Basin-wide Assessment of Climate Change Impacts on Hydropower Production

Final Report

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Mekong River Commission

Revision History

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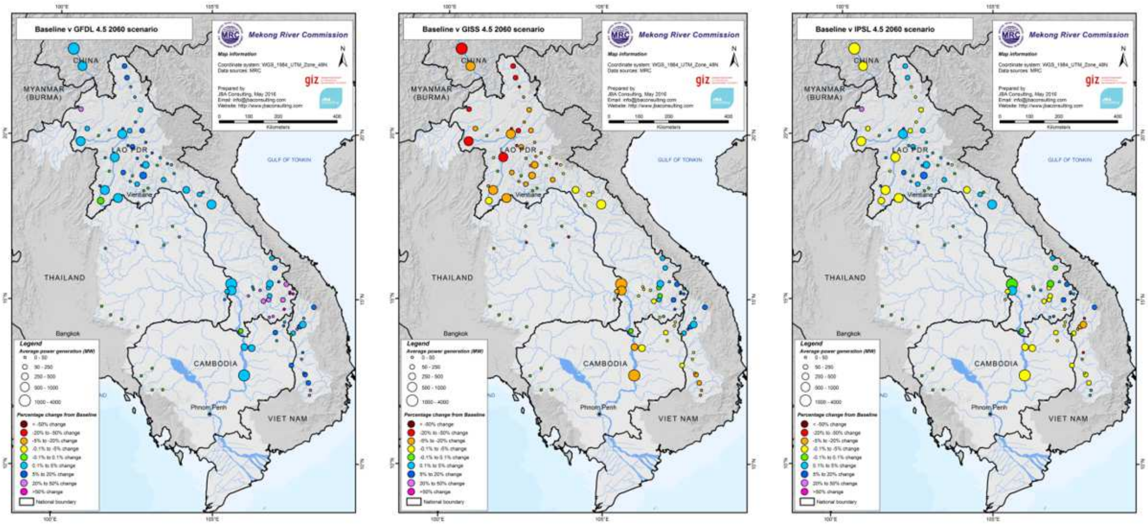
SUMMARY

Findings of the Analysis

Hydropower is seen by many including IPCC as a key component of a renewable energy policy for mitigating the effects of climate change. In the Lower Mekong Basin hydropower is seeing a rapid increase in the construction of new facilities and it is expected that annual power generated will increase from 27.4 TWh/yr to 128.1 TWh/yr (468%) between 2010 and 2060. Although this is a very significant increase, the total estimated electricity demand in the four LMB countries in 2025 is estimated at 820 TWh (ICEM 2010) so hydropower regionally can supply only part of the total demand.

Reservoirs built for hydropower generation typically can be put to multiple uses and many impact positively on water supply in dry season and flood control in the wet season. Such uses can be part of an adaptation strategy in the case of increasing flood and drought. In the Mekong hydropower is typically being constructed as Build Operate Transfer (BOT) schemes so scope to influence operations during the concession period once contracted may be limited so early forward planning for a multipurpose role of the reservoirs under a changed climate is desirable.

Study results showing the impact of climate change on hydropower generation in the Mekong basin are presented in this report. CCAI carefully selected 9 climate scenarios covering different emission assumptions and climate model (GCM) indications of change. Different climate models behave quite differently in their projections of precipitation change for the same emission scenarios so the selection tries to cover the full range of projected change. The climate scenarios used were classified by CCAI as 'Wetter', 'Drier' or 'Seasonal Change' dependant on the GCM model. The projected changes were then run in the MRC hydrological models incorporating development changes for epochs based on 2030 and 2060. Hydrological results are available for 3 different IPCC AR5 emission scenarios RCP2.1, RCP4.5 and RCP8.5 giving 9 scenarios per epoch tabulated in Table 1. In the 2060 scenarios considered there is a range of positive and negative change varying in magnitude and spatial extent as shown in Figure S1.



FigureS0.1 Change in Mean Annual Hydropower Production for 3 Scenarios all 2060 RCP4.5, blue indicates strong increase yellow – red indicates reduction in power. Seasonal Change on right hand side suggest a positive change in Northern Laos but decrease in mainstream dam generation and 3S basin. Full results for all scenarios are given in Appendix 1.

There are few comparable studies but the new results suggest more impact on hydropower production in the Mekong basin than the Asian average change given by IPCC, whose Special Report on Renewable Energy indicates likely changes of a few percent in Asia (SRREN 2011). Other studies, especially where glaciers and areas of snow melt are important show greater change and this study also finds the greatest changes to occur in the upper Mekong/Lancang basin or at the mainstream dams most dependent on flow from there.

In the LMB, for a ‘wetter’ scenario, water yields increase and as a result hydropower potential increases as would be expected. Sustained increases of 5% or more would significantly improve the returns on hydropower investment. On the other hand the drier scenario impacts heavily even on average hydropower production though mainstream dams are more affected. The Seasonal change scenario has a negative impact in Vietnam (-4.2%) for a moderate climate emission and hence warming (RCP4.5) but a lesser reduction for a more severe emission scenario RCP8.5 indicating the complex interplay of reservoir storage, inflows, power releases and spills shown in Table S1.

	Wetter RCP2.6	Drier RCP2.6	Seasonal RCP2.6	Wetter RCP4.5	Drier RCP4.5	Seasonal RCP4.5	Wetter RCP8.5	Drier RCP8.5	Seasonal RCP8.5
Cambodia	-0.5%	-1.3%	-0.1%	3.2%	-6.7%	-1.2%	3.8%	-17.7%	-1.5%
China	0.5%	-3.0%	-1.1%	2.3%	-19.4%	-5.3%	4.2%	-40.8%	-19.1%
Thailand	-0.2%	-4.5%	-3.3%	3.1%	-16.8%	-0.4%	5.3%	-39.5%	-2.2%
Vietnam	1.4%	0.8%	0.0%	8.0%	1.2%	-4.2%	9.0%	0.7%	-0.1%
Laos	5.8%	-1.9%	0.0%	5.6%	-12.1%	0.7%	7.5%	-31.1%	-0.7%

Table S 1 Projected change in Annual Average Hydropower Production in 2060 relative to the baseline climate.

Of possibly greater concern is the analysis of the change in hydropower production potential in a dry year. The changes in potential minimum generation in a dry year are greater than the change in the average generation and may be close to zero in some areas during critical parts of the season using operating rule curves based on the baseline climate.

Implications for Adaptation Strategy

It is already apparent that Hydropower construction in the LMB is proceeding rapidly as a means of economic and social advancement using a proven renewable resource. This change over could be incorporated in the design of plants that do not yet exist. Operation of existing dams in the future could also be changed as an adaptive measure depending on actual changes of climate experienced.

Whilst average energy production may actually increase or not be impacted greatly by climate change, more extreme dry periods in the majority of scenarios may significantly reduce the dependable energy potential and for those periods alternative sources of power will be needed. One potential is to harness some of the reservoir area for solar power generation. Better monitoring and forecasting of available water in storage and natural inflows could also help reduce the most severe shortages.

It is not yet clear if there will be increases in hydropower generation potential due to climate change due to the uncertainty of the future projections but if this is the case then the regulatory regime should be such that government revenues increase as a result.

The study has not been able to address the issue of increased extreme flood flows that may influence spillway design and thus safety of the dam and the downstream areas at risk. To do this more study of extreme rainfall and flows generated is needed that was beyond the scope of this work and the accuracy of analysis that could be done on the 24 year time series of simulation available.

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1 Introduction

1.1 Project Background and aims

The Mekong River Commission (MRC) Climate Change Adaptation Initiative (CCAI) is seeking to enhance regional capabilities in climate change adaptation.

One of the priority activities of CCAI is a basin-wide assessment of climate change impacts on various sectors including hydropower production potential:

- Flood
- Drought
- Fisheries
- Ecosystems
- Food Production and Food Security
- Hydropower

This is expected to inform preparation of the Mekong Adaptation Strategy and Action Plan (MASAP).

This assignment covers analysis of the impact of climate change on Hydropower Potential in the Lower Mekong Basin. The main aim of the study is to provide relevant indicators **of change in potential hydropower generation** for the LMB. This has been done primarily by utilizing the existing IQQM Water Resource modelling completed for CCAI by IKMP Modelling Team (MT). The report should be read in conjunction with the assessment reports for other sectors including particularly scenario formulation, initial change factors, Hydrological Assessment, Drought Indicators and Basinwide flood (MRC CCAI 2015a-d). This study of hydropower production fits into the overall workplan as shown in Figure 1.1.

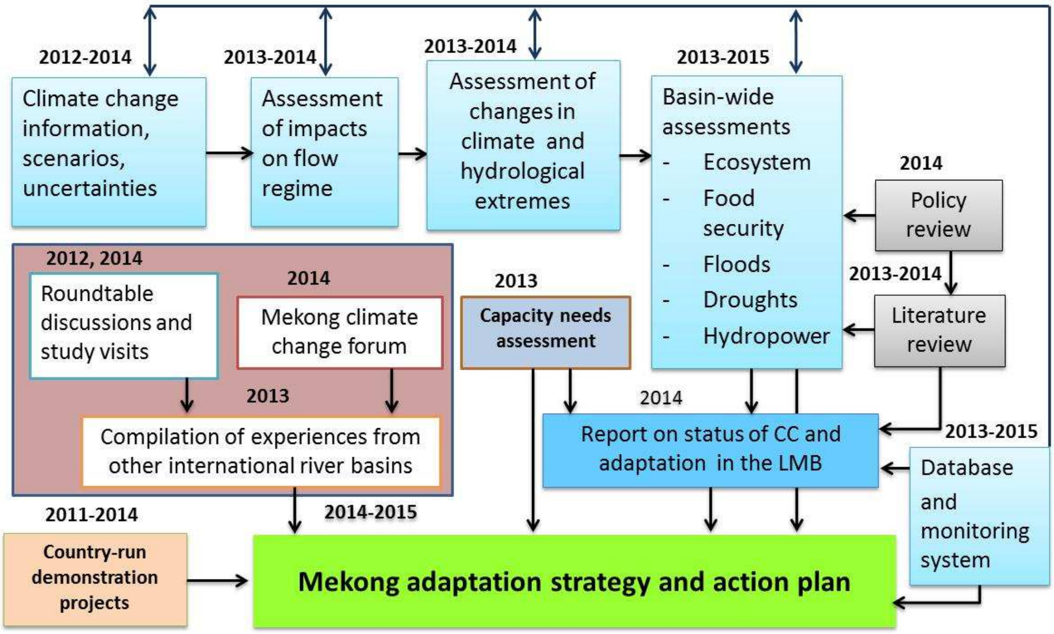


Figure 1.1 MRC CCAI Programme of Work to produce the first Mekong Adaptation strategy and action plan

In recent decades, the Mekong River Basin countries have experienced rapid economic growth which has been accompanied with increasing demand for electricity. Hydropower is recognized as an important energy source for the Mekong River Basin countries.

Climate change is expected to have significant implications for hydropower development in the Mekong basin. In 2009, MRC carried out the first assessment of impacts of climate change and development on the Mekong flow regimes (MRC, 2009). The assessment results indicated that Mekong flow regimes will be affected significantly by climate change and large-scale water resources development. However, the study recommended that further works need to be carried out to reduce uncertainties in climate change projections and to enhance model capacity for improving accuracy of model simulations and impact assessment. The CCAI studies aim to address this uncertainty using the latest available models and techniques. However although the future temperature projections from different models are in broad agreement, the direction of change in precipitation is less clear, scenarios have been selected to cover the range of possible futures and other studies commissioned to determine the approaches to be taken for adaptation planning.

In the Mekong as a whole, flows only from the upper basin are influenced by conditions of glacier change, snowmelt and permafrost which are all sensitive to a changing climate including the effects of temperature thus a comprehensive modelling of the impact of climate change is needed and the results translated to each sector (Figure 1.2).

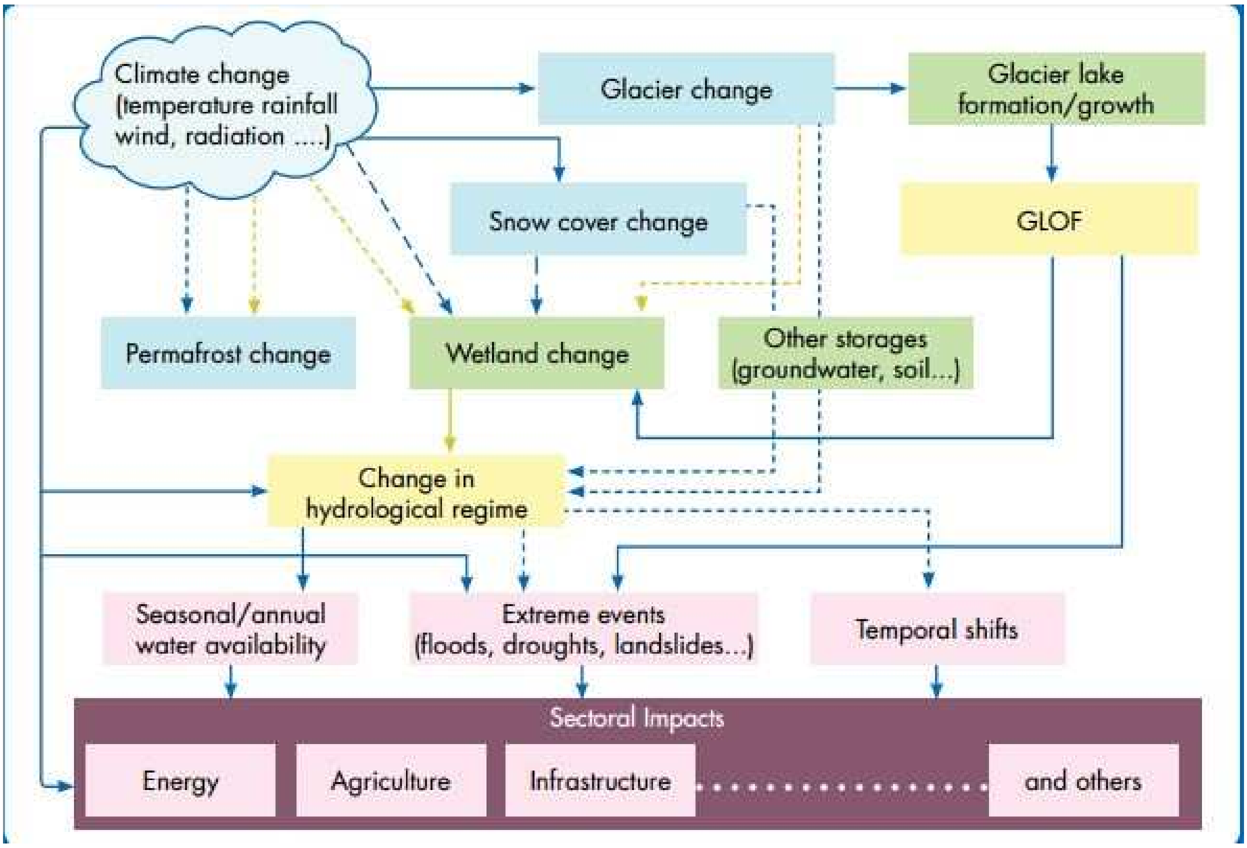


Figure 1.2 Linkages between Changes in Climate and changes in the hydrology and impact to sectors including hydropower (After ICIMOD 2016). Although glacial lakes are identified in this figure, the small extent of glacier in the upper Mekong would suggest this is unlikely threat and more likely is landslide blockages of the river or into an existing reservoir,

1.2 Scoping Study on Climate Change and Hydropower in the Mekong River Basin: a synthesis of research.

In 2014 a scoping study for Climate Change and Hydropower commissioned by GIZ for CCAI provides a literature review of studies related in particular to climate change, hydrological processes and hydropower development in the Mekong River Basin (MRB) (Beilfuss & Triet, 2014). The study assesses the impact of climate change on existing and potential hydropower development and the role which hydropower development in the MRB may have on mitigating climate change impacts but found no quantitative information. In Chapter 3 this is therefore presented.

As changes to reservoir inflows are uncertain, the impact on climate change to potential hydropower generation is also uncertain. The study suggests that the impact on hydropower generation of changes in Mekong discharges will depend on the design and operation of the infrastructure. Larger reservoir systems have the capacity to store inflows which may be able to provide buffering to increased variability of flows however no quantitative data is presented.

Other climate change impacts on potential hydropower generation discussed include reservoir evaporation, altered timing of reservoir inflows, extreme flooding events and reservoir sedimentation. Extreme flood volumes may affect the risk of structural failure of dams or key hydraulic components.

The study highlights that large-scale hydropower development in the MRB offers an opportunity to reduce Green House Gas (GHG) emissions compared to fossil fuel intensive energy development. However, although large scale hydropower reservoirs in the MRB have the potential to mitigate climate change impacts by providing water supply and reducing the impact of extreme events on populations, the reservoirs are currently optimised for hydropower production rather than for multiple benefits. There are however, a growing number of scientific studies that suggest that tropical reservoirs may be significant sources of methane emissions, and may offset the beneficial effects they have in climate change mitigation efforts.

