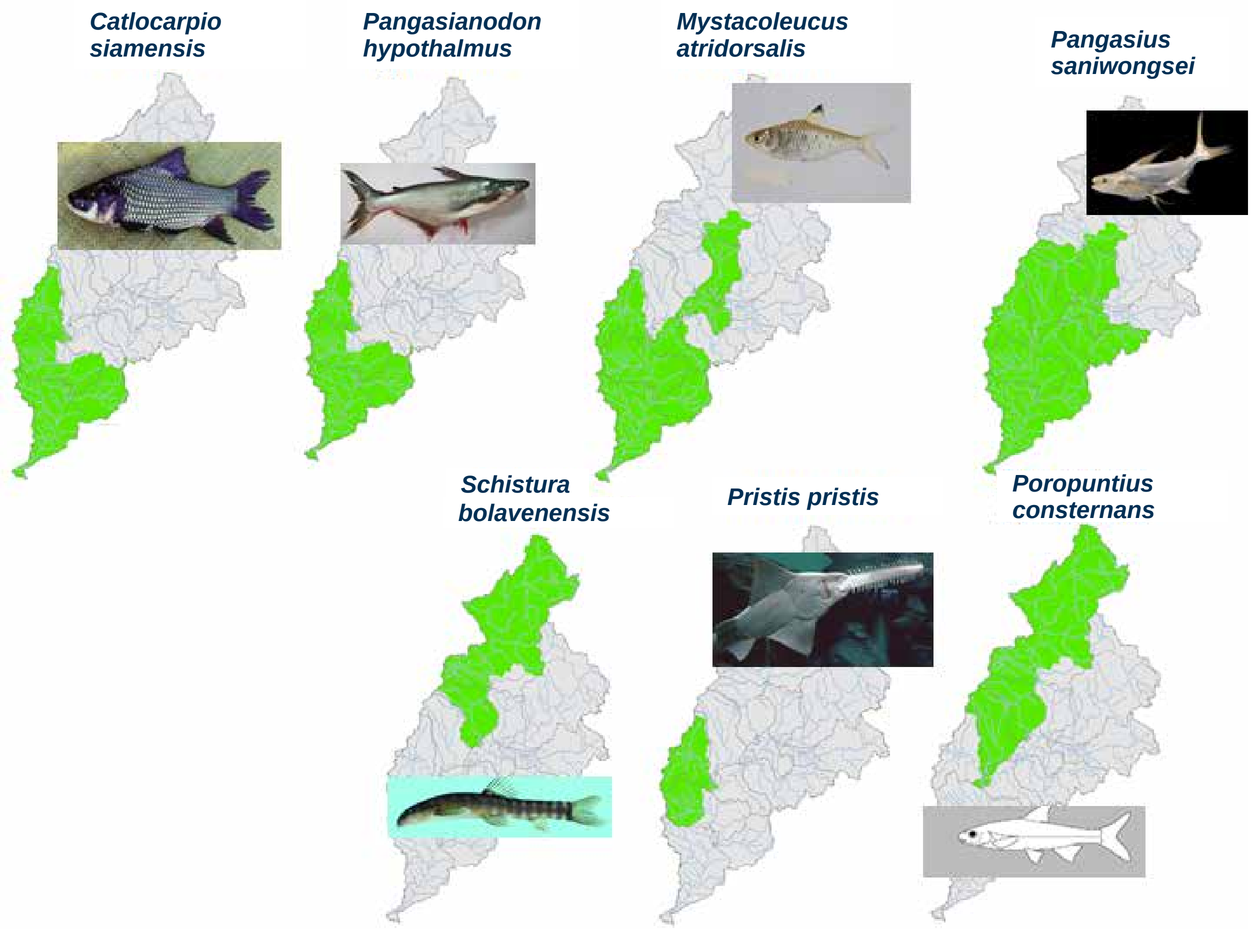


Table F.3: Fish Species Included in Analysis

Scientific name	English name	Lao name	IUCN Red List status	Super-endemic	Migratory
Schistura bolavenensis	n.a.	Pa eet	Endangered	Yes	No
Catlocarpio siamensis	Giant carp	Pa kaho	Critically endangered	No	Yes
Pangasius sanitwongsei	Giant pangasius	Pa leum	Critically endangered	No	Yes
Mystacoleucus atridorsalis	n.a.	Pa teb	Least concern	No	Yes
Pangasianodon hypophthalmus	Striped catfish	Pa souy	Endangered	No	Yes
Poropuntius consternans	n.a.	Pa chad	Endangered	No	No
Pristis	Large-tooth sawfish	Pa kheo luaey	Critically endangered	No	Yes

Note: n.a. = not applicable.

F.1.2 Assessment of Pathways

Some parts of the cause-and-effect network for fish can be calculated quantitatively if model data or GIS data are available on which calculations can be made and from which effects can be calculated as opposed to qualitatively described. This includes the effect of hydropower operation on flow regime, which is calculated using hydrological modeling, and changes in riparian habitat structure, land take, and land use, which is calculated using GIS data. Because each fish species has a different geographical range, the effects are determined for each separately. The final rating of the impact score of the corresponding pathway is then derived using an unweighted average of scores for all selected fish species. The methods for quantitative analysis of the pathways are described in the following section.

F.1.3 Assessment of Effect of Flow Regime Alteration on Fish

Climate change and hydropower development can alter the flow regime. These changes in flow regime have been calculated using hydrological modeling (Appendix B). Several indicators were selected to quantify the differences in flow between the present situation and all future development pathways (Table F.4). These indicators describe the main aspects of the flow curve—magnitude, duration, frequency—that are ecologically relevant and that the proposed development pathways affect (Richter et al. 1996). The magnitude indicators show the amount of water under average, very low, and very high flow conditions. Duration is the length of time during which there are low- or high-flow conditions. Frequency is how often there are very low- and very high-flow conditions; 1991 was excluded from the calculation of indicators because it included a period during which model values were not correctly calculated for several months.

The impact score is calculated as an absolute percentage of change between the present situation and the pathway. The direction of change (increase or decrease) is not reflected in the outcome value of the hydrological indicator because increases and decreases in flow magnitude reduce the abundance and diversity of fish species (Poff and Zimmerman 2010). Therefore, the direction of change of the indicators is ignored in the calculation.

The impact score was calculated for each model calculation point that falls within the distribution range of the species (Figure F.2). Subsequently, the total deviation was calculated as the median of all calculation points. The deviation percentages of the magnitude indicators were calculated according to the formula:

$$\text{abs}((\text{Value}_{\text{scenario}} - \text{Value}_{\text{present}})/(\text{Value}_{\text{present}}/100))$$

Table F.4: Hydrological Indicators Used to Calculate Changes in Flow Discharge Characteristics

Flow characteristic	Very low flow	Low flow	Average flow	High flow	Very high flow
Magnitude	Twentieth percentile of annual minimum discharge		Median of median annual discharges		Eightieth percentile of annual maximum discharge
Duration		Average number of days per year with discharge < the 25th percentile of present situation		Average number of days per year with discharge > the 75th percentile of present situation	
Frequency	Non-exceedance frequency of 20th percentile of present situation of annual minimum discharge				Exceedance frequency of 80th percentile of present situation of annual maximum discharge

Duration indicators were calculated as percentages of deviation scaled to the maximum amount of deviation possible. The maximum duration difference between the present situation and the scenario is 274 days (365 days in the year - 91 days, which corresponds to the number of days less than the 25th percentile and greater than the 75th percentile in the present situation). The following formula was used:

$$abs((Value_{scenario} - Value_{present})*100/274)$$

The frequency indicators were calculated using the following formula:

$$abs((Value_{scenario} - Value_{present})/(Value_{present}/100))$$

For each indicator, this percentage is translated into impact based on the description in Table F.5.

Table F.5: Impact

Impact	%
Negligible	0–5
Slight	5–15
Moderate	15–30
Large	30–50
Severe	>50

The final impact score is an average of all indicator impact scores per fish species.

F.1.4 Habitat Fragmentation and Loss of Habitat

Physical blocking of rivers by dams and changes in aquatic habitats can fragment aquatic habitat. Physical blockage of dams that hamper connectivity was assessed in terms of reduction in the largest unblocked habitat expressed in river kilometers (see, for example, *Poropontius consternans*, Map F.1) and degree of fragmentation of the species habitat. The length of unblocked river and the number of areas in which a species range is fragmented was calculated using ArcMap 10.4.1, then the difference in percentage reduction in the longest unblocked river section and percentage increase in fragmentation between the present situation and all other development pathways was assessed. A large reduction in the connected areas could pose a risk to the carrying capacity of the population if too little habitat remained available for a viable population. This is especially the case for migratory fish, which cover a large range between habitats.

Habitat fragmentation and reduction caused by changes in aquatic habitats were assessed according to differences between impounded and free-flowing areas. Reservoirs are deep and relatively stagnant and therefore provide a habitat different from that of free-flowing rivers with alternating pools and riffles. Reservoirs create two types of effects: they cause fragmentation, and they reduce the amount of preferred habitat. The percentage of river transformed from free flowing to reservoir was used as an indicator. Again, this is species specific, but because reservoirs have an additive effect on fragmentation, the fish-preferred habitat is blocked (and a different type of habitat is produced), which should be an addition to the fragmentation score.

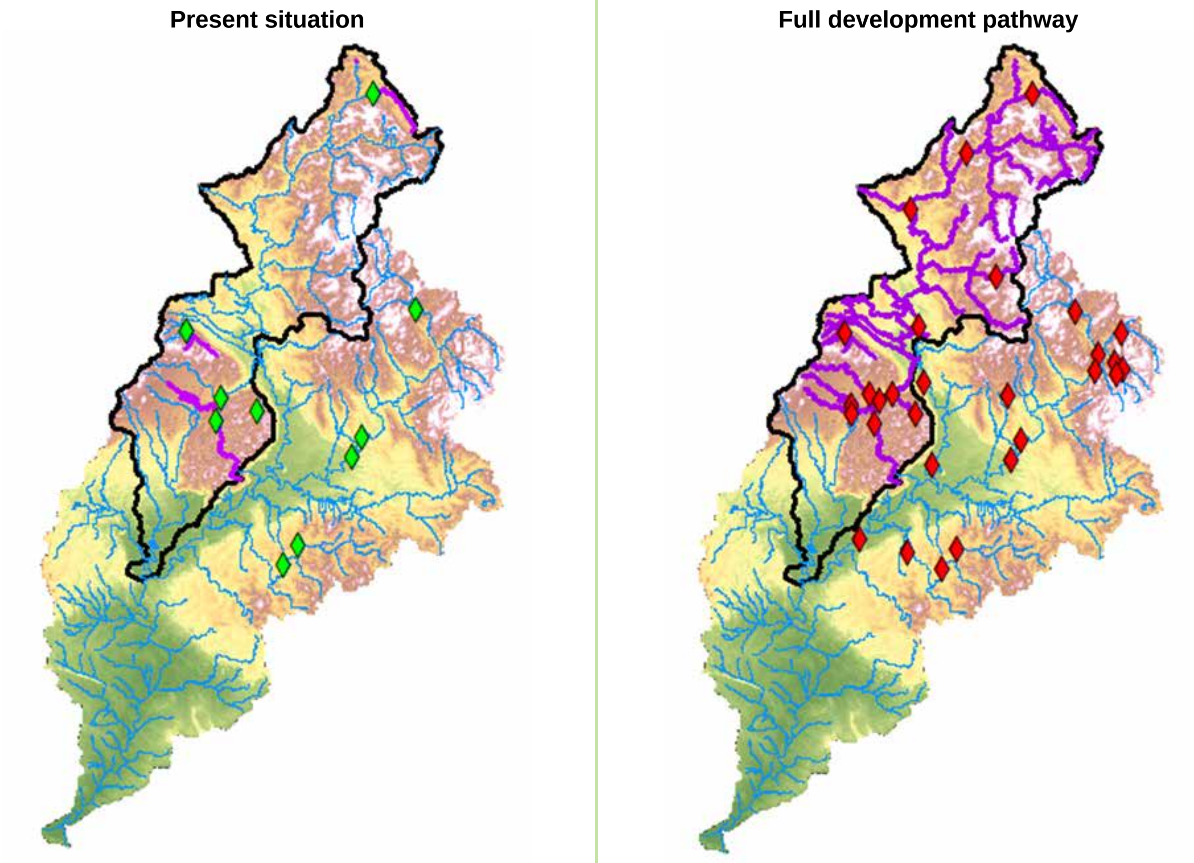
Three types of indicators are calculated:

1. Reduction in largest unblocked area, which is an indicator of potential reduction in the carrying capacity of a population, called *connectivity*
2. Reduction in number of areas in which a species range is split up
3. Reduction in habitat caused by reservoirs

The connectivity score is the score of indicator 1, and the fragmentation score is the sum of indicators 2 and 3. The final score is the average of the connectivity and fragmentation scores. The percentage was translated into an effect, as described in Section F.1.3.

Flow alteration can also fragment habitat, which can lead to dis-connectivity between floodplains and channels or within channels. The effect of flow alteration on habitat fragmentation is estimated using the low-flow indicators of hydrological alteration (Table F.4).

Map F.1: Method for Assessing Connectivity Changes Affecting *Poropuntius consternans*



Note: The historical species range of *P. consternans* is demarcated with a black line, and tributaries without dams are shown in blue. Areas upstream of dams that are no longer accessible to *P. consternans* are depicted in purple. In the present situation, most of the current range is connected and accessible, whereas under the full development pathway, only a small area in the southern part of the range remains connected.

F.2 Cumulative Impact Assessment Analysis and Results

F.2.1 Effect of Flow Regime Change on Aquatic Ecology

Climate change, water abstraction, and hydropower plants can alter flow. The most dominant driver of flow alteration is reservoir dams. Table F.6 shows the details of all calculated hydrological indicators for all fish species and all pathways. The hydrological indicators depict the absolute values of differences under each pathway compared with the present situation. For details on the methodology, see Section F.1.3.

The hydrological indicators show large deviations in very low and very high flows. There are large differences between species and between pathways (Table F.7). Because all pathways involve dam construction, they all harm fish species to varying degrees. The largest effects are for the full development pathway, whereas the conservative pathway has the fewest negative effects. On average, all pathways, although mostly full development, affect *Schistura bolavenensis* most. This fish species is super-endemic and is an important species for food.