2 Approach for the Basinwide Assessment of Climate Change Impact on Hydropower Potential

2.1 Introduction

The basinwide assessment makes use of available outputs and data from MRC modelling tools that use inputs provided by Member countries to the MRC. Changes in actual hydropower generation are occurring due to rapid development of new hydropower so for determining the impact of climate change care must be taken to compare ‘like for like’ simulations that have a change in climate only. There would be a mismatch for example if an MRC 2007 baseline was directly compared with a 2030 or 2060 scenario simulation for particular dams for example as the scenario includes other development changes.

2.2 Definitions of Potential Hydropower Generation

‘Hydropower Potential’ has more than one facet so it is worth to set out the working definitions to be used in the analysis.

The maximum potential or ‘Gross Potential’ is the theoretical maximum power available when all flow in all rivers is harnessed to generate hydropower making use of the whole topographic potential for driving water level difference. This theoretical potential is the maximum power that could possibly be generated and is not constrained by turbine capacity or storage. This is illustrated as Case 1 in Figure 2.1. This theoretical maximum hydropower production would be affected by a changing climate if this affected flow and water yields.

In reality this Gross Potential cannot be realized for a number of reasons such as geological constraints on where plant can be sited or other environmental reasons so a reduced Hydropower Potential that is still theoretical can be calculated as illustrated as case 2 in Figure 2.1. This is also referred to as the ‘Technical Hydropower Potential’.

The actual maximum hydropower potential in a river system is constrained by the installed capacity of turbines and storage and this is illustrated as Case 3 in Figure 2.1.

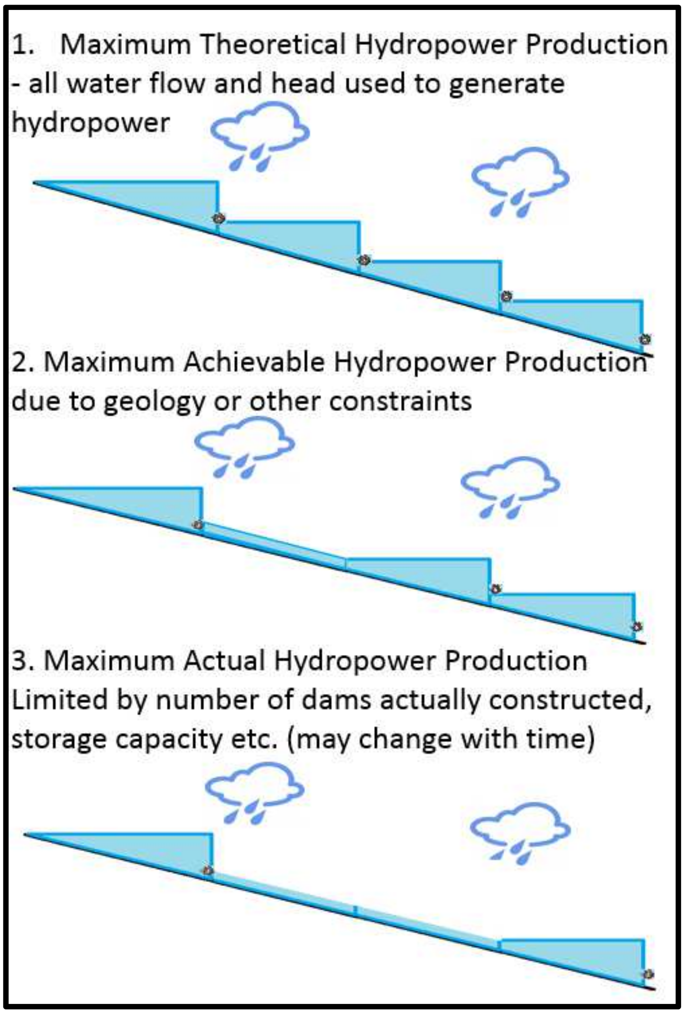


Figure 2.1 Definitions of Hydropower Potential

The maximum actual hydropower generation potential in the Lower Mekong Basin is changing rapidly due to the ongoing construction of new dams and power plants.

2.3 Change in Hydropower Production Potential

The modelling completed for CCAI by IKMP forms the basis of the data used for this study and is thus consistent with the other sector studies and uses the same scenarios and approach. Using the model results gives an estimate of the actual hydropower production potential (ie Case 3 in the definitions above) but as mentioned in section 2.1 comparisons must be made for scenarios where climate is the only variable that is changed.

Because hydropower in the LMB is relatively undeveloped in the 2007 Baseline condition, analysis of the hydropower dams relative to the baseline infrastructure does not give a good representation of the **changes in the total hydropower potential** as there were only a few dams and generating stations already developed in 2007. It is believed that the change in potential should be concerned more with the change in potential in the future when as envisaged by the MRC Member Countries there will be a large number of hydropower stations.

The 2030 scenarios modelled by IKMP include more hydropower stations than in the baseline 2007 as there is rapid development expected but it is in the 2060 simulations that there are a wide number of hydropower stations included in the modelling. The 2060 Scenarios thus give us a better estimate of the change in total hydropower potential.

The 2030 and 2060 Infrastructure were thus used in models rerun with the existing (1985-2008) climate input to give changes from the baseline dependent only on climate change as needed for this project. The modelling includes other development changes such as increased irrigation or urbanisation but these are the same in the model scenarios being compared.

2.4 CCAI Hydropower Indicators

CCAI monitoring of Hydropower Production is to be based on the Indicator of Annual Hydropower Generation in the whole LMB expressed in GigaWatt Hours per year (GWh/y). As GWh/yr gives a large number, in this report Terra Watt hours/year are also used which is a factor of 1000 less than GWh/y ie 1TWh/yr is 1000GWh/y.

Average daily Power Generation can also be useful to consider especially when there is a requirement for a baseload supply of electricity but potentially a seasonally influenced supply thus for a daily average hydropower output is also used expressed in terms of MW.

Indicators of hydropower production have been analysed based on the country the dam is located in as well as whether the dam is situated on the Mekong or a tributary of the river.

Other hydrological indicators may be relevant and these are considered further in Chapter 7 but are primarily part of the hydrological assessment.

2.5 Available data

Recently the SWAT, IQQM and ISIS models have been upgraded for basin-wide assessment of climate change and water resources development impacts on hydrology, flood, drought, food and energy security and ecosystem for the Lower Mekong Basin (IKMP 2013). CCAI has updated new knowledge and databases of climate change projections according to the 5th Assessment Report of Intergovernmental Panel on Climate Change (IPCC) which was released in 2013. The uncertainties of climate change projections are investigated (CCAI, 2015a). New climate change scenarios are defined for the Lower Mekong Basin (LMB) in order to use for basin-wide assessment of climate change impacts on water and water related resources and sectors (CCAI, 2015b).

Final versions of the Integrated Quantity and Quality (IQQM) models were obtained for each of the relevant scenarios. Power generation for each dam in each scenario was extracted from the IQQM models for analysis. Storage areas for the baseline 2060 dams were extracted to evaluate evaporation losses. Flood flows have been considered but the very short time series for estimation of flood statistics is not used and future work is needed.

2.6 Development and Expected Hydropower Construction

Indicators of Hydropower production were extracted for a range of development and climate change scenarios. The near-term future centred on 2030 (2021-2040) and medium-term future centred on 2060 (2051-2070). Basin-wide water resource development scenarios were formulated by BDP2 to represent different combinations of nationally planned sector development, particularly in active water use. This includes developments for domestic and industrial water use, irrigation, hydropower and flood control (BDP phase 2, 2011). These development scenarios are used in the available modelling though in this study only changing relating to hydropower production are analysed and reported. The number of dams modelled during each scenario is shown in Table 2.1.

Of the dams modelled the proportion of mainstream to tributary dams in 2030 is 17 mainstream (including 6 large Chinese dams) 74 on tributaries in LMB and in 2060 the same 17 mainstream dams are modelled but 99 tributary dams are included. The Gross Storage associated with the modelled dams is highlighted in Figure 2.2.

The dams on the mainstream in China have by far the greatest storage than the proposed mainstream dams in the LMB which have little storage and are thus effectively ‘run-of-river’. This does not however mean that they operate with a natural flow as the flows in the mainstream Mekong of the LMB are heavily dependent on the releases from upstream storage especially in the dry season.

Country	Baseline (2007)	2030 scenarios	2060 scenarios
Cambodia	1	8	12
Lao PDR	5	51	72
Thailand	12	11	12
Vietnam	5	14	14
China	2	6	6
Total	24	91	116

Table 2-1 Number of dams modelled in each ‘epoch’ for CCAI by IKMP(2014) using updated models

Country	**Development 2007**			**20-Year Plan 2030**			**Long-Term Plan 2060**		
	No	Installed capacity (MW)	Live storage (10^6 m3)	No	Installed capacity (MW)	Live storage (10^6 m3)	No	Installed capacity (MW)	Live storage (10^6 m3)
Lao PDR	11	662.4	5,639.0	56	18,335.7	40,127.5	84	20,271.9	50,273.8
Thailand	7	744.7	3,566.3	7	744.7	3,566.3	7	744.7	3,566.3
Cambodia	1	1.0	0.1	4	4,761.0	2,449.5	11	5,507.0	15,714.5
Vietnam	5	1,104.0	789.8	15	2,583.0	3,155.7	15	2,583.0	3,155.7
China	2	2,900.0	624.0	6	15,450	23,193.0	6	15,450	23,193.0
Total LMB	**24**	**2,512.1**	**9,995.2**	**82**	**26,424.4**	**49,299.0**	**117**	**29,106.6**	**72,710.3**
Total MB	**26**	**5,412.1**	**10,619.2**	**88**	**41,874.4**	**72,492**	**123**	**44,556.6**	**95,903.3**

Table 2-2 Hydropower Capacity and Storage Volumes used in BDP2 (2010). Note small changes where data has been updated relative to Table 2.1

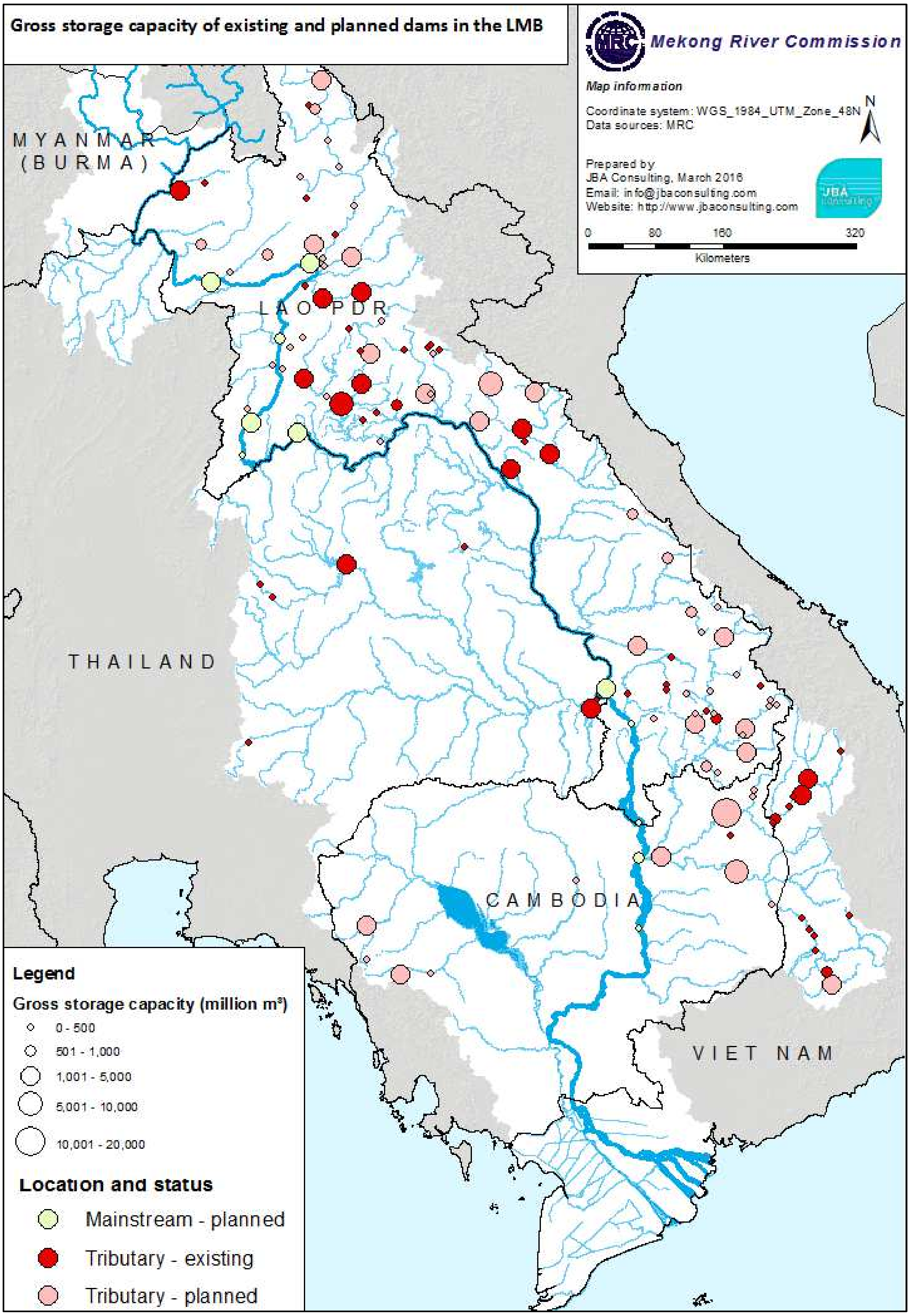


Figure 2.2. Hydropower projects (existing and planned in 2016) and their gross storage capacities.

2.7 MRC Significant Tributaries Study – Hydropower (Muir, 2010)

Muir (2010) describes work completed on the hydropower aspect of the multivariate approach to assessment of tributary significance for MRC. The study was not concerned with Climate Change but gives much useful analysis of hydropower potential and the available modelling in 2010.

Hydropower development existed or was under construction, licensed or planned in 26 Mekong tributary basins. The total installed capacity of the tributary dams was 14,992.3MW and 15,443.4MW for 2009 dams and 2010 updated dams respectively. The most important tributary basins for energy production include Se Kong, Nam Cadinh, Nam Ngum, Nam Ou and Nam Nhiep.

Muir quotes earlier studies of the technical hydropower production potential (See Section 2.1 Case 2) in tributaries from two earlier studies for context:

Country	Mekong Secretariat[1/]		WATCO[2/]	
	Installed Capacity[3/] (MW)	Energy Production[3/] (GWh/a)	Installed Capacity[3/] (MW)	Energy Production[3/] (GWh/a)
Cambodia[4/]	13,258	70,093	1,540	7,681
Lao PDR			11,546	56,995
Thailand[5/]			401	1,157
Viet Nam[6/]			1,934	9,611
Total			15,421	75,444

Table 2-3 Technical Hydropower potential in Tributaries according to studies in 1970 and 1984 (See Table 2.1 for definition of technical potential which is Case 2)

1/ "*Inventory of Promising Tributary Projects in the Lower Mekong Basin - Volume II: Laos*" [Mekong Secretariat, 1970]. Volume I (Khmer Republic and Viet Nam) and Volume III (Thailand) were not available in MRC's library in Vientiane.

2/ "*Lower Mekong Water Resources Inventory - Summary of Project Possibilities*" [WATCO, 1984].

3/ Mainstream dams are not included in the table 2.3.

The study discussed the hydropower generation potential of the LMB and compared the MRC modelling for BDP (table 2.2) with the available figures from Member Countries that are compiled into the ISH Hydropower database. It was concluded that for the purpose of the significance studies there was a difference that could not be ignored without further investigation. Subsequently both models and the database have been updated.

2.8 MRC Hydropower Database (2010 and 2015)

The MRC Hydropower database of 2010 was updated by ISH in 2014/15 to include the latest available data in Member Countries. The total planned energy production by all the planned tributary projects is 65.2 TWh, whereas mainstream dams are planned to generate 62.9TWh as shown in Table 3.2 below.

Status[1/]	E		C		L		PP		PH		Total		
	Existing		Under Construction		Licensed		Planned (Level 1)		Planned (Level 2)				Total
Country	Main-stream	Tributary	Main-stream	Tributary	Main-stream	Tributary	Main-stream	Tributary	Main-stream	Tributary	Main-stream	Tributary	All Projects
Cambodia		3		1,954			11,740	2,780	5,096	2,784	16,836	7,520	**24,356**
Lao PDR		15,265	6,035	12,546	5,126	9,744	24,560	6,830			35,721	44,385	**80,106**
Thailand		904										904	**904**
Vietnam		11,184		1,056				181				12,422	**12,422**
Lao - Thai					5,015		5,318				10,333		**10,333**
Total LMB		**27,356**	**6,035**	**15,556**	**10,141**	**9,744**	**41,618**	**9,791**	**5,096**	**2,784**	**62,891**	**65,230**	**128,121**

Table 2-4 Hydropower Production totals from MRC Hydropower Database (GWh/year). "Lao-Thai" indicates transboundary projects where the dam or reservoir spans the river where it forms the border between Lao PDR and Thailand.