Water extraction, which irrigation demand dominates, is less important than the effect of dams (Asian Development Bank 2010). In the Sekong Basin, the irrigated area is 3,605 hectares in the wet season and 2,743 hectares in the dry season (Meynell 2014), although expansion of the agricultural sector and increases in water abstraction for drinking water and domestic water are becoming increasingly important (Asian Development Bank 2010; Freshwater Health Index 2018). In the Sekong, Sesan,

Table F.6: Values for Hydrological Indicators per Fish Species for Each Pathway

Species and pathway	Amount of change in magnitude of different flows			Amount of change in duration of different flows		Amount of change in frequency of different flows		Average score
	Low flow	Average flow	High flow	Low flow	High flow	Low flow	High flow	
Pangasius sanitwongsei								
Full	62.6	0.8	13.5	12.0	4.4	80.0	40.0	30.5
Conservative	13.0	0.1	0.3	0.5	0.1	20.0	0.00	4.9
Intermediate	44.0	0.9	8.9	6.4	1.4	80.0	20.0	23.1
Schistura bolavenensis								
Full	40.5	2.4	27.5	22.3	6.7	80.0	80.0	37.1
Conservative	0.00	0.00	0.0	0.0	0.0	0.0	0.00	0.0
Intermediate	40.8	2.3	20.1	14.7	3.6	100.0	60.0	34.5
Poropuntius consternans								
Full	40.5	2.4	21.9	15.7	5.2	80.0	70.0	33.7
Conservative	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Intermediate	40.8	2.3	16.2	9.8	3.2	80.0	40.0	27.5
Mystacoleucus atridorsalis								
Full	64.7	1.4	15.4	13.9	5.4	90.0	40.0	33.0
Conservative	26.2	0.2	1.2	0.8	0.2	40.0	20.0	12.7
Intermediate	45.6	1.6	9.7	6.9	2.8	80.0	20.0	23.8

Table F.7: Effect of Flow Regime Change on Aquatic Ecosystem and Fish Stocks

Pressure or pathway	Present situation	Full development	Intermediate development	Conservative development
Climate change	Slight	Slight	Slight	Slight
Water extraction	Slight	Slight	Slight	Slight
Catchment changes	Slight	Moderate	Moderate	Slight
Hydropower dams and reservoirs	Moderate	Large	Moderate	Slight
Impact score	Slight	Large	Slight to moderate	Slight

and Srepok basins, irrigation is planned for 270,000 hectares of land in addition to the current 60,000 hectares (Asian Development Bank 2010). These developments could place additional pressure on water resources and hence the aquatic ecosystem, including fish stocks, especially in the dry season (Freshwater Health Index 2018). Therefore, under the present situation, the effect of water abstraction is considered low, but for future situations, it is considered low moderate, mainly in the dry season.

The flow regime is further affected by climate change (Table F.7). Projections for the Sekong Basin predict a slight increase in flow during the wet season and a larger decrease in the dry season (see Appendix B). Decrease in flow in the dry season can especially harm fish by shrinking their habitat. Therefore, a similar effect is given to climate change as to water abstraction: low in the current situation and low moderate in future scenarios.

Absolute indicator values were used for the assessment, but the direction of change of these indicators provides insight into the type of alteration that takes place in the river system. The magnitude of low flows increases, and the magnitude of high flows decreases. A reduction in high flows will result in a reduction in channel-floodplain connectivity, which harms species that depend on these connections, although any direction of change in flow parameters can decrease abundance and diversity of fish species (Poff and Zimmerman 2010). Therefore, the values of the indicators provide insight into several ecologically relevant aspects of the flow and can be used to assess the effect of flow alteration on fish species.

F.2.2 Habitat Fragmentation and Connectivity

Dams block rivers, which causes habitat fragmentation and loss of connectivity. Dams decrease the length of river that species can use, fragment ranges, and transform aquatic habitats from lotic (flowing) to lentic (stagnant) conditions.

These changes were analyzed quantitatively based on ArcGIS data (Figure F.3, Table F.8, and Figure F.4). For several fish species, the longest stretch of connected river in their distribution range is between dams. This is the case for *Poropuntius consternans* and *Schistura bolavenensis* under the full development pathway, in which the longest stretch is between Sekong 3A and 3B. These species are the most affected fish species, especially in the full and intermediate development pathways. Both species are important for food, and *Schistura bolavenensis* is a super-endemic species. In the intermediate and full development pathways, the longest connected area for *Schistura bolavenensis* is between the A Loui and Sekong 5 dams.

Figure F.3: Increase in Fragmentation for Each Fish Species Under Different Development Pathways

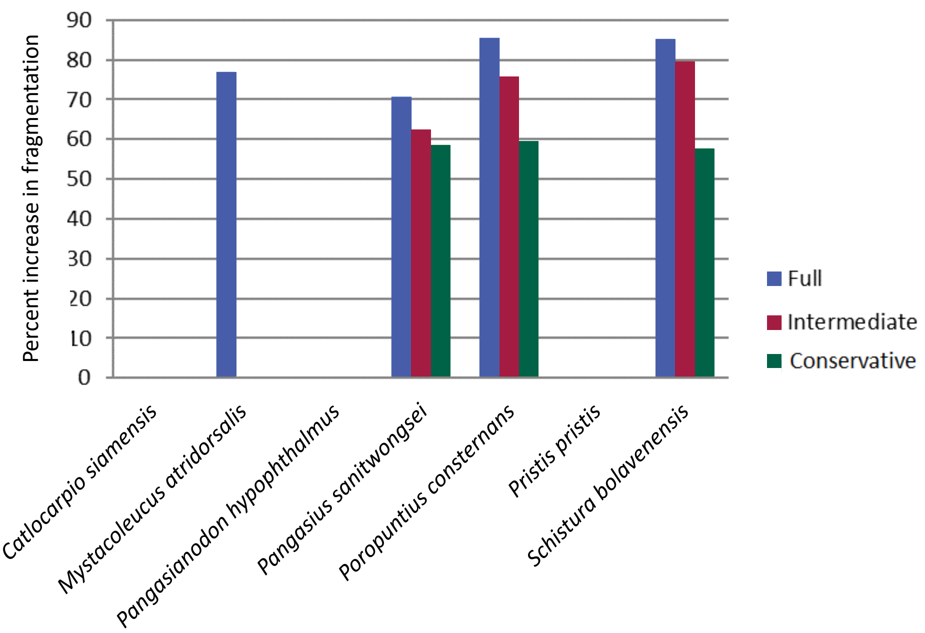
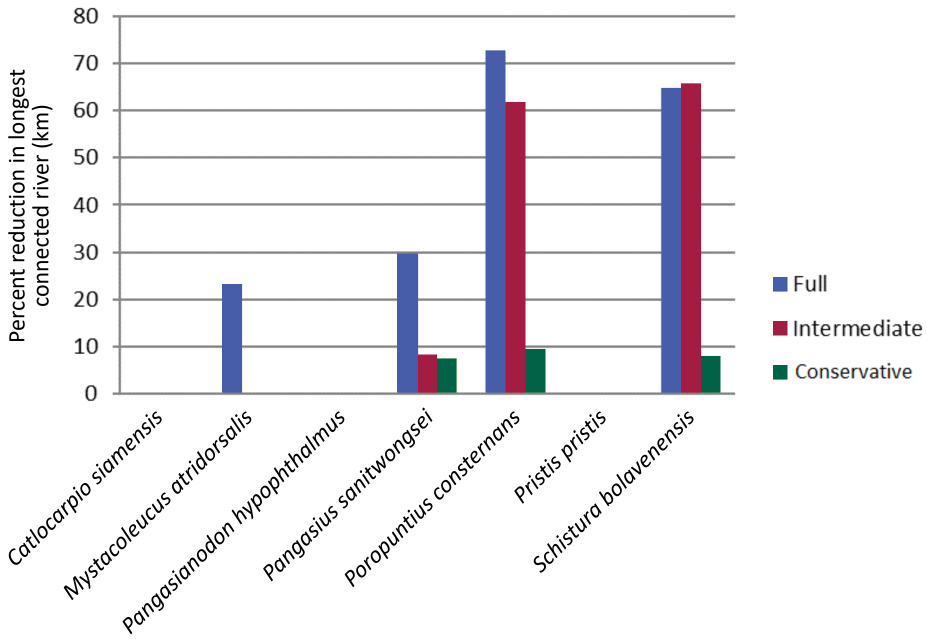


Table F.8: Effect on Ranges of Critical Fish Species of Hydropower Development Under Different Development Pathways

Indicator	*Mystacoleucus atridorsalis*	*Pangasius sanitwongsei*	*Poropuntius consternans*	*Schistura bolavenensis*
Full development pathway				
Dams in range	Sekong Downstream A, Sekong Downstream B, Sekong 3B	Sekong 3B, Sekong Downstream B, Sekong Downstream A, Xe Katam, Xe Katam–Xe Namnoy 1, Xe Namnoy 1, Houay Ho, Houay Makchan, Xe Pian, Xe Pian–Xe Namnoy, Nam Kong 3, Nam Kong 2, Nam Kong 1	Sekong 4B, Sekong 4A, Sekong 5, Houay Lamphan, Sekong 3A, Houay Makchan, Xe Katam 2, Xe Namnoy 1, Xe Katam, Xe Pian, Xe Pian–Xe Namnoy, A Loui, Dak E Mule	Sekong 4B, Sekong 4A, Sekong 5, Houay Lamphan, Sekong 3A, Houay Makchan, Xe Katam 2, Xe Namnoy 1, Xe Katam, Xe Pian, Xe Pian–Xe Namnoy, A Loui, Dak E Mule
River converted to reservoir (kilometers)	3,340	112.2	327.5	327.5
Reduction to total range (%)	1.8	4.1	18.8	23.8
Intermediate development pathway				
Dams in range	No dams	Xe Katam, Xe Katam–Xe Namnoy 1, Xe Namnoy 1, Houay Ho, Houay Makchan, Xe Pian, Xe Pian–Xe Namnoy, Nam Kong 3, Nam Kong 2, Nam Kong 1	Sekong 4B, Sekong 4A, Sekong 5, Houay Lamphan, Kouay Makchan, Xe Katam 2, Xe Namnoy 1, Xe Kamtam, Xe Pian, Xe Pian–Xe Namnoy, A Loui, Dak E Mule	Sekong 4B, Sekong 4A, Sekong 5, Houay Lamphan, Kouay Makchan, Xe Katam 2, Xe Namnoy 1, Xe Katam, Xe Pian, Xe Pian–Xe Namnoy, A Loui, Dak E Mule
River converted to reservoir (kilometers)	0.00	78.8	312.1	312.1
Reduction to total range (%)	0.00	4.2	11.5	17.9
Conservative development pathway				
Dams in range	No dams	Xe Katam, Xe Katam–Xe Namnoy 1, Xe Namnoy 1, Houay Ho, Houay Makchan, Xe Pian, Xe Pian–Xe Namnoy, Nam Kong 3, Nam Kong 2, Nam Kong 1	Houay Lamphan, Houay Makchan, Xe Katam 2, Xe Namnoy 1, Xe Katam, Xe Pian, Xe Pian–Xe Namnoy, A Luoi, Dak E Mule	Houay Lamphan, Houay Makchan, Xe Katam 2, Xe Namnoy 1, Xe Katam, Xe Pian, Xe Pian–Xe Namnoy, A Luoi, Dak E Mule
River converted to reservoir (kilometers)	0.00	78.8	136.1	136.1
Reduction to total range (%)	0.00	4.2	5.0	7.8

Figure F.4: **Decrease in Connectivity for Each Fish Species Based on Blockage by Dams**



Note: Species not shown do not have dams in their range. km = kilometers.

The final impact scores for fragmentation and connectivity in all development pathways are presented in Table F.9. This shows an average score for all fish species. For details on the calculations, see Section F.1.4. Water abstractions are considered less important than habitat fragmentation and connectivity and are therefore not taken into account.

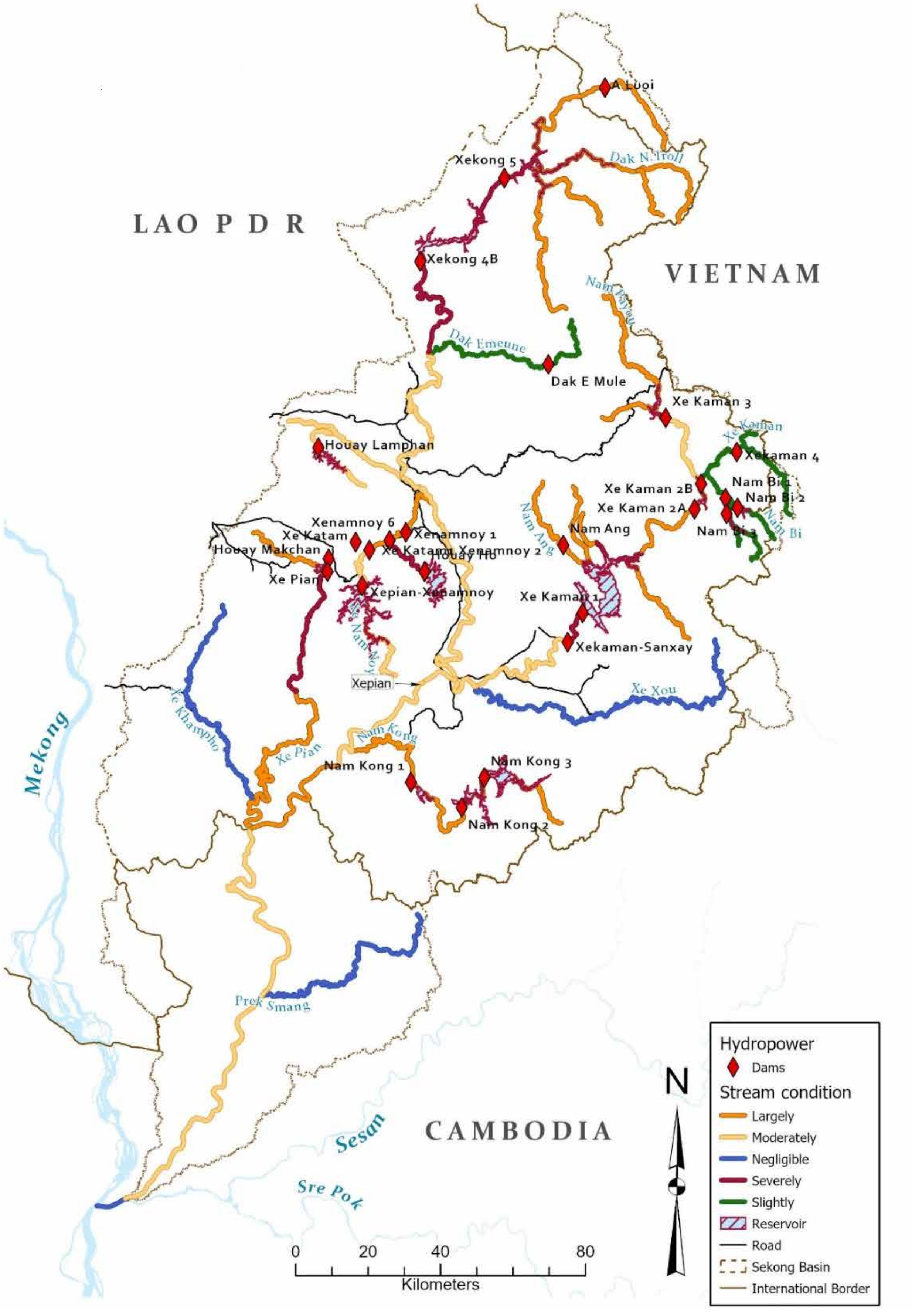
The summary of river modification for various river sections under each development pathway is illustrated in Maps F.2, F.3, and F.4 and under the present situation in Map F.5. The colors show the degree of modification assessed as a combined score averaged over modifications to flow regime, sediment transport, and fish connectivity.