It may also be observed that Hydropower production in the LMB is expected to increase from 27.4 TWh/yr to 128.1 TWh/yr (468%) due to new construction, a very significant increase.

Although the database has been updated by ISH there remain differences between the modelling and database values of expected energy production. The implications of this for the climate change study are to ensure that it is CHANGES that are considered rather than absolute values. The hydropower database containing the data received from Member Countries is thus considered our best estimate of energy production then where the modelling analysis differs from this it should be considered as giving relative changes due to the changing climate rather than absolute estimates of energy output.

2.9 Strategic Environmental Assessment (SEA) of Mainstream Dams (2010)

ICEM (2010) identified that, according to the designs at the time, the 12 proposed LMB mainstream dams represent up to 14,697 MW. (ICEM Australia, 2010). The annual power that LMB mainstream projects could competitively supply is 65TWh/yr, slightly less than the figure for tributaries given in the previous section (Table 2.3) but consistent with other studies.
The study did not consider Climate Change Implications.

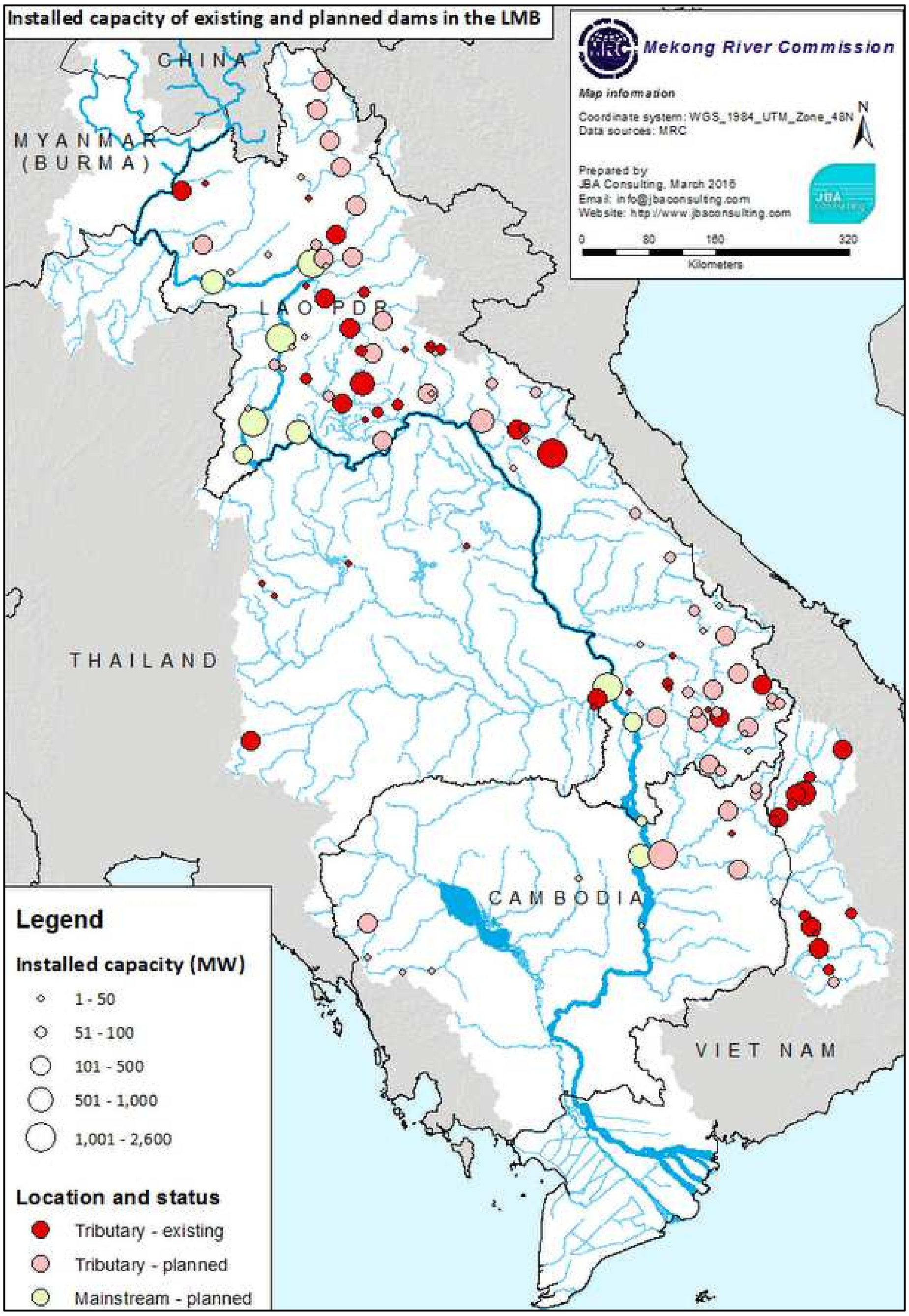


Figure 2.3. Hydropower projects (existing and planned in 2016) and their installed power capacities

3 Climate change scenarios

3.1 CCAI Scenarios

The climate change scenarios used in this study are consistent with those used in all other CCAI Basinwide Assessment studies and were carefully chosen from the completed list of available results from IPCC CMIP5 archive as described by Kiem et al (2013) and JBA 2014. The chosen results derive from the GISS, GFDL and IPSL general circulation models (GCMs) which were found to perform reasonably in terms of a monsoon climate. For each GCM three emission scenarios are assessed reflecting different development paths. Other changes are included in each scenario such as irrigation, dam development etc as used for BDP2 in 2010.

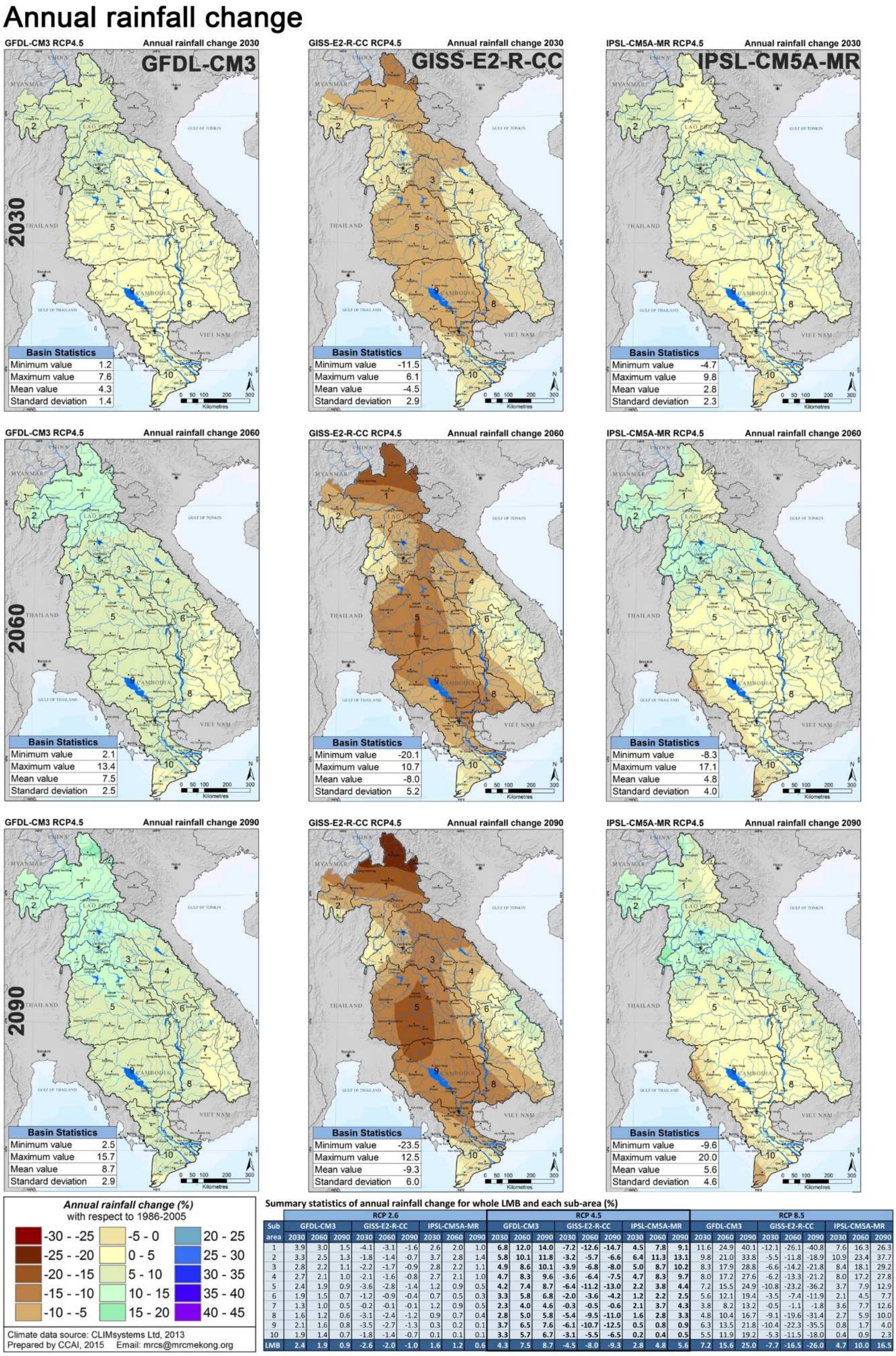
The three GCMs used in this study represent:

1. A ‘**drier overall’** lower bound of projected future impacts (GISS-E2-R-CC)
    a. Associated with an 8% decrease in annual basin wide rainfall under a medium emissions, 2060 scenario.
    b. Associated with a 1.6ºC increase in annual temperature under a medium emissions 2060 scenario.
2. A ‘**wetter overall’** upper bound of projected future impacts (GFDL-CM3)
    a. Associated with an 8% increase in annual basin-wide rainfall in a medium emissions, 2060 scenario.
    b. Associated with a 1.5ºC increase in annual temperature under a medium emissions 2060 scenario.
3. An ‘**increased seasonality**’ whereby a ‘drier’ dry season rainfall is combined with a ‘wetter’ wet season rainfall (IPSL-CM5A-MR).
    a. Associated with a 5% increase in annual basin-wide rainfall in a medium emissions, 2060 scenario. (-11% in the dry season and +8% in the wet season).
    b. Associated with a 1.5ºC increase in annual temperature under a high emissions 2060 scenario

The selected GCMs have been combined with various emissions scenarios (RCP2.1, RCP4.5 and RCP8.5) to provide a wide range of climate projections as shown in Table 3.1. The overall changes precipitation for RCP4.5 Scenarios are given in Figure 3.1. Water yield and other seasonal parameters are analysed in the hydrological assessment report.

No.	**Type of scenarios**		**Emission scenarios**	**GCM**	**Climate sensitivity**
	Level of change	**Pattern of change**			
Low climate change scenarios					
1	Low	Wetter overall	RCP2.6	GFDL-CM3	Low
2		Drier overall		GISS-E2-R-CC	
3		Wetter wet seasons & drier dry seasons		IPSL-CM5A-MR	
Medium climate change scenarios					
4	Medium	Wetter	RCP4.5	GFDL-CM3	Medium
5		Drier		GISS-E2-R-CC	
6		Wetter wet seasons & drier dry seasons		IPSL-CM5A-MR	
High climate change scenarios					
7	High	Wetter	RCP8.5	GFDL-CM3	High
8		Drier		GISS-E2-R-CC	
9		Wetter wet seasons & drier dry seasons		IPSL-CM5A-MR	

Table 3-1 Scenarios Used for CCAI Basinwide Assessments



Summary statistics of annual rainfall change for whole LMB and each sub-area (%)

	RCP 2.6									RCP 4.5									RCP 8.5								
Sub	GFDL-CM3			GISS-E2-R-CC			IPSL-CM5A-MR			GFDL-CM3			GISS-E2-R-CC			IPSL-CM5A-MR			GFDL-CM3			GISS-E2-R-CC			IPSL-CM5A-MR		
area	2030	2060	2090	2030	2060	2090	2030	2060	2090	2030	2060	2090	2030	2060	2090	2030	2060	2090	2030	2060	2090	2030	2060	2090	2030	2060	2090
1	3.9	3.0	1.5	-4.1	-3.1	-1.6	2.6	2.0	1.0	6.8	12.0	14.0	-7.2	-12.6	-14.7	4.5	7.8	9.1	11.6	24.9	40.1	-12.1	-26.1	-40.8	7.6	16.3	26.3
2	3.3	2.5	1.3	-1.8	-1.4	-0.7	3.7	2.8	1.4	5.8	10.1	11.8	-3.2	-5.7	-6.6	6.4	11.3	13.1	9.8	21.0	33.8	-5.5	-11.8	-18.9	10.9	23.4	37.7
3	2.8	2.2	1.1	-2.2	-1.7	-0.9	2.8	2.2	1.1	4.9	8.6	10.1	-3.9	-6.8	-8.0	5.0	8.7	10.2	8.3	17.9	28.8	-6.6	-14.2	-21.8	8.4	18.1	29.2
4	2.7	2.1	1.0	-2.1	-1.6	-0.8	2.7	2.1	1.0	4.7	8.3	9.6	-3.6	-6.4	-7.5	4.7	8.3	9.7	8.0	17.2	27.6	-6.2	-13.3	-21.2	8.0	17.2	27.8
5	2.4	1.9	0.9	-3.6	-2.8	-1.4	1.2	0.9	0.5	4.2	7.4	8.7	-6.4	-11.2	-13.0	2.2	3.8	4.4	7.2	15.5	24.9	-10.8	-23.2	-36.2	3.7	7.9	12.9
6	1.9	1.5	0.7	-1.2	-0.9	-0.4	0.7	0.5	0.3	3.3	5.8	6.8	-2.0	-3.6	-4.2	1.2	2.2	2.5	5.6	12.1	19.4	-3.5	-7.4	-11.9	2.1	4.5	7.7
7	1.3	1.0	0.5	-0.2	-0.1	-0.1	1.2	0.9	0.5	2.3	4.0	4.6	-0.3	-0.5	-0.6	2.1	3.7	4.3	3.8	8.2	13.2	-0.5	-1.1	-1.8	3.6	7.7	12.6
8	1.6	1.2	0.6	-3.1	-2.4	-1.2	0.9	0.7	0.4	2.8	5.0	5.8	-5.4	-9.5	-11.0	1.6	2.8	3.3	4.8	10.4	16.7	-9.1	-19.6	-31.4	2.7	5.9	10.0
9	2.1	1.6	0.8	-3.5	-2.7	-1.3	0.3	0.2	0.1	3.7	6.5	7.6	-6.1	-10.7	-12.5	0.5	0.8	0.9	6.3	13.5	21.8	-10.4	-22.3	-35.5	0.8	1.7	4.0
10	1.9	1.4	0.7	-1.8	-1.4	-0.7	0.1	0.1	0.1	3.3	5.7	6.7	-3.1	-5.5	-6.5	0.2	0.4	0.5	5.5	11.9	19.2	-5.3	-11.5	-18.0	0.4	0.9	2.3
LMB	2.4	1.9	0.9	-2.6	-2.0	-1.0	1.6	1.2	0.6	4.3	7.5	8.7	-4.5	-8.0	-9.3	2.8	4.8	5.6	7.2	15.6	25.0	-7.7	-16.5	-26.0	4.7	10.0	16.5

Figure 3.1 Annual Rainfall Change for different scenarios (from CCAI Atlas of Climate Change)

4 Previous Studies of Climate Change Impacts on Hydropower

4.1 Introduction

As noted in the Scoping Study (Beilfuss et al 2014) there are few available studies that have been able to quantify the effect of Climate Change on Hydropower production and most are purely descriptive. However, there are now some studies available for comparison and are presented in this chapter. The range of figures identified give confidence that the scenarios and analysis are comparable to study elsewhere.

4.2 Previous Studies on the Effects of Climate Change on Hydropower

4.2.1 IPCC Special Report on Renewable Energy Sources (SRREN)

Chapter 5 of the IPCC SRREN report is dedicated to hydropower (Kumar et al (2011)). Although the report is primarily about Renewal Energy in general, chapter 5 quotes a number of sources regarding the likely impact of Climate Change on Hydropower Production. The potential hydropower generation in Asia is highest of any in the world though as yet only a fraction of the potential is developed (Figure 1.2).

The change in production with Climate Change is linked closely with water yield changes which are presented at a global scale as shown in Figure 4.2 below. The Mekong region appears to be within a band of change for 2100 of 10-20%. The table of change presented in SRREN suggests lower change in Hydropower production to 2050 as shown in Table 4.1.