Table F.9: **Impact Scores for Habitat Fragmentation and Connectivity**

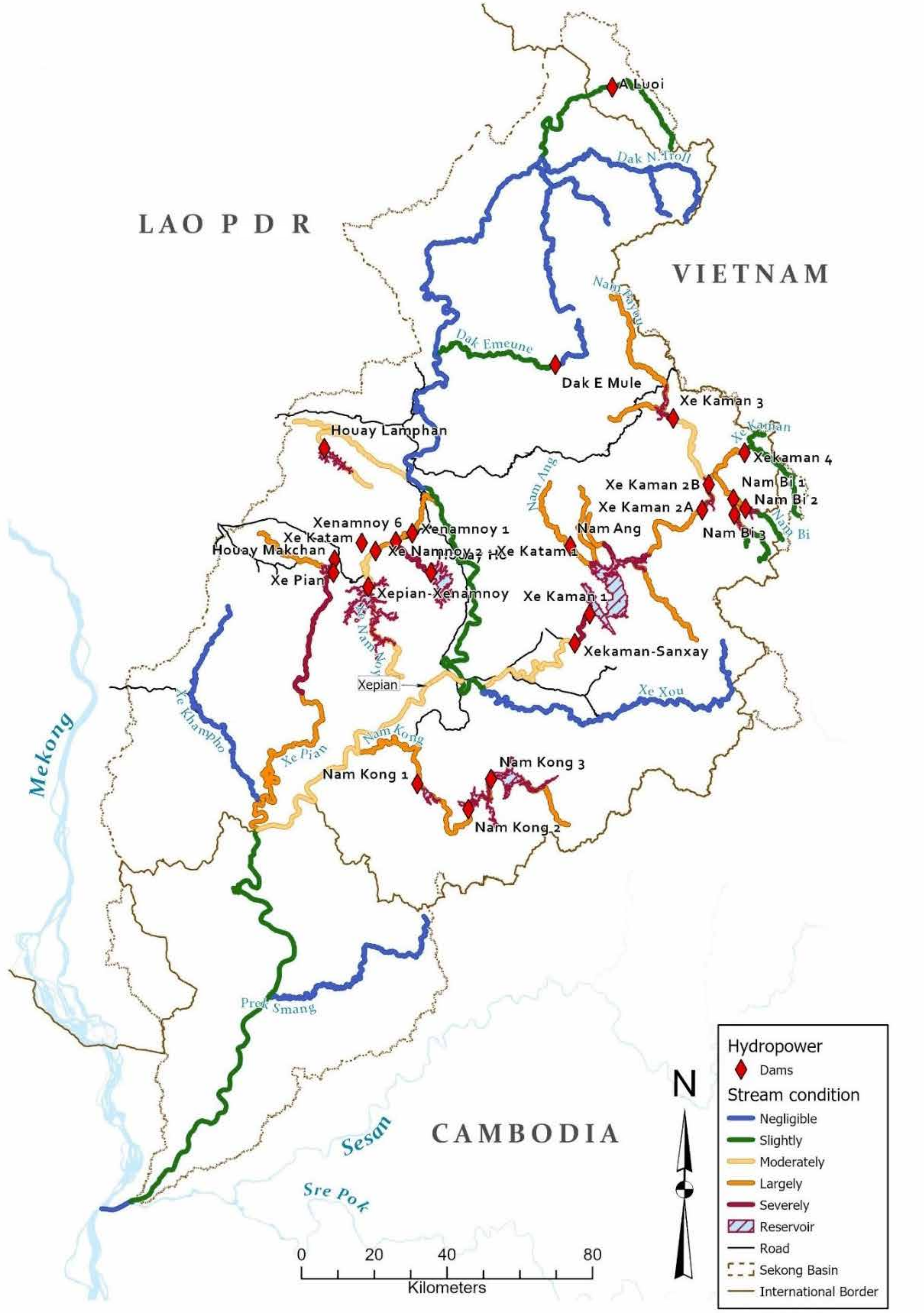
Pressure or pathway	Full development	Intermediate development	Conservative development
Connectivity	**27**	**19**	**4**
Fragmentation			
Subscore 1	39	26	23
Subscore 2	7	4	2
Total score	**46**	**30**	**28**
Final % (average)	**36**	**25**	**14**
Impact score	**Large**	**Moderate**	**Slight**