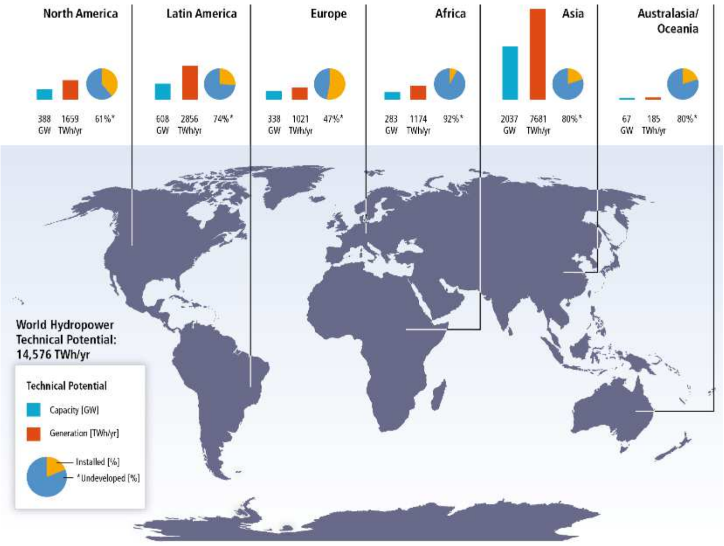


Figure 4.1 Global Potential for Hydropower Production (SRREN Kumar et al 2011)

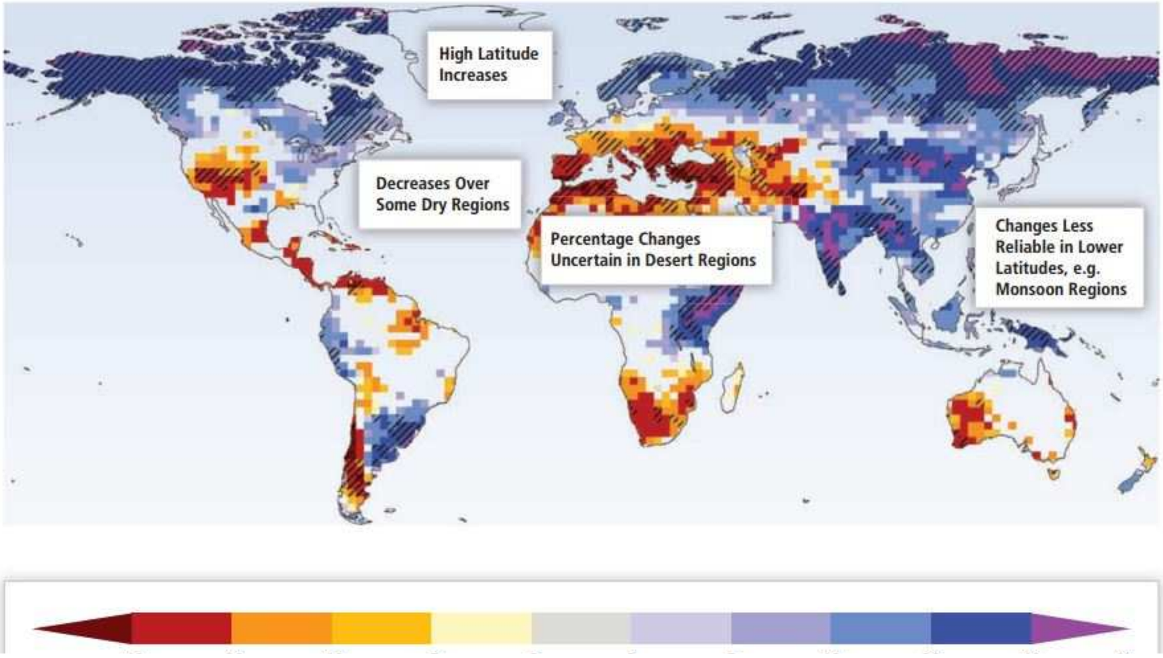


Figure 4.2 Global Distribution of Change in Runoff Median of 12 model projections for SRES A1B Scenario to 2099 as presented in IPCC SRREN report (2011)

The values extracted for the CCAI assessment is closer to the change in water runoff given in Figure 4.2 than the hydropower production changes quoted in SRREN.

REGION	Power Generation Capacity (2005)	Power Generation (2005)	Change by 2050	Change by 2051	Other Studies Quoted
	MW	TWh/yr	TWh/yr		
Africa	22	90	0	0.00%	
Asia	246	996	2.7	0.27%	
Europe	177	517	-0.8	-0.15%	-6% (2070)*
North America	161	655	0.3	0.05%	Some ++ others --*
South America	119	661	0.3	0.05%	
Oceania	13	40	0	0.00%	

*As quoted in Kumar et al IPCC SRREN report

Table 4-1 Changes in Global Hydropower Production with Climate Change (IPCC SRREN, Kumar et al (2011))

4.3 Studies of the Impact of Climate Change on Hydropower Potential outside of the Mekong

There are few studies that have reached any firm conclusions regarding the change in hydropower potential due to climate. Lutz et al (ICIMOD 2016) conclude that it is likely that the Brahmaputra and Ganges Basins will see an increase in flow from the Himalya whereas towards the end of the 21st century a decline in glacier melt will affect the Indus negatively. There is however uncertainty in the capacity of GCM models to predict changes in precipitation in the complex monsoon and orographic influences of the Himalayan mountain and Tibetan plateau.

Schaefli et al (2007) quantified likely changes in hydropower production in the Swiss Alps including consideration of the modelling uncertainties. They found that for the period 2070-2100 a significant negative impact could be expected. The median decrease was estimated as 36% relative to the control period. They also found that spillway flows could increase. The maximum seen previously for their case study dam of 60m3/s increased to 177m3/s in their simulations which had a median global increase in temperature of +2.6° C.

Ouranos (2015) studied the likely impact of Climate on the Probable Maximum Flood (PMF) for dams in Canada. Using regional climate models and estimates of changes in Precipitation (PMP) it was found that Median changes in PMF peak ranged between -0.8% to +20% but with substantial variation. The overall range of PMF-peak flows for all scenarios considered ranged from -25% to +90%. Changes in total PMF volume were generally less extreme than peak flows, and in many cases, projected reductions in snowpack partially offset the projected increases in PMP for the watershed.

5 Analysis of Hydropower production in the Modelling Results Available for CCAI

5.1 Modelled Hydropower Generation

The purpose of this study is to analyse the hydropower generation changes predicted in the existing modelling for CCAI. This modelling includes a long chain of work stemming from the first modelling by MRC for the decision support framework (DSF) in 2001-2004 through BDP2 in 2006-2010 and updating for FMMP and CCAI studies of climate change in 2013-2015. The inputs to the SWAT model are based on the observed timeseries of hydrological data available in 1985-2008 and calibration of the models to that time period. For future climate simulations the temperature, precipitation, windspeed, relative humidity are perturbed using change factors derived from GCM models and processed using the simclim software.

The results of the SWAT model are fed into a basinwide water resource model 'IQQM' which includes simulation of irrigation, other water uses and hydropower generation. Hydropower operations are simulated using rule curve of monthly releases for a particular reservoir pond level. An efficiency is applied. The rule curve is derived using an optimization routine to maximize the power generation for particular storage, inflow and turbine capacity.

Each reservoir is represented specifically in the model and rule curves are derived based on the overall configuration taking account of the upstream degree of control and expected releases. Thus different control curves may be applied for 2007, 2030 and 2060 simulations at a particular reservoir.

The IQQM program was used by IKMP provide an estimate of the hydropower production for each scenario simulated. The 2030 and 2060 Scenario simulations have changes in both infrastructure (dams, irrigation, water consumption) and climate. For this study two additional runs were performed so a direct comparison could be made for the change due to climate only:

1. 2030 Infrastructure run with Baseline 1985-2008 Climate
2. 2060 Infrastructure run with Baseline 1985-2008 Climate

For either 2030 or 2060 Infrastructure the impact of climate change on hydropower production could then be calculated by taking the difference between a scenario and the corresponding 'baseline climate' simulation.

Analysis of the hydropower production potential indicated in 2060 by the model reveals:

Average in GwH	Baseline
China	79,197
Cambodia	27,329
Thailand	875
Vietnam	10,341
Laos	92,951
Main	154,457
Tributary in LMB	56,235
Mainstream LMB only	75,261

Table 5-1 Simulated Energy Production in IQQM for Baseline Climate using all dams expected to be in operation by in 2060

It can be seen that the model is giving hydropower production values for tributary dams that are somewhat lower (56TWh/year) than those given by Member Countries in the hydropower database for all tributary dams (65 TWh/year) but slightly higher values for LMB mainstream dams (75 TWh/year compared with 63 TWh/year). The differences for tributary dams are likely to be due to refinements in the estimation of flows in tributaries for the hydropower studies of individual dams compared with the overall basinwide model used by MRC. For mainstream dams the simplified simulation in IQQM that does not take account of backwater effects which affect generation for mainstream dams. The energy from mainstream dams is slightly overestimated, and so a correction is applied in the calculations to allow for this.

Figure 5.1 and Figure 5.2 show the simulated average hydropower outputs for the 2030 and 2060 baseline scenarios in the Lower Mekong Basin countries and the main dams included in the China part expressed as average power production (MW).

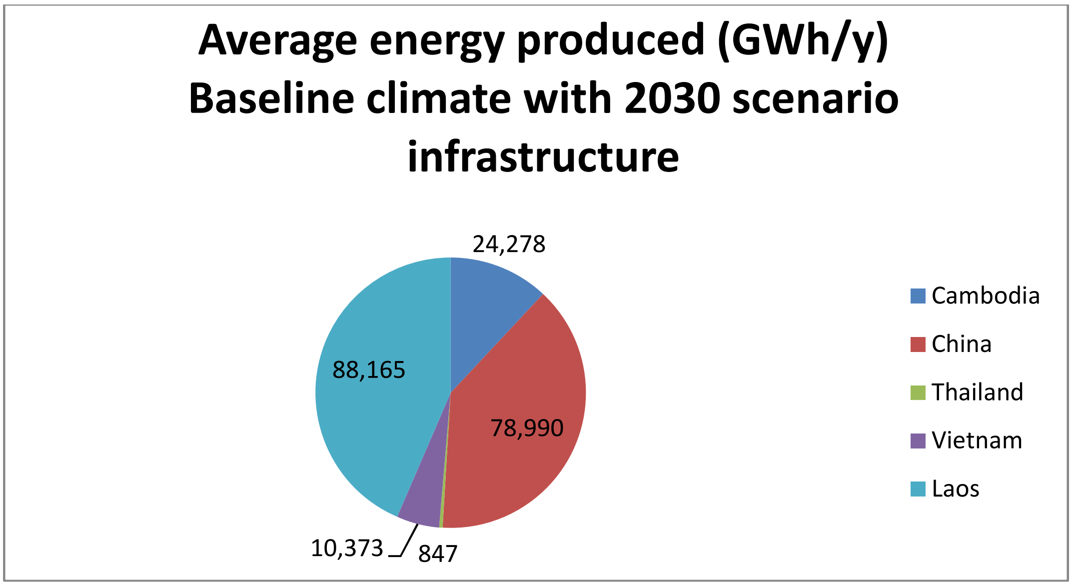


Figure 5.1: Average energy produced per country simulated; Baseline Climate 2030 scenario dams

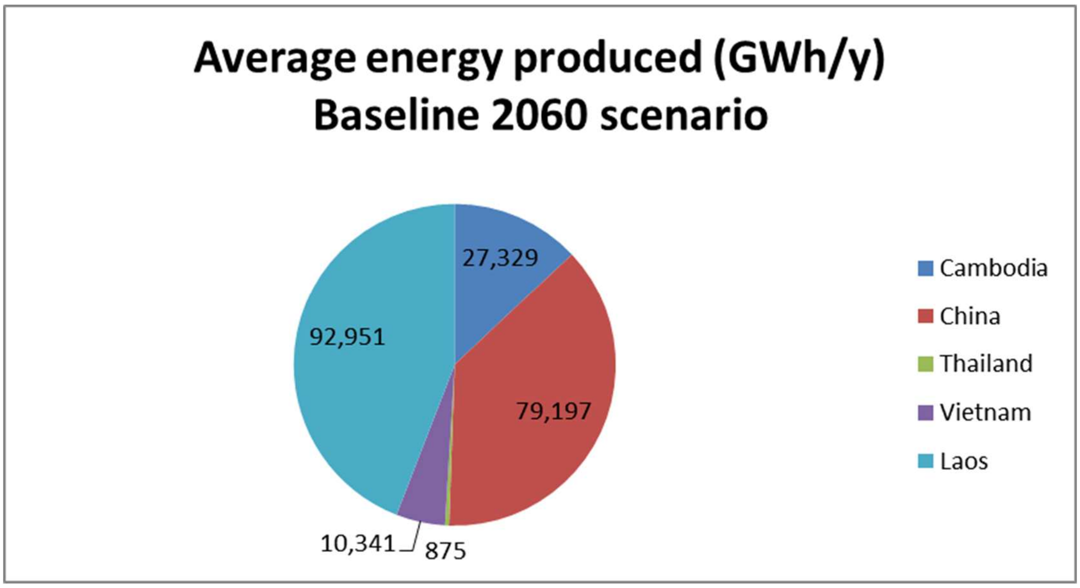


Figure 5.2: Average energy produced per country; Baseline Climate 2060 scenario dams

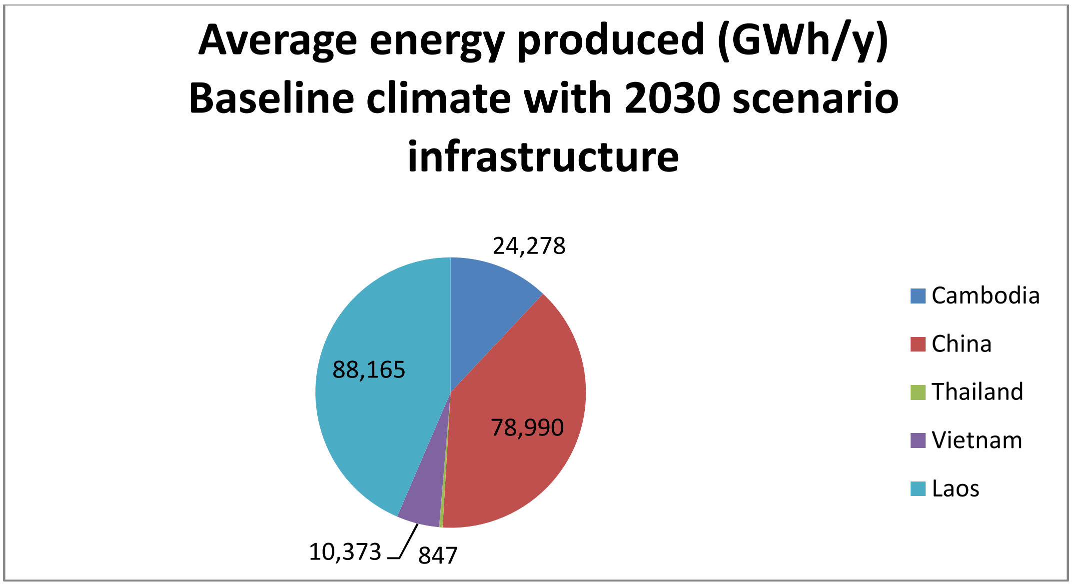


Figure 5.1s 5.1 and 5.2 show in both scenarios Laos and China are the dominant producers of hydropower energy in the Mekong Basin. Thailand is the smallest producer. The proportion of energy produced by each country is not similar for the 2030 and 2060 development scenarios although total amounts generated are higher in 2060.

5.2 Change in Average Hydropower Production for various Climate Change Scenarios.

5.2.1 Percentage change in Energy Production 2030 dams

Figure 5.3 and Table 5-2 show the percentage change in the average energy production in each country emissions climate change scenarios during 2030 compared to the 2030 baseline.

Figure 5.3: Percentage change in energy production under 2030 scenarios

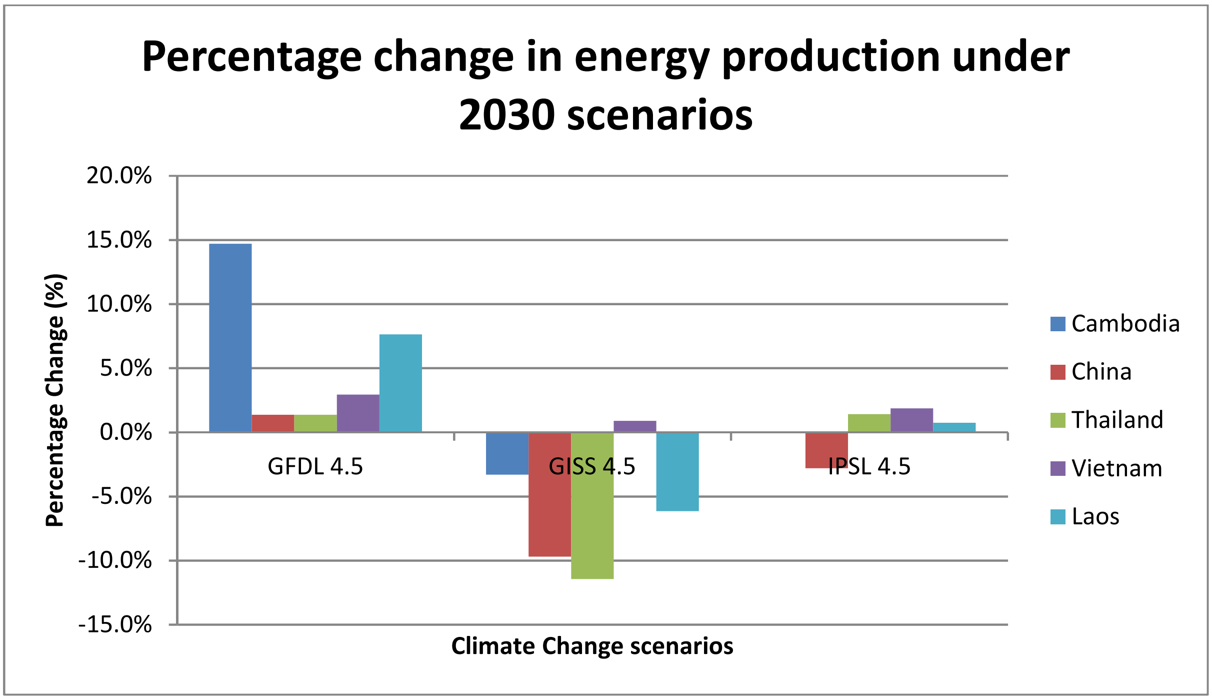


Table 5-2: Percentage change in energy production under 2030 scenarios

	GFDL 4.5	GISS 4.5	IPSL 4.5
Cambodia	14.70%	-3.30%	0.00%
China	1.40%	-9.70%	-2.80%
Thailand	1.40%	-11.50%	1.40%
Vietnam	2.90%	0.90%	1.90%
Laos	7.60%	-6.20%	0.70%
LMB basin-wide change in annual water yield	5%	-8%	2%

For the ‘drier’ GISS scenario, all countries apart from Vietnam see a decrease in energy production. The largest decrease in energy production is seen in Thailand. For the ‘wetter’ GFDL scenario all countries see an increase in energy production. For the ‘increased seasonality’ IPSL scenario there is no change in Cambodia and a small increase in Thailand, Vietnam and Laos. There is a small decrease in energy production in China for the IPSL scenario.

5.3 Percentage change in Energy Production 2060 dams

Figure 5.4 and Table 5-3 5.3 show the percentage change in the average energy production in each country for the climate change scenarios during 2060 compared to the 2060 baseline.

Figure 5.4: Percentage change in energy production under 2060 scenarios

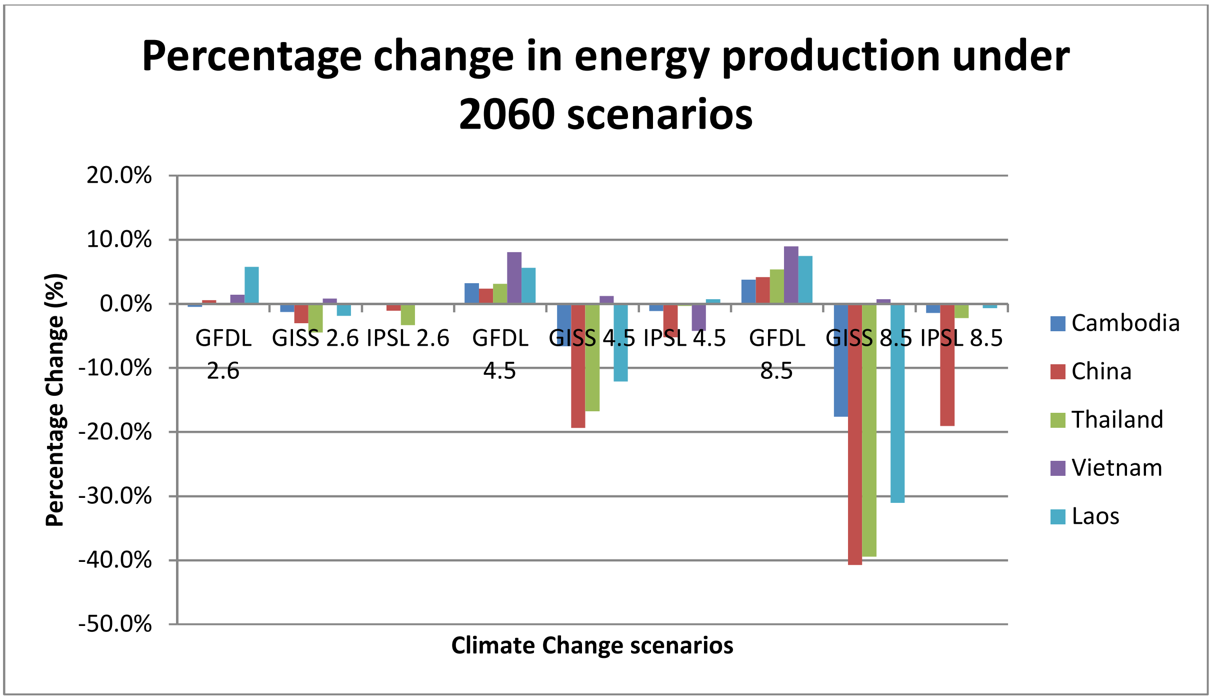


Table 5-3: Percentage change in energy production under 2060 scenarios and the basin-wide change in annual water yield.

	GFDL RCP2.6	GISS RCP2.6	IPSL RCP2.6	GFDL RCP4.5	GISS RCP4.5	IPSL RCP4.5	GFDL RCP8.5	GISS RCP8.5	IPSL RCP8.5
Cambodia	-0.50%	-1.30%	-0.10%	3.20%	-6.70%	-1.20%	3.80%	-17.70%	-1.50%
China	0.50%	-3.00%	-1.10%	2.30%	-19.40%	-5.30%	4.20%	-40.80%	-19.10%
Thailand	-0.20%	-4.50%	-3.30%	3.10%	-16.80%	-0.40%	5.30%	-39.50%	-2.20%
Vietnam	1.40%	0.80%	0.00%	8.00%	1.20%	-4.20%	9.00%	0.70%	-0.10%
Laos	5.80%	-1.90%	0.00%	5.60%	-12.10%	0.70%	7.50%	-31.10%	-0.70%
LMB basin-wide change in annual water yield	2%	-4%	1%	8%	-14%	-1%	19%	-31%	20%

Figure 5.4 and Table 5-3 clearly show that for most countries energy production decreases during the 'drier' GISS scenarios. The biggest decrease is seen in China and Thailand in the high emissions GISS RCP 8.5 scenario. Even in the medium emissions scenario most countries still see a significant decrease in energy production (between 6% and 20% decrease). The only country in which energy production does not decrease in the GISS scenarios is in Vietnam.

Most countries see an increase in energy production during the 'wetter' GFDL scenarios. The increase in energy production is most prominent in all countries during the high emissions GFDL RCP 8.5 scenario with Vietnam seeing the largest increase of 9%. During the GFDL 2.6 the increase across the whole MRB is less than 6% and for Thailand and Cambodia there is actually a decrease in energy production.

The pattern is less clear for the 'increased seasonality' IPSL scenarios. For the low emissions IPSL scenario there is no change in the energy production in Vietnam or Laos and very little change in Cambodia. There is a small decrease in energy production for China and Thailand. For the medium emissions IPSL scenario most countries see a decrease in energy production, although this is still small. During the high emissions IPSL scenario all countries see a decrease in energy production with the largest decrease in China.

5.3.1 Mainstream and Tributary dams 2060

Figure 5.5 shows the average energy production under each 2060 climate change scenario for dams for the period 1985 - 2008. Dams have been categorized according to their position on the mainstream Mekong or a tributary. The mainstream dams, not including China, are also presented.

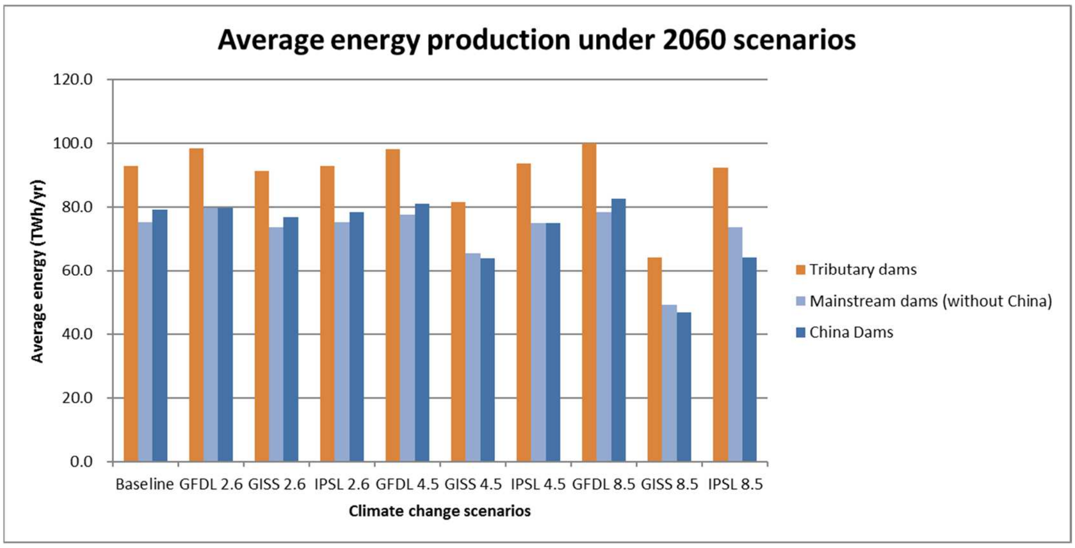


Figure 5.5: Average energy production under 2060 scenarios

Figure 5.5 shows that the change in energy production under the climate change scenarios compared to the baseline is greater for the Mainstream dams than the Tributary dams. The change in average energy for the Mainstream dams is particularly significant under the GISS medium and high emission scenarios. There is a decrease in energy production under these scenarios for the Tributary dams but the change is much smaller than for the Mainstream dams.

5.3.2 Monthly Energy Production

Figure 5.6 and Figure 5.7 show the percentage change in energy production per month under the 2060 medium emission climate change scenarios.

Figure 5.6: Percentage change in energy production for Mainstream dams

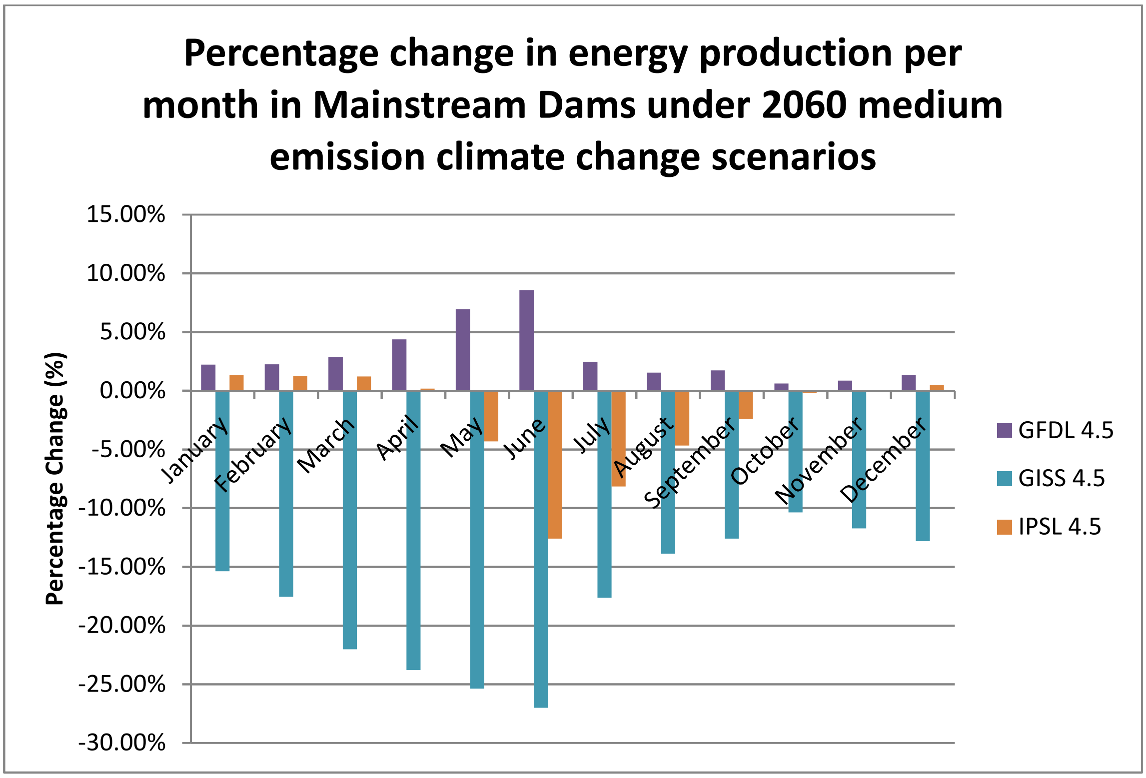


Figure 5.7: Percentage change in energy production for Tributary dams

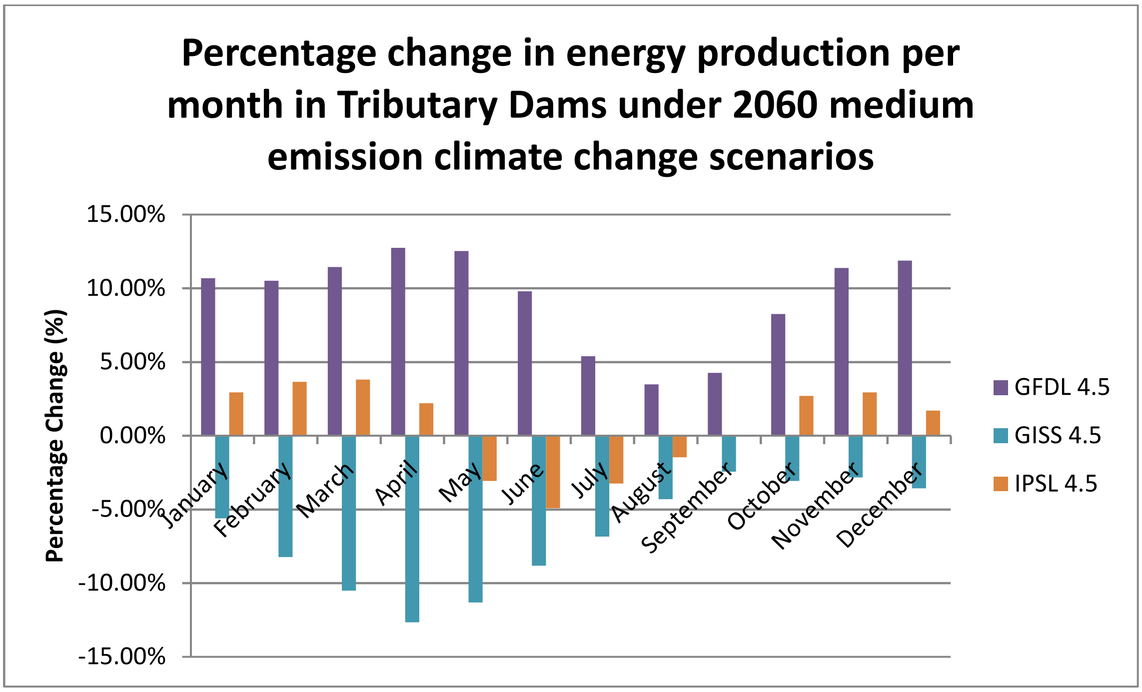


Figure 5.6 and Figure 5.7 show that for the Mainstream dams, in the ‘wetter’ GFDL scenario, the largest increase in energy production occurs during the months of May and June. The smallest increase occurs during the months October to December. For the Tributary dams the biggest increase also occurs in May and June but the smallest increase occurs in August.

For the ‘drier’ GISS scenario, energy production decreases for Mainstream dams from the beginning of the year and the greatest change is in June. The smallest decrease in energy production occurs during October. For the Tributary dams energy production also decreases from the beginning of the year but peaks in April. The smallest decrease in energy production occurs during September for Tributary dams.

For the 'increased seasonality' IPSL scenarios, energy production increases between November and April and decreases between May and October for Mainstream dams. For Tributary dams energy production increases between October and April and decreases between May and September.

Although only the medium emission scenarios are presented here, the pattern in percentage change is much the same for the low and high emissions scenarios.

5.4 Spatial distribution of change

Maps have been produced to show the percentage change in energy production under each 2060 climate change scenario for individual dams across the Lower Mekong Basin (Appendix A). These help to show the spatial variation in the percentage changes in energy production under climate change scenarios compared to the baseline as well as depicting the size of hydropower dam according to the average power generation.

GFDL

The maps (section A.1) highlight that for the GFDL low emissions scenarios most dams have a small change in energy production (between -5% and +5%). The dams which have a larger increase tend to be the smaller dams in southern Laos and Vietnam. For the medium emissions GFLD scenario most dams have a small increase in energy production (0.1% to 5%). Again the smaller dams in southern Laos and Vietnam have the largest increase in energy production (above 20%). For the high emissions scenario there is an increase in the number of dams with increases in energy production between 5% and 20%.

GISS

For the GISS low emissions scenarios most dams have a small decrease in energy production (-0.1% to -5%). Dams situated in the north of Laos have a larger decrease in energy production whereas dams towards the south of Laos tend to have a small increase. For the medium emissions scenario it is the dams in northern Laos which have the largest decrease in energy production (-20% to -50%). The effect of climate change is much more varied in the south of Laos and Vietnam with the percentage change increasing and decreasing widely, although decreases in energy production tend to be along the Mekong rather than on Tributary dams. For the high emissions scenario the pattern is much the same with the largest decreases in energy production for the dams in the north of Laos and much more of a mix of percentage change towards the south. For the dams in the southern part of the LMB the largest decreases are seen on the main river dams.