Map F.2: Degrees of River Modification Under Full Development Pathway

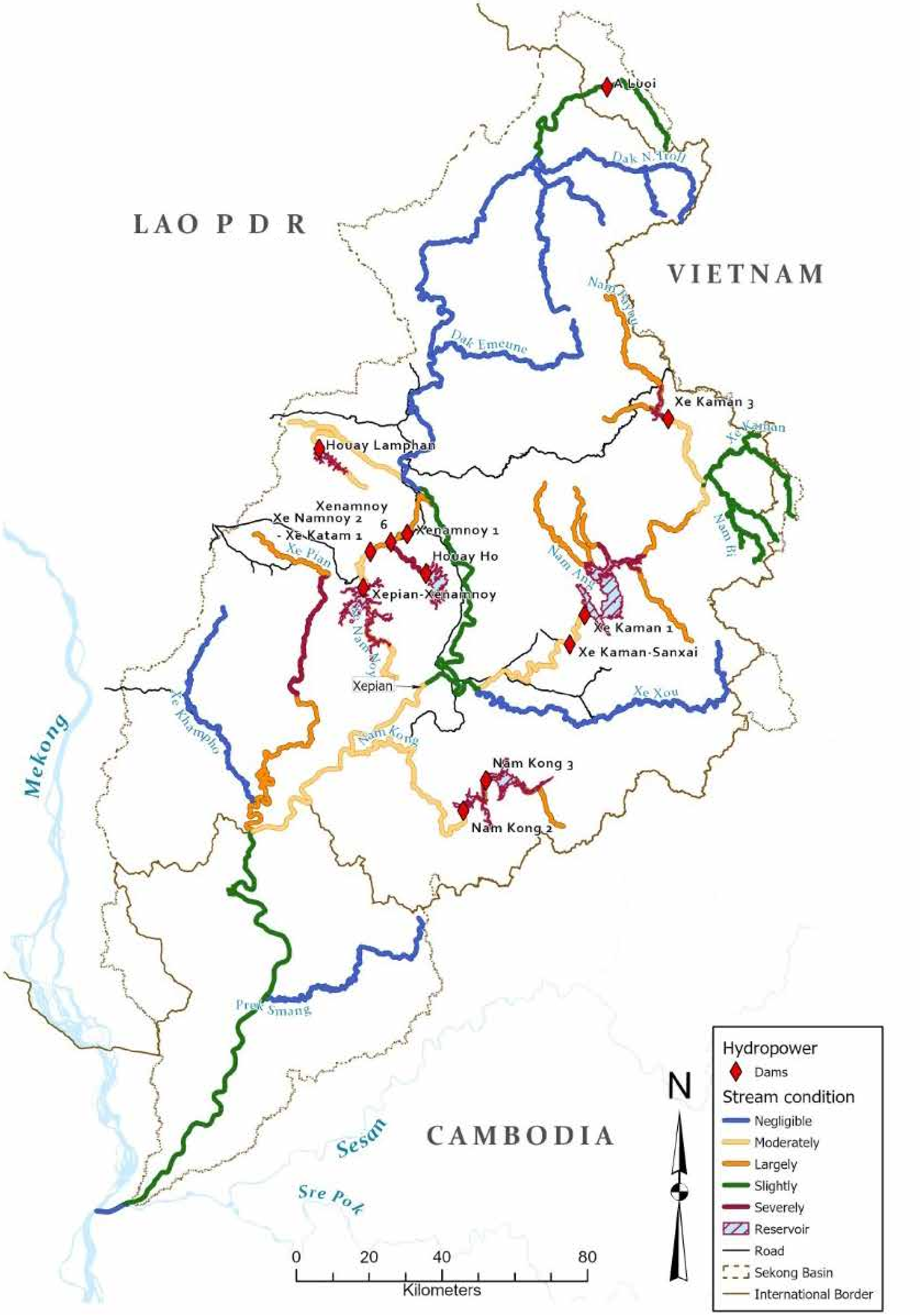
Map F.3: Degrees of River Modification Under Intermediate Development Pathway



Map F.4: Degrees of River Modification Under Conservative Development Pathway



Map F.5: Degrees of River Modification in Present Situation



APPENDIX G
HYDROPOWER MODELING AND POWER OPTIMIZATION ASSESSMENT

G.1 Reservoir Operation

To achieve the greatest power generation, reservoirs should be operated so that there is as little spill as possible and the reservoir water level is kept as high as possible. There is some tension between these two goals: it is necessary to lower the reservoir water level to have available volume to store incoming water and so avoid spill. Optimization involves determining the reservoir guide curve that is the best compromise between the two goals.

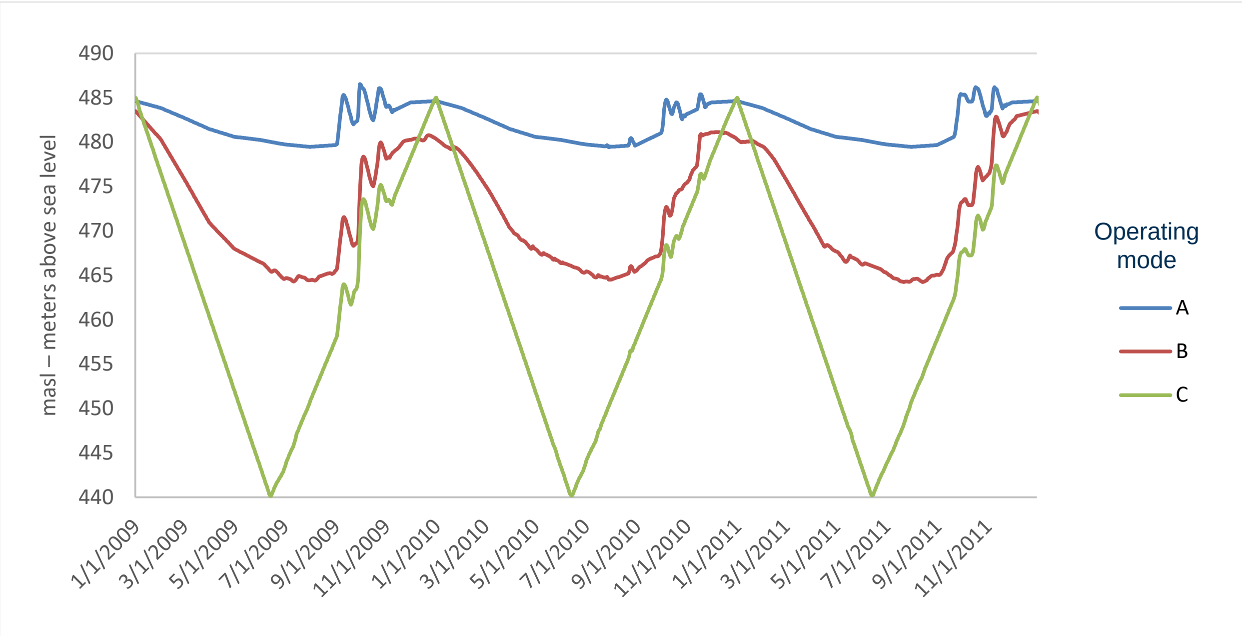
Operation rules may not precisely reflect the outcome of optimization. Other factors besides the guide curve are also important: for instance, guaranteeing power during high-demand periods, providing a stable output, varying prices for energy in wet and dry seasons, and time of day pricing. Environmental releases may also affect power production potential.

For a cascade of dams, different operation regimes may be beneficial. A large upstream reservoir may be used to store all water in the wet season to be used in the dry season, reducing generation at the upstream power plant but benefiting downstream plants.

We analyzed three modes of operation: (1) maximization of energy output (keep water level as high as possible without major spills) (mode A), (2) maximization of firm energy and power (mode B), and (3) dry season generation (mode C) (Figure G.1).

In mode A, the power plant is run close to a run-of-river project, with use of the reservoir restricted to avoid major spilling in the wet season. In mode B, the aim is to run the power plant at a constant output, with the firm power as high as possible. This is favored when the price for firm power is high. This mode could also include

Figure G.1: Modeled Reservoir Water Level at Sekong 5 for Different Modes of Operation



Note: Mode A = maximization of energy output; mode B = maximization of firm energy and power; mode C = dry season generation.

peaking generation but with little to no seasonal variation. In mode C, the reservoir is emptied in advance of the monsoon, and wet season inflow is used to fill the reservoir. This generates as much power as possible in the dry season. This could be feasible if there are seasonal variations in power price or to maximize the power output of a cascade with run-of-river power plants and an upstream reservoir.