IPSL

For the IPSL scenarios the changes in energy production is much more varied across the LMB. For the low emissions scenarios most dams have between -5% and +5% change in energy production. Many of the tributary dams in the south of the LMB have very little change (-0.1% to 0.1%). For both the medium and high emissions scenario there is a larger proportion of dams with more extreme increases and decreases in energy production compared to the low emissions scenario. However there does not seem to be any spatial pattern to where there is an increase or decrease in energy production.

5.5 Hydropower Production during Drought Years

5.5.1 Minimum Energy Production

Figure 5.8 shows the minimum energy production on any particular day under the 2060 scenarios during the 24 year simulation.

Figure 5.8: Minimum energy production per country

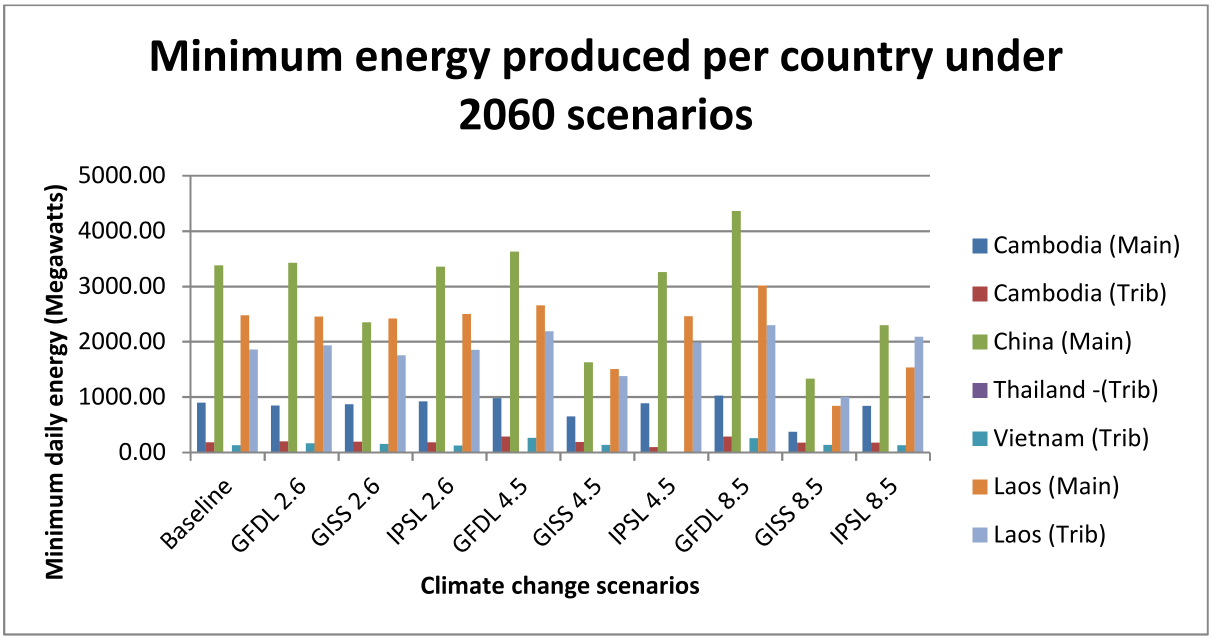


Figure 5.8 shows that the 'drier' GISS scenarios are when the smallest daily minimums occur per country. In the GISS 8.5 scenario energy production in every country apart from China may decrease to less than 1000MW. For most climate change scenarios the minimum energy production does not fall below 2000MW for the China and Laos Mainstream dams.

Table 5-4 shows the percentage change in minimum energy produced per country under 2060 different climate change scenarios.

Table 5-4: Percentage change in minimum energy produced per country under 2060 climate change scenarios

	GFDL 2.6	GISS 2.6	IPSL 2.6	GFDL 4.5	GISS 4.5	IPSL 4.5	GFDL 8.5	GISS 8.5	IPSL 8.5
Cambodia (Main)	-5.66%	-3.45%	2.80%	8.82%	-27.71%	-1.15%	14.58%	-58.70%	-6.60%
Cambodia (Trib)	7.21%	4.32%	-0.35%	54.27%	0.53%	-49.26%	54.89%	-3.49%	-2.94%
China (Main)	1.30%	-30.50%	-0.76%	7.28%	-51.89%	-3.61%	28.94%	-60.54%	-32.01%
Thailand -(Trib)	0.58%	-0.16%	11.48%	29.93%	-88.98%	44.45%	58.94%	-100.00%	79.81%
Vietnam (Trib)	26.81%	17.76%	-2.45%	105.30%	4.24%	-98.77%	102.97%	4.74%	-0.46%
Laos (Main)	-1.02%	-2.35%	0.88%	7.12%	-39.13%	-0.84%	21.70%	-66.01%	-38.08%
Laos (Trib)	4.10%	-5.70%	-0.22%	17.63%	-25.72%	6.87%	23.85%	-46.10%	12.42%

Table 5-4 shows that the largest decreases in the minimum energy produced as expected occur during the drier GISS 4.5 and 8.5 scenarios. The changes can be dramatic with near total loss of hydropower production.

The largest increases in minimum energy production occur during the GFDL 4.5 and 8.5 scenarios. For the IPSL scenarios, some countries see a decrease in the minimum energy production such as Cambodia and Vietnam whilst others see an increase such as Thailand. There is also a noticeable difference between mainstream and tributaries.

The control rules within the model have not been changed for these scenarios so actual operation adapted to the changed climate could help to mitigate the loss of hydropower in severe drought years.

6 Other Aspects of Climate Change Impact on Hydropower

6.1 Evaporation Losses

The effect of evaporation losses on hydropower production during each climate change scenario is taken into account in the IQQM model and therefore in the extracted results discussed already. However, further analysis is presented here to establish the volume of water which may be lost due to evaporation.

Estimates for monthly basin-wide potential evaporation for a range of climate change scenarios are presented in the Basin-wide Assessment of Climate Change Impacts Technical Report[1] and are shown in Table 6.1. The figures presented are potential evaporative demands (PET) which may differ from actual evaporation due to water availability and exposure, open water evaporation is on average lower than a crop evapotranspiration for example.

			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry	Wet	Annual
Reference Period		Value	96	103	129	133	126	111	111	108	100	101	92	87	640	657	1,297
		% change															
Low emission (RCP2.6)	Drier overall	Value	98	104	130	134	128	113	113	109	101	103	92	88	644	666	1,310
		% change	2%	0%	1%	1%	1%	1%	2%	1%	1%	2%	0%	0%	1%	1%	1%
	Increased seasonal variability	Value	86	94	121	128	124	109	108	105	96	95	85	79	592	638	1,230
		% change	-10%	-9%	-6%	-4%	-2%	-2%	-2%	-2%	-4%	-6%	-7%	-10%	-8%	-3%	-5%
	Wetter overall	Value	97	104	131	136	129	114	114	110	102	104	93	89	650	671	1,320
		% change	2%	1%	2%	2%	2%	2%	3%	2%	2%	2%	1%	1%	2%	2%	2%
Medium emission (RCP4.5)	Drier overall	Value	103	105	133	136	134	117	117	112	103	109	92	89	659	691	1,350
		% change	8%	2%	3%	2%	6%	5%	6%	4%	3%	7%	1%	2%	3%	5%	4%
	Increased seasonal variability	Value	100	107	136	145	138	120	118	113	103	105	97	90	675	696	1,371
		% change	4%	4%	6%	9%	9%	8%	6%	5%	3%	3%	6%	4%	5%	6%	6%
	Wetter overall	Value	98	104	131	136	129	114	114	110	102	104	93	89	652	674	1,326
		% change	2%	1%	2%	2%	2%	3%	3%	2%	2%	3%	2%	1%	2%	3%	2%
High emission (RCP8.5)	Drier overall	Value	112	109	138	141	140	120	122	117	105	118	93	92	685	722	1,406
		% change	17%	6%	7%	6%	11%	8%	10%	9%	5%	16%	2%	5%	7%	10%	8%
	Increased seasonal variability	Value	117	122	156	168	156	135	133	126	114	117	111	102	776	782	1,558
		% change	22%	18%	21%	26%	24%	21%	20%	17%	14%	15%	21%	17%	21%	19%	20%
	Wetter overall	Value	109	114	147	155	145	127	132	123	113	120	102	97	724	760	1,484
		% change	14%	10%	14%	16%	15%	14%	19%	14%	13%	18%	11%	11%	13%	16%	14%

2060

Table 6-1 Estimates for monthly basin-wide PET in mm/month (From CCAI Basinwide Assessment of Impacts on Hydrology

Table 6.1 shows that under most climate change scenarios there is projected to be an increase in basin-wide potential evapotranspiration. The change in projected evapotranspiration tends to be small but ranges 0-26% change in monthly total. The largest increase in PET occurs during the ‘Increased seasonal variability’ high emissions scenario. The largest reduction in PET occurs during the ‘Increased seasonal variability’ low emissions scenario.

The values for evapotranspiration (mm) for the reference period (baseline) and each climate change scenario have been applied to the average storage area per month for all the dams in the 2060 development scenario. The percentage change in evaporation and also percentage change in loss of volume compared to the total gross storage of all the 2060 development scenario dams has then been calculated (Table 6-2).

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[1] Basin-wide Assessment of climate Change Impacts on Water and Water Related Resources and Sectors in the Lower Mekong Basin; Climate change impacts on hydrology of the Lower Mekong Basin – Volume 1: Water level, flow and salinity (2015).

		Loss in volume from total gross storage of 2060 dams									
	Monthly average surface area of all dams (ha)	Baseline	Drier (RCP 2.6)	Increased seasonality (RCP 2.6)	Wetter (RCP 2.6)	Drier (RCP 4.5)	Increased seasonality (RCP 4.5)	Wetter (RCP 4.5)	Drier (RCP 8.5)	Increased seasonality (RCP 8.5)	Wetter (RCP 8.5)
Jan	903168	0.068%	0.069%	0.061%	0.068%	0.073%	0.070%	0.069%	0.079%	0.082%	0.077%
Feb	879896	0.071%	0.071%	0.065%	0.071%	0.072%	0.073%	0.071%	0.075%	0.084%	0.078%
Mar	857895	0.086%	0.087%	0.081%	0.088%	0.089%	0.091%	0.088%	0.092%	0.104%	0.098%
Apr	840979	0.087%	0.088%	0.084%	0.089%	0.089%	0.095%	0.089%	0.092%	0.110%	0.102%
May	836363	0.082%	0.084%	0.081%	0.084%	0.087%	0.090%	0.084%	0.091%	0.102%	0.095%
Jun	864790	0.075%	0.076%	0.074%	0.077%	0.079%	0.081%	0.077%	0.081%	0.091%	0.086%
Jul	901652	0.078%	0.079%	0.076%	0.080%	0.082%	0.083%	0.080%	0.086%	0.094%	0.093%
Aug	935084	0.079%	0.080%	0.077%	0.080%	0.082%	0.082%	0.080%	0.085%	0.092%	0.090%
Sep	958143	0.075%	0.075%	0.072%	0.076%	0.077%	0.077%	0.076%	0.078%	0.085%	0.084%
Oct	961570	0.076%	0.077%	0.071%	0.078%	0.082%	0.079%	0.078%	0.089%	0.088%	0.090%
Nov	948851	0.068%	0.068%	0.063%	0.069%	0.068%	0.072%	0.069%	0.069%	0.082%	0.075%
Dec	928539	0.063%	0.064%	0.057%	0.064%	0.064%	0.065%	0.064%	0.067%	0.074%	0.070%

Table 6-2 Change in loss due to evaporation for 2060 climate change scenarios expressed as proportion of storage

		Change in Evaporation of 2060 dams								
	Evaporative Loss from Reservoirs in m3/s	Drier (RCP 2.6)	Increased seasonality (RCP 2.6)	Wetter (RCP 2.6)	Drier (RCP 4.5)	Increased seasonality (RCP 4.5)	Wetter (RCP 4.5)	Drier (RCP 8.5)	Increased seasonality (RCP 8.5)	Wetter (RCP 8.5)
Jan	32	2.1%	-10.4%	1.0%	7.3%	4.2%	2.1%	16.7%	21.9%	13.5%
Feb	34	1.0%	-8.7%	1.0%	1.9%	3.9%	1.0%	5.8%	18.4%	10.7%
Mar	41	0.8%	-6.2%	1.6%	3.1%	5.4%	1.6%	7.0%	20.9%	14.0%
Apr	42	0.8%	-3.8%	2.3%	2.3%	9.0%	2.3%	6.0%	26.3%	16.5%
May	39	1.6%	-1.6%	2.4%	6.3%	9.5%	2.4%	11.1%	23.8%	15.1%
Jun	36	1.8%	-1.8%	2.7%	5.4%	8.1%	2.7%	8.1%	21.6%	14.4%
Jul	37	1.8%	-2.7%	2.7%	5.4%	6.3%	2.7%	9.9%	19.8%	18.9%
Aug	38	0.9%	-2.8%	1.9%	3.7%	4.6%	1.9%	8.3%	16.7%	13.9%
Sep	36	1.0%	-4.0%	2.0%	3.0%	3.0%	2.0%	5.0%	14.0%	13.0%
Oct	36	2.0%	-5.9%	3.0%	7.9%	4.0%	3.0%	16.8%	15.8%	18.8%
Nov	33	0.0%	-7.6%	1.1%	0.0%	5.4%	1.1%	1.1%	20.7%	10.9%
Dec	30	1.1%	-9.2%	2.3%	2.3%	3.4%	2.3%	5.7%	17.2%	11.5%

Table 6-3 Change in Evaporation for 2060 from Reservoirs expressed in % compared to 2007

The change in evaporation from reservoirs is influenced both by the change in evaporative demand and the change in water surface due to changing inflows. The differences in evaporation reflect the changes in evaporative demand overall for 2060 as shown in the hydrological change reporting (Table 6.2) but due to changing water surface in certain months the change is higher (maximum 22% and other times lower (minimum -10%).

The loss in volume relative to gross reservoir storage is small but is at a maxima for the 'Increased seasonality' (IPSL) RCP 8.5 scenario. The smallest increase occurs during the 'Increased seasonality' RCP 2.6 scenario. The months of April and May tend to be where the largest losses in storage occur due to the increased potential evapotranspiration. Some of the potential evaporation losses will be offset by potential increases in rainfall and the impact on reservoir operations and hydropower production is small.

The evaporation losses and changes to rainfall are both taken into account in the IQQM models so are included in the hydropower production calculated as reported in Sections 4 & 5.

6.2 Flood Flows and Spillway Capacity

The Basinwide analysis of hydrological change considers only the change in flood flows at key sites on the mainstream. Changes in peak flows of up to 20% were found.

The Basin-wide Flood Mapping study also considered flood flows in detail. It found that simulated flows from SWAT should not necessarily be taken as providing a good representation of the extremes of flood frequency particularly for tributaries where most dams are situated so analysis of the short time series is not appropriate for estimating change in the extremes used in spillway design.

The analysis completed however does suggest that the change in flood frequency expressed as a factor is relatively constant and that quite high factors are being found in the simulations for some tributaries (30-100%). Whilst any increase of the extreme flood peaks in tributaries that dams should be designed for such as 1:10,000 year events may be limited by the maximum amount of precipitation that may be carried in the atmosphere, it is by no means certain that this will not also be increased with a warming climate.

Quantification of this increase is beyond the scope of the modelling analysis carried out for CCAI so far but it is recommended that the issue is given further attention in the future and that dams being designed in the LMB consider the potential for higher extreme flows than is apparent in the historic record.

6.3 Sedimentation

Model results for sediment movement were not available so this aspect cannot currently be analysed. It is expected that sedimentation will increase due to high rainfall intensity in most scenarios.

The models are being updated for the MRC Council Study and the results will be available in late 2017 for changes due to a limited range of climate scenarios using an eWater Source model and ISIS mobile bed hydrodynamic modelling of the mainstream.

7 Conclusions

7.1 Average Hydropower Production

The likely changes in hydropower production under climate change have been quantified by analysing the results of the basin-wide simulations completed by IKMP for CCAI and used in each of the sectorial based analyses.

Because Hydropower is being developed rapidly in the basin the dams expected to be constructed by 2060 are used for the analysis rather than the small number existing in the original baseline reference condition of 2007. The number of dams in the 2060 scenarios is closer to the potential hydropower production in the LMB so meets the requirement for an analysis of the change in potential hydropower production. Comparing the energy outputs with the more detailed data in the MRC Hydropower database suggests that the model is in reasonable agreement although the energy from mainstream dams is slightly overestimated and so a correction is applied in the calculations to allow for this.

In terms of change it is found that quite significant increases or decreases can occur depending on the climate scenario. The mainstream dams are more sensitive to change than the total of tributary dams. For the part of the basin China only those dams on the main Mekong/Lancang are considered though these are a significant proportion of the hydropower potential of the whole basin as shown in Table 7.1.

	Wetter 2.6	Drier 2.6	Seasonal 2.6	Wetter 4.5	Drier 4.5	Seasonal 4.5	Wetter 8.5	Drier 8.5	Seasonal 8.5
Cambodia	-0.5%	-1.3%	-0.1%	3.2%	-6.7%	-1.2%	3.8%	-17.7%	-1.5%
China	0.5%	-3.0%	-1.1%	2.3%	-19.4%	-5.3%	4.2%	-40.8%	-19.1%
Thailand	-0.2%	-4.5%	-3.3%	3.1%	-16.8%	-0.4%	5.3%	-39.5%	-2.2%
Vietnam	1.4%	0.8%	0.0%	8.0%	1.2%	-4.2%	9.0%	0.7%	-0.1%
Laos	5.8%	-1.9%	0.0%	5.6%	-12.1%	0.7%	7.5%	-31.1%	-0.7%

Table 7-1 Summary of overall mean change for 9 Scenarios in 2060 (3 RCP Emission Scenarios and 3 different GCM model realisations)

The effect on mainstream or tributary dams is highlighted and it can be seen for example that under Drier (GISS) RCP 8.5 scenario the mainstream dams have a lower output than tributaries in contrast to the baseline.

During a drought year, the effect of climate change is to significantly worsen the period when there is insufficient flow for power generation and, in some cases, simulation suggests a total loss of capacity can occur.

7.2 Recommendations

Given the vulnerability of the hydropower sector to climate change, it is important that the likely changes over the period of investment and infrastructure life can be estimated. Not only the actual income from generation is influenced but the infrastructure is also at risk for extreme events. Much investment is already planned and the governments and developers of the schemes in the LMB should be aware of the possible changes and wherever possible the qualitative data should be made available. The CCAI Basinwide assessments have started that quantification but there is much more that can be continued in conjunction with monitoring of climate changes and utilizing the improved model and analysis techniques that the climate community are evolving.

It is recommended that a specific study of the approaches to extreme flood estimation in the LMB is completed and the ways in which these could be adapted to include climate change impacts is carried out. This study could include an inventory of the present design standards (including the MRC Preliminary Design Guidance for mainstream dams) and design maximum floods of the dams already constructed.

The likely impacts of climate change on sedimentation in reservoirs and hence the life of a scheme has not yet been quantified as model results were not available. It is likely that the MRC/TSD work on this aspect will be completed in 2017 so any update of this assessment can include this.

For MRC Indicators the Hydropower production monitoring should include not only the total annual production but should also assess the yearly maxima and minima.

For the MASAP preparation the aspects coming out of this work relate to:

1. Assessing the costs and benefits of using hydropower dams in a multipurpose way for adaptation to increased flood and drought in a tranboundary context;
2. Ensuring future dams are regulated to acceptable standards of safety including allowances for climate change.
3. Making sure ancillary structures such as access roads, power channels, power stations and social programmes are climate proofed.
4. The regulatory regime should also be investigated further to come up with proposals of how increased or decreased potential generation can be allowed for to fairly allow developers and governments to manage risk and return in a changing climate.
5. Complete the sediment study and quantify reservoir sedimentation effects.
6. Using Hydropower reservoirs to contribute directly to food production (possible floating hydroponic production areas as well as fisheries) and energy sources (floating solar power).

8 References

BDP phase 2, 2011. *Assessment of basin-wide development scenarios. Main report,* http://www.mrcmekong.org/assets/Publications/basin-reports/BDP-Assessment-of-Basin-wide-Dev-Scenarios-2011.pdf: MRC.

Beilfuss, R. & Triet, T., 2014. *3.1 Scoping Study on Climate Change and Hydropower in the Mekong River Basin: a synthesis of research,* https://www.giz.de/de/downloads/giz2014-en-study-climate-change-hydropower-mekong.pdf: GIZ.

CCAI, 2015a. *Review of approaches for developing climate change scenarios and addressing scenario uncertainties in adaptation planning for the Lower Mekong Basin (LMB) - Final Draft,* Lao PDR: MRC.

CCAI, 2015b. *Proposed climate change scenarios to be used for CCAI basin-wide assessment,* Lao PDR: MRC.

ICEM Australia, 2010. *Strategic environmental assessment of hydropower on the Mekong mainstream. Summary of final report.,* http://www.mrcmekong.org/assets/Publications/Consultations/SEA-Hydropower/SEA-FR-summary-13oct.pdf: MRC.

ICIMOD (2016) Research Report 2016/3. : Lutz, A; Immerzeel, WW; Bajracharya, SR; Litt, M; Shrestha, A (2016) Impact of climate change on the cryosphere, hydrological regimes and glacial lakes of the Hindu Kush Mimalayas: A review of current knowledge. ICIMOD Research Report 2016/3. Kathmandu.

IKMP, 2014a. Technical Reference Report (Draft), SWAT Model (Baseline 2007) Application in Mekong River Basin , Draft Technical Reference Report, Information and Knowledge Management Programme, Mekong River Commission.

IKMP 2014b. Technical Reference Report (Draft), IQQM Model (Baseline 2007) Application in Mekong River Basin, Draft Technical Reference Report, Information and Knowledge Management Programme, Mekong River Commission.

IKMP, 2014c. Final Technical Report, Improvement of the ISIS Baseline Scenario Model, Final Technical Report, Information and Knowledge Management Programme, Mekong River Commission.

IKMP, 2014d. Final Technical Report, The ISIS Baseline Model for Mekong River in Upper Kratie (Chiang Sean-Pakse) , Final Technical Report, Information and Knowledge Management Programme, Mekong River Commission.

IPCC (SRRES) 2011. See Kumar et al

JBA Consulting, 2014. *Exploratory analysis of climate change factor ranges - Final Report,* s.l.: GIZ/MRC

Kiem A (2013) Climate Change Adaptation planning in the Lower Mekong Basin - Review of Climate Scenario and downscaling approaches. Report for MRC CCAI.

Kumar, A., T. Schei, A. Ahenkorah, R. Caceres Rodriguez, J.-M. Devernay, M. Freitas, D. Hall, Å. Killingtveit, Z. Liu, 2011: Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation SRRES [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

MRC, 2009. *Technical paper no. 29. Impacts of climate change and development on Mekong flow regimes. First assessment - 2009,* http://www.mrcmekong.org/assets/Publications/technical/tech-No29-impact-of-climate-change.pdf: MRC.

Muir, T. C., 2010. *Significant tributaries for hydropower in the LMB,* Significant Tributaries Study: MRC Vientiane.

MRC CCAI (2015a) Review of approaches for developing climate change scenarios and addressing scenario uncertainties in adaptation planning for the Lower Mekong Basin (LMB) draft 2015

MRC CCAI (2015b): Defining basin-wide climate change scenarios for the Lower Mekong Basin (LMB) – Draft. Climate Change and Adaptation Initiative, Mekong River Commission, Lao PDR.

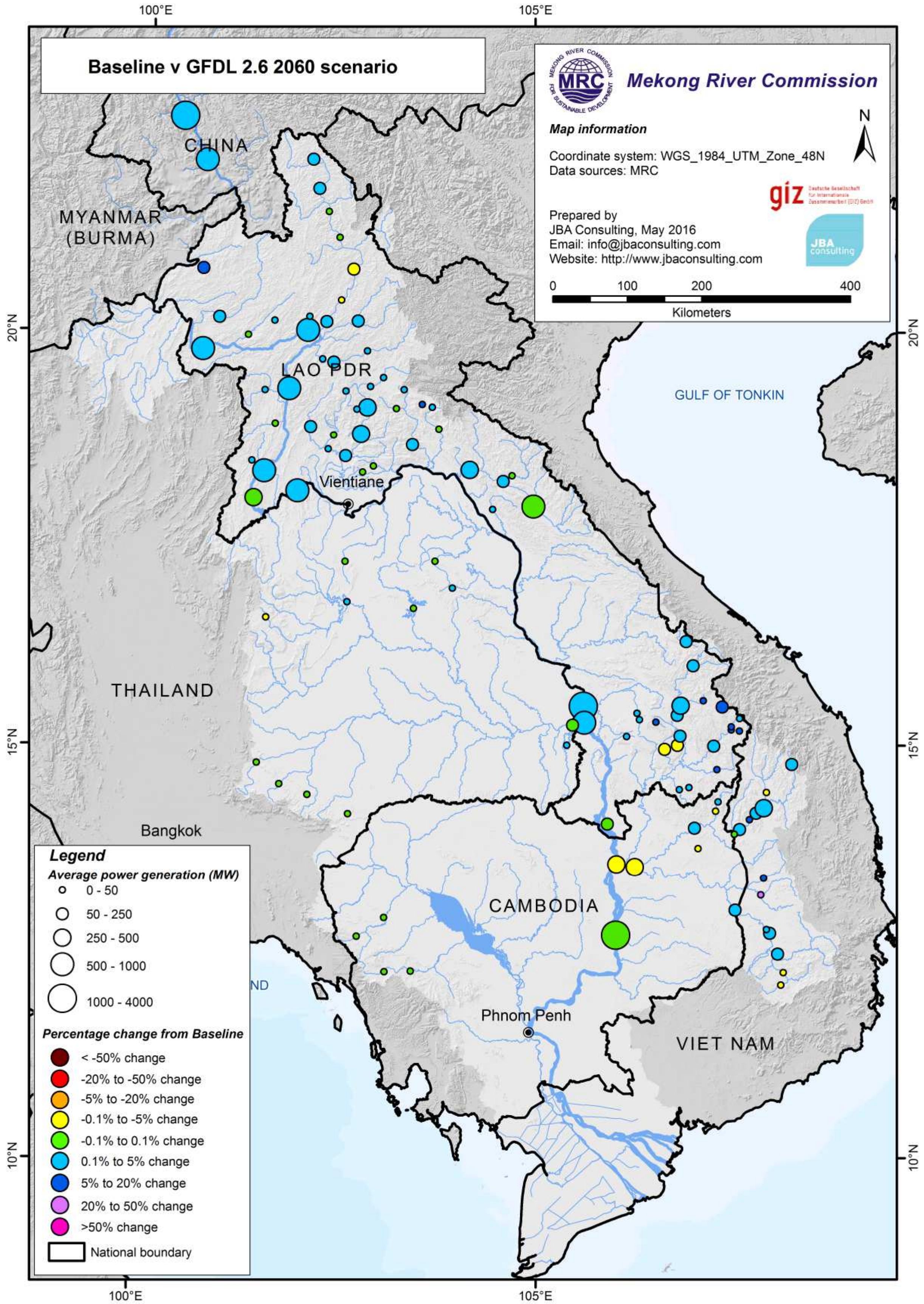
MRC CCAI (2015c): Proposed climate change scenarios to be used for CCAI basin-wideassessment – Working Paper. Climate Change and Adaptation Initiative, Mekong River Commission, Lao PDR.

MRC CCAI (2015d): Proposed development scenarios to be used for CCAI basin-wide assessment – Working Paper. Climate Change and Adaptation Initiative, Mekong River Commission, Lao PDR.
Ouranos, 2015. Probable Maximum Floods and Dam Safety in the 21st Century Climate. Report submitted to Climate Change Impacts and Adaptation Division, Natural Resources Canada

Schaefli B, Hingray B, Musy A. (2007). Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties. Hydrology and Earth System Sciences, European Geosciences Union 11(3) 2007.