If one considers an individual reservoir hydropower plant such as Sekong 5, mode A generates more power than mode B, which generates more power than mode C because loss of head more than counteracts the reduction in spill from active use of the entire reservoir volume. We do not know the details of the power purchase agreements for the the hydropower plants (HPPs) in the Sekong River Basin, but based on available information, it is likely that Sekong HPPs will be operated to maximize firm power (mode B).

Only the larger reservoirs are suited for seasonal storage. In the Sekong River Basin, these include Sekong 5, Houay Lamphan Gnai, Houay Ho, Xe Pian–Xe Namnoy, Xe Kaman 1, Nam Kong 1, and Nam Kong 3. Smaller reservoirs could be used for peaking operation but cannot be optimized for firm power generation. In our model, reservoirs with volume of less than 10 percent of annual flow are operated as run-of-river hydropower. This applies to all mainstream Sekong projects except Sekong 5.

G.2 Technical Assumptions

It has been necessary to make a number of assumptions regarding hydropower calculations because information is lacking about technical parameters for each project. We have assumed that there is a constant release of 2 percent of average flow for all mainstream hydropower plants to provide flow in fish passes, navigation locks, and other releases not producing energy. We have also assumed that reservoir volume curves increase linearly from low- to high-regulated water level. In reality, there will be more water stored in the upper, wider portion of the reservoir than in the lower, narrower portion, but this makes little difference to the results.

The efficiency of all hydropower plants was set to 0.87. This includes efficiency of electromechanical equipment and all head loss in the system. We assumed that units are designed for operation at peak efficiency or maximum output with reasonably high efficiency. We also assumed intermittent operation in low-flow periods for run-of-river HPPs, meaning that efficiency is kept high. We used full supply levels according to information that the Ministry of Energy and Mines provided.

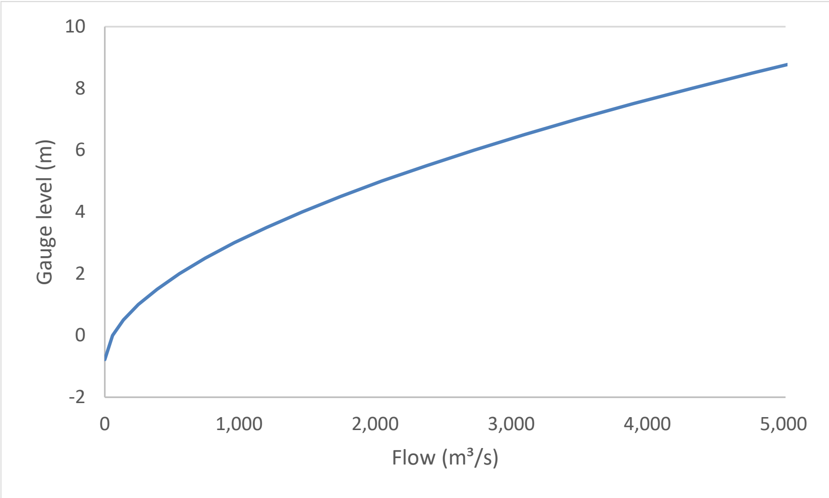
G.3 Tailwater Curves

For low-head hydropower plants, the elevation of the tailwater is important because it greatly affects available head for generation. We have tailwater curves for Sekong 4A and 4B, although we are not certain whether they are correct because the locations of the dams in the feasibility studies do not correspond to the latest official locations. For the other projects, we did not have access to tailwater curves. The water level of the downstream reservoirs will affect most of the Sekong mainstream projects. The downstream reservoirs in the model do not affect Sekong Downstream B and A, but the two upper projects will most probably be affected to some degree.

Because the Sekong mainstream reservoirs are long and narrow, we have assumed that there is a gradient in the water levels. For simplicity, we assumed that the tailwater level of an HPP is 1 meter higher than the headwater level at the downstream dam. This will gradually become the case, if not higher, because sediment accumulation at the upstream end of each of the reservoirs backs up river levels in the reaches approaching the reservoir.

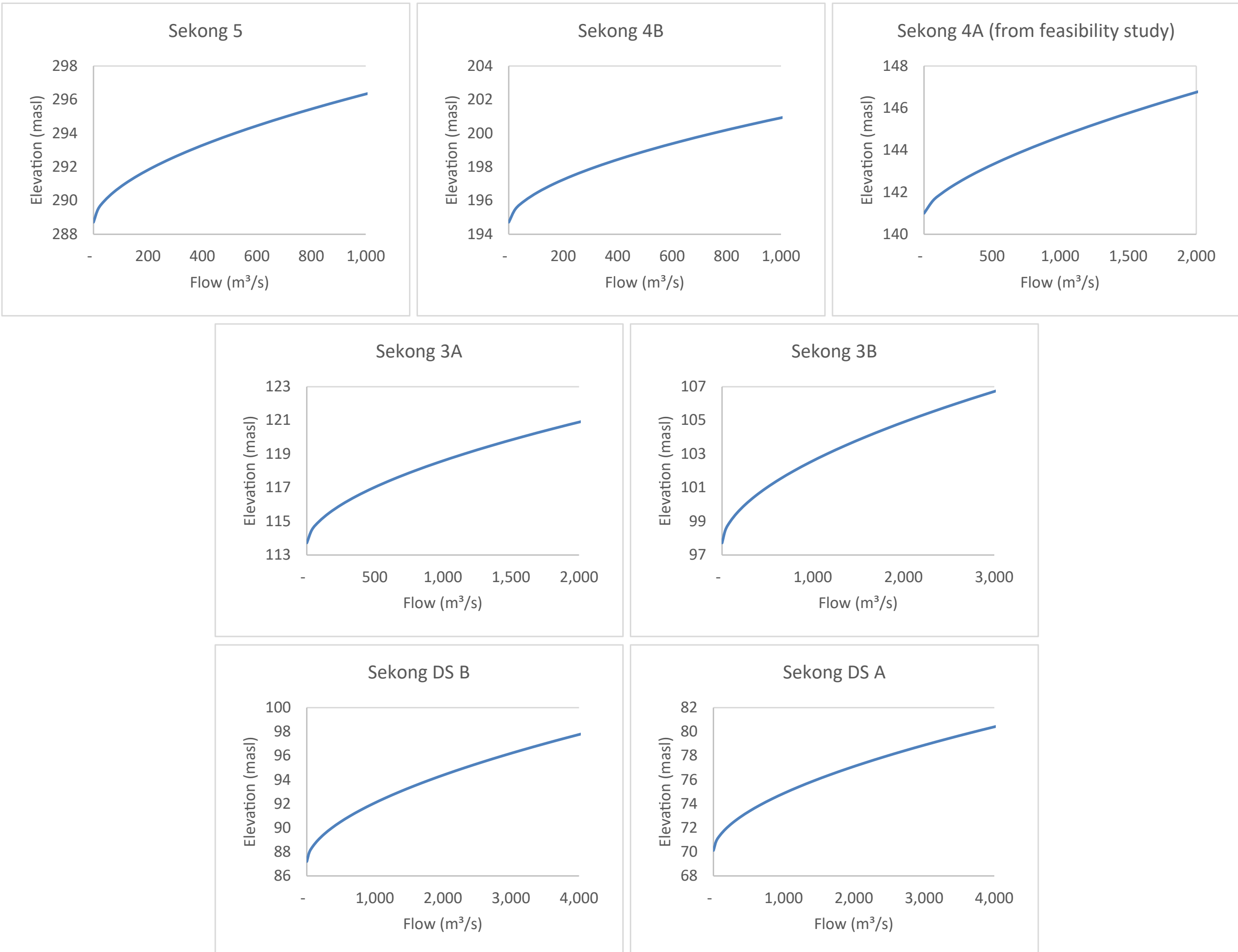
For higher flows and for Sekong Downstream B and A, we generated tailwater curves based on the Siem Pang gauging station, located on the Sekong in Cambodia. We adjusted the curve for each project based on the difference between the width of the Sekong River at the project site and the width at Siem Pang (see Figure G.2). We tried to ensure that the average tailwater level based on the tailwater curve matched the given tailwater elevation or median head in the feasibility studies (Figure G.3).

Figure G.2: Siem Pang Rating Curve



Source: http://cam-crds.nis.gov.kh/site/docs/CCpolicy/Cambodian_Water_Resources_Profile_FINAL_21-04-14.pdf.
Note: m = meters; m^3/s = cubic meters pers second.

Figure G.3: Assumed Tailwater Curves



Note: masl = meters above sea level; m^3/s = cubic meters per second; DS = downstream.

G.4 Sekong Mainstream Power Generation

Simulations have been done for 1991 to 2014 (Table G.1). To avoid having the initial conditions of the model affect the model results, the presented numbers are averages of 1992 to 2014.

There are several potential reasons for the differences in power generation between our model and the results of the feasibility studies. First, there are significant differences in assumed annual inflow at each dam site. In general, the model uses 15 to 20 percent lower annual inflow than the feasibility studies assume. Second, the production figures given in feasibility reports are assumed not to involve the upstream regulation benefits of the future Sekong 5 project. Third, some feasibility studies do not include downstream reservoirs in their calculated tailwater level, thus overestimating available head. There are probably also differences in number and type of units and assumed efficiency curves and operating rules. We had to make a simple assumption to fit all projects (0.87 constant).

To reduce the effect of the first factor, we adjusted the feasibility study energy output figures proportionally to correspond to the reduced inflow in our model. The results are shown in the final column in Table G.2, which shows that, in most cases, we are obtaining more production from the same adjusted mean inflow with the exception of Sekong 3A and 3B, for which our model shows 6 to 7 percent less production. From the feasibility studies of Sekong 3A and 3B, we believe the generation estimated for these projects is too high because they included the period from 1979 to 1989, which had higher flows than observed today. The regulation of flows from Sekong 5, Xe Kaman, Nam Kong, and other reservoirs is probably the reason for the larger modeled power production of Sekong Downstream A. Sekong 4B, being directly downstream of Sekong 5, also receives considerable benefits from the Sekong 5 reservoir. Sekong 4A most probably has a different tailwater curve because it stems from the old dam location.

The comparison between our model and the feasibility study results shows there is reasonable agreement; it is likely that variation is due to uncertainties and assumptions inherent in the model.

There is little difference between modes A and B (Figure G.4) (the blue line covers the red), but mode C is somewhat different. There is a considerable contribution from the reservoirs in all scenarios and relatively little spill. The rated discharge of the hydropower plants is also relatively high compared with the flow in the river, which reduces spill. Therefore, the average production figures do not change from mode to mode.

Table G.1: Sekong Mainstream Power Generation

Hydropower project	Model results			Figures reported in project feasibility studies
	Maximize generation	Maximize firm power	Seasonal storage	
	(GWh/year)			
Sekong 5	1,239	1,200	1,159	1,500
Sekong 4B	736	756	757	750
Sekong 4A	734	749	752	780
Sekong 3A	368	370	371	460
Sekong 3B	307	310	310	400
Sekong Downstream B	176	180	181	210
Sekong Downstream A	423	438	439	380
Total	**3,983**	**4,003**	**3,970**	**4,480**

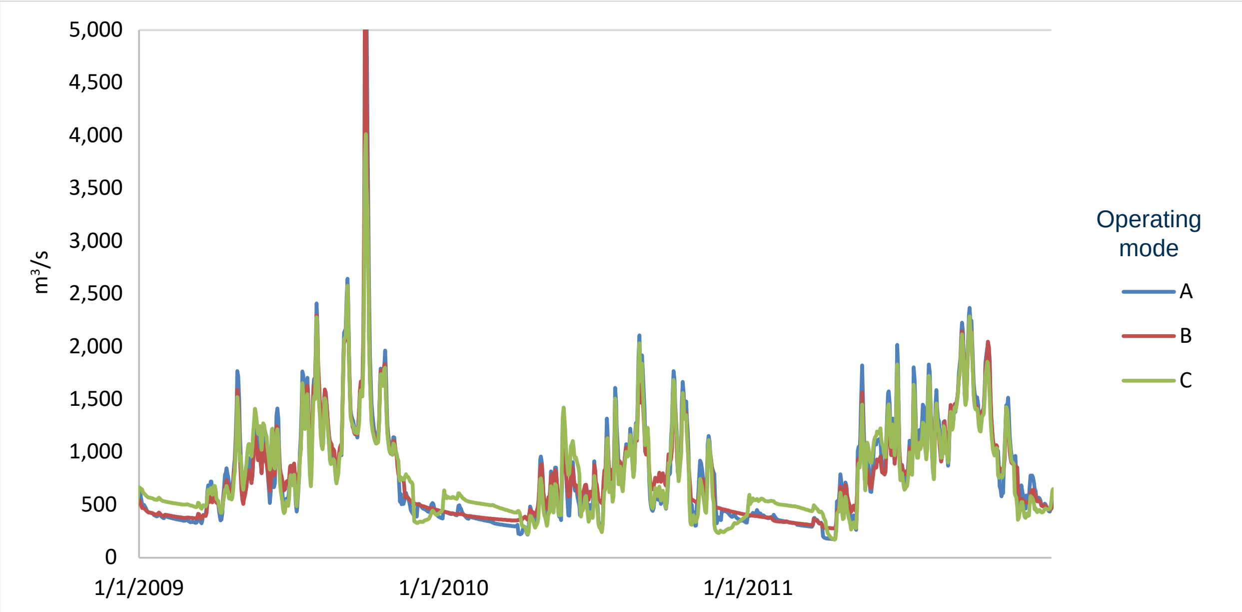
Note: GWh = gigawatt-hours.

Table G.2: Flow Comparison

Hydropower project	Estimated average flow, feasibility study	Average flow HEC-ResSim model	Model flow versus feasibility study	Adjusted improvement on feasibility study energy with equal annual inflow
	(m³/s)		%	
Sekong 5	125	91	74	10
Sekong 4B	132	117	89	14
Sekong 4A	227	184	81	18
Sekong 3A	247	213	86	-7
Sekong 3B	335	276	83	-6
Sekong Downstream B	399	316	79	8
Sekong Downstream A	796	798	100	15

Note: HEC-ResSim = Hydrologic Engineering Center - Reservoir System Simulation ; m³/s = cubic meters per second.

Figure G.4: Flow at Sekong Downstream A for Modeled Scenarios



Note: Design flow for Sekong Downstream A is 1,105 m³/s. Mode A = maximization of energy output; mode B = maximization of firm energy and power; mode C = dry season generation; m³/s = cubic meters per second.