A. APPENDIX 1

A.1 Maps of Change in Mean Hydropower Production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Average power generation (MW)
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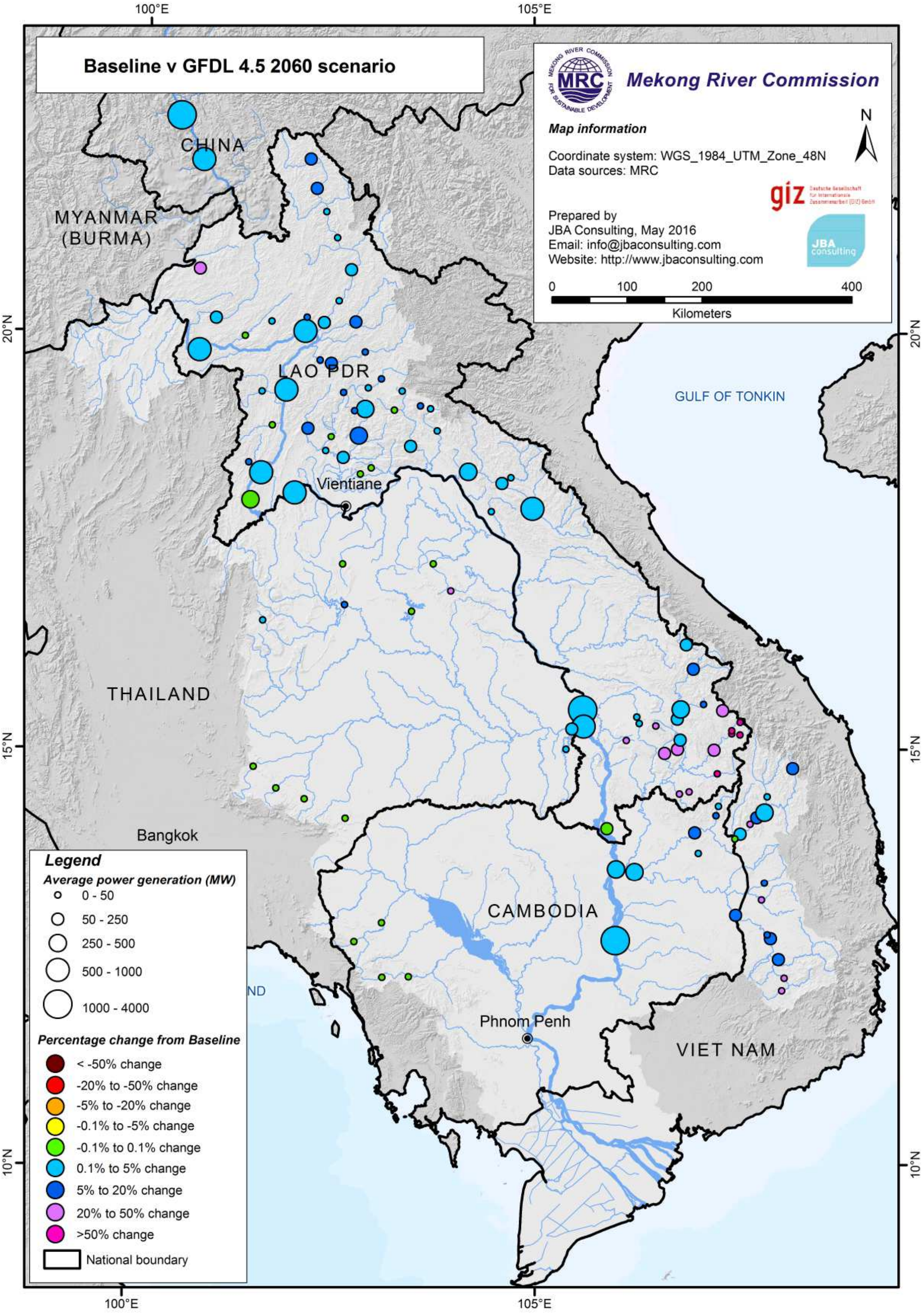
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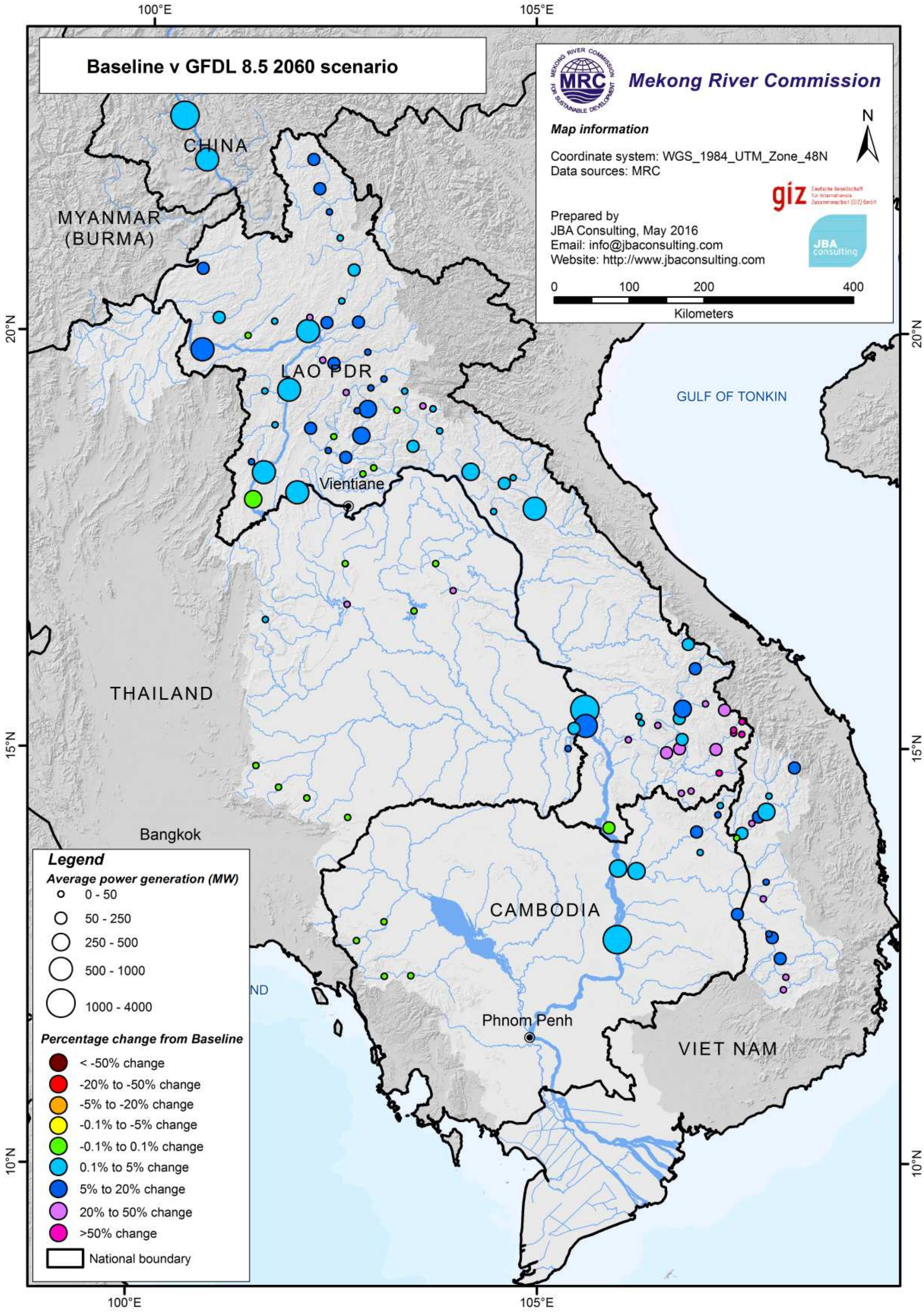
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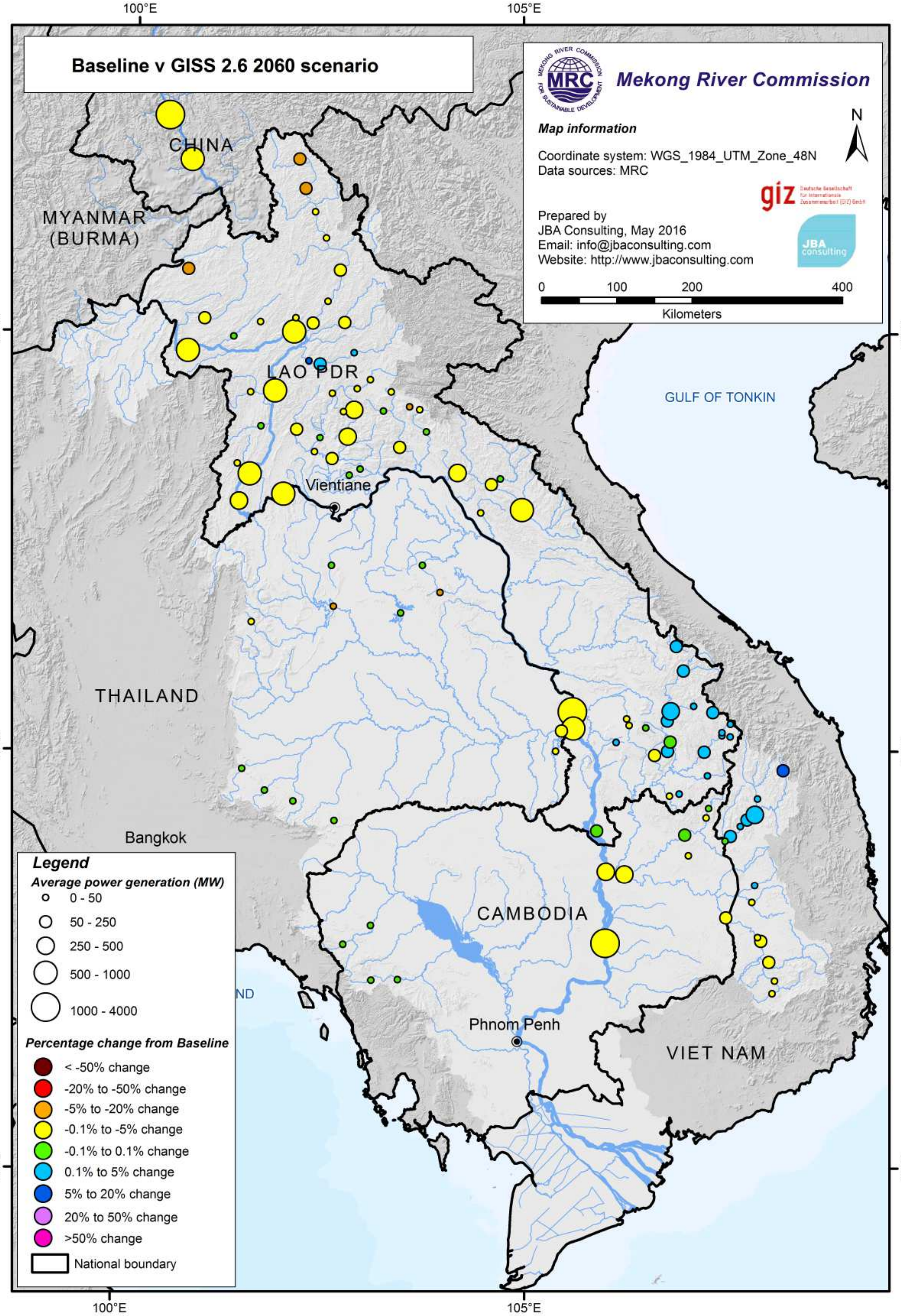
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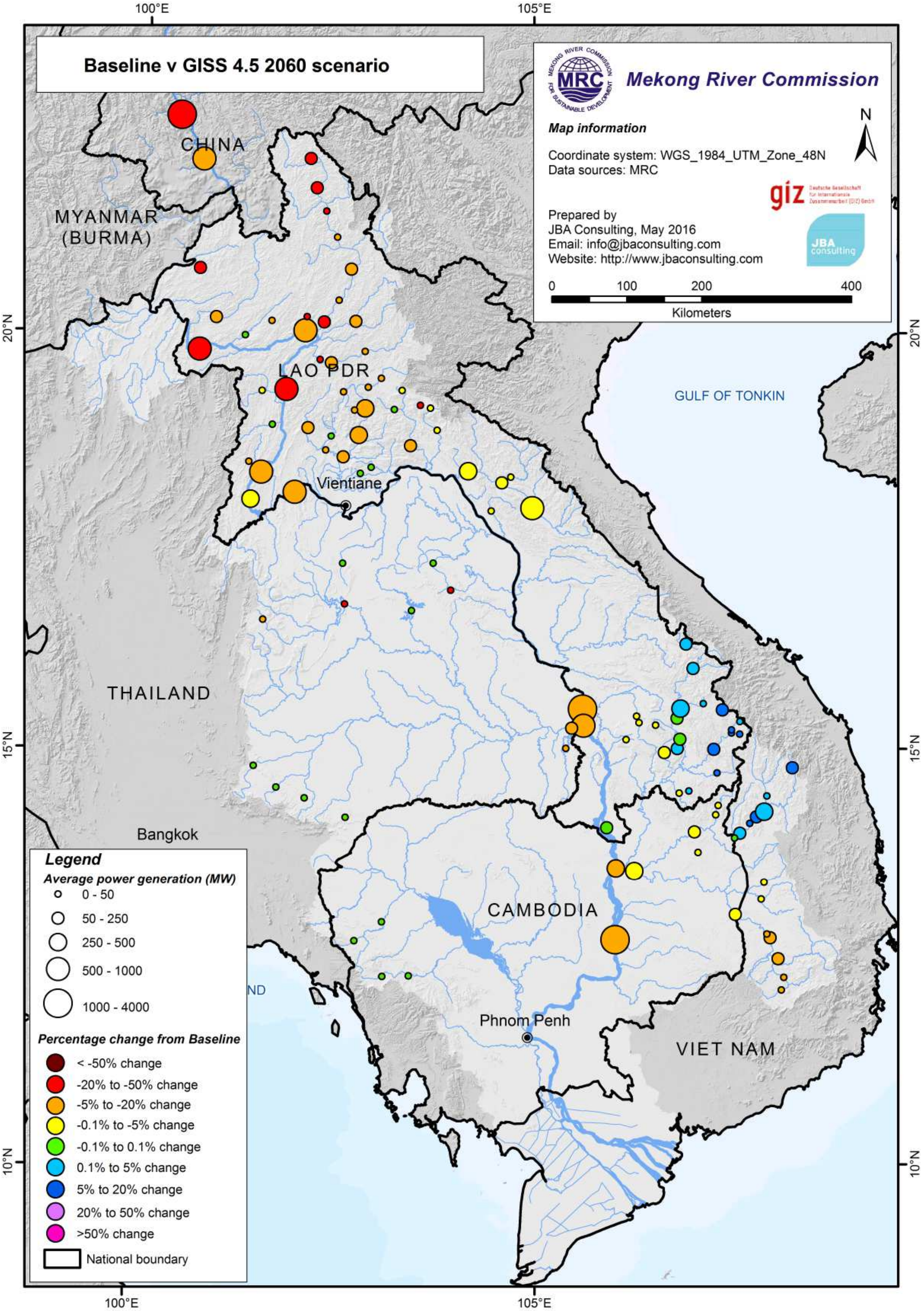
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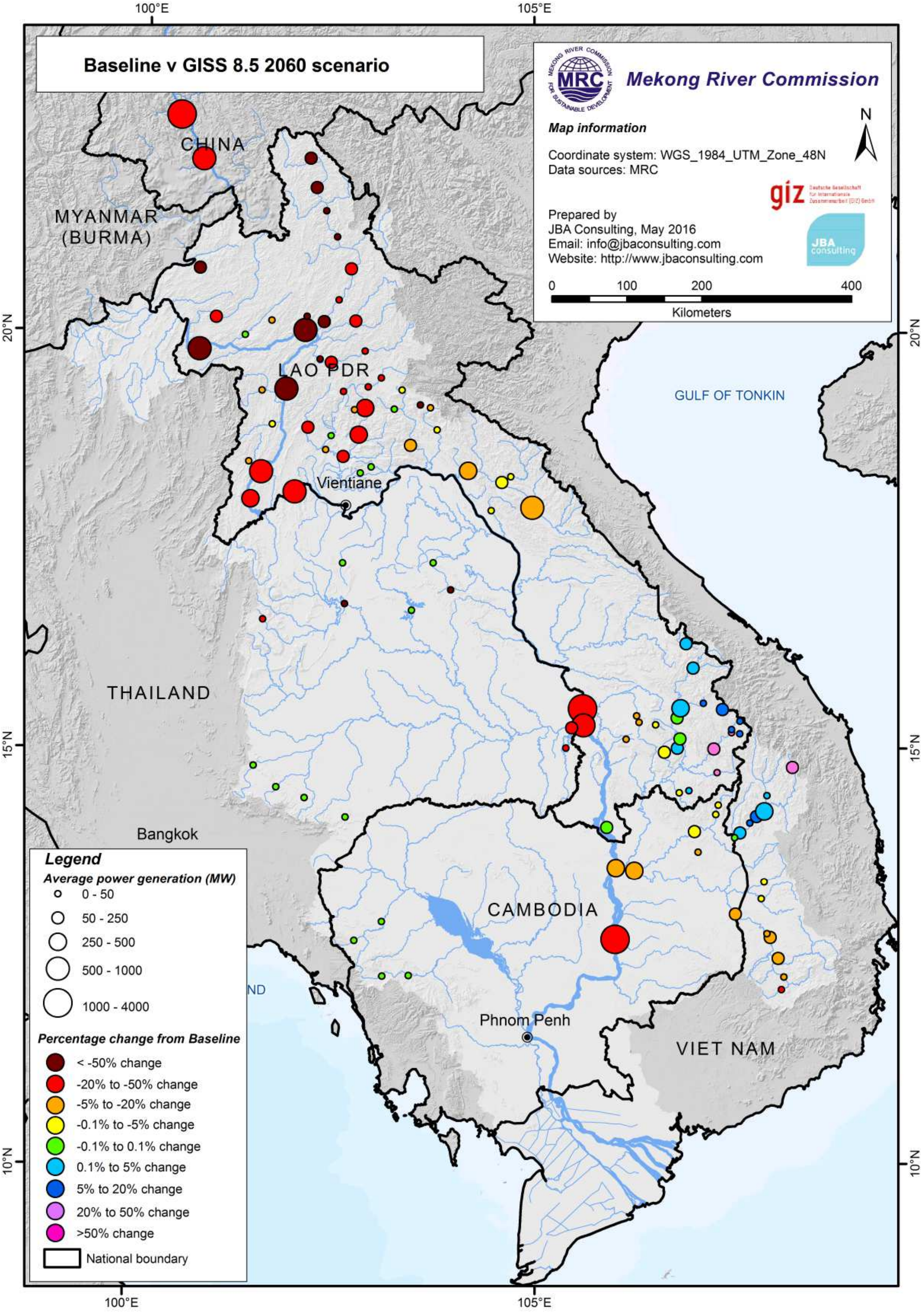
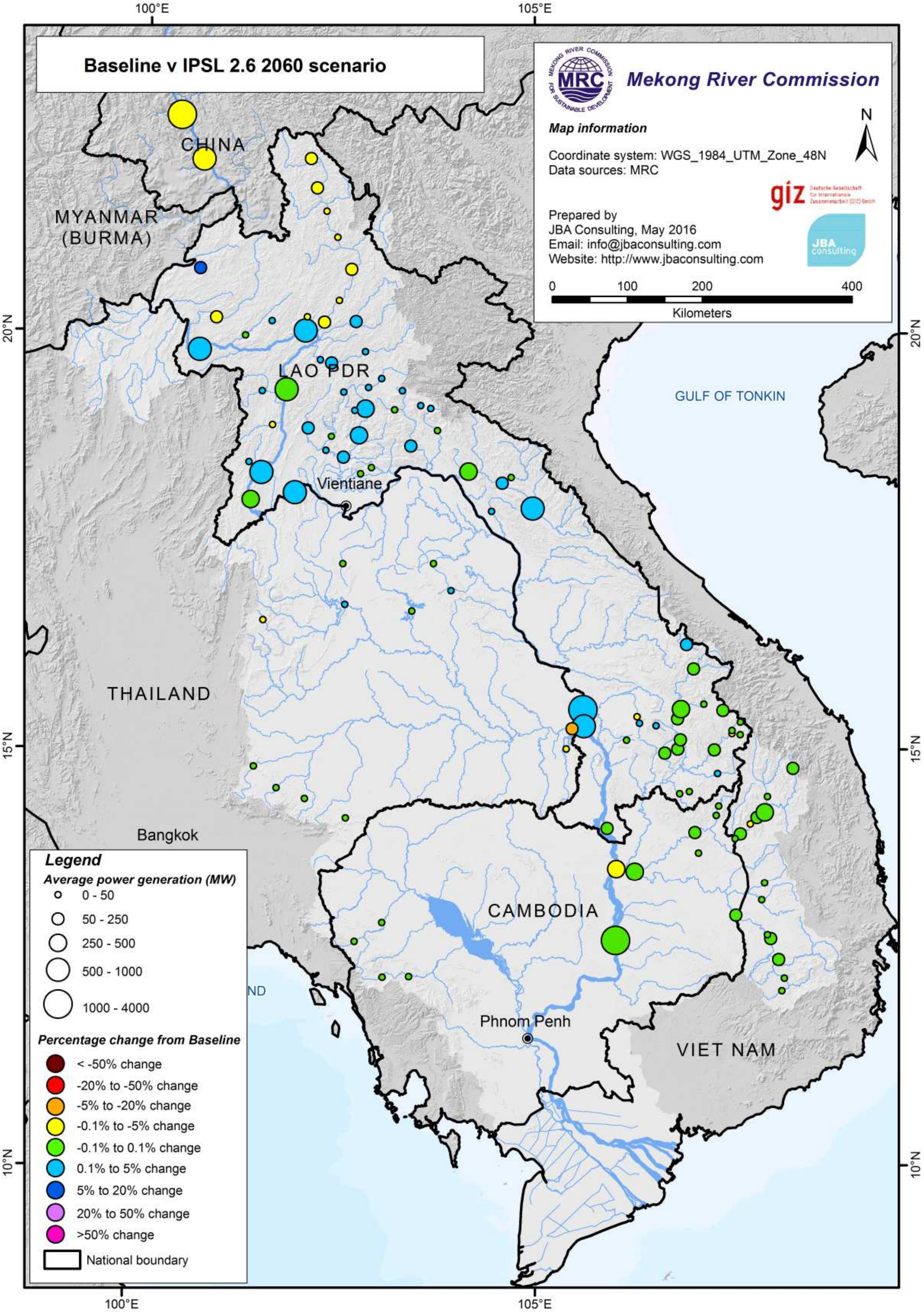


Baseline v GISS 8.5 2060 scenario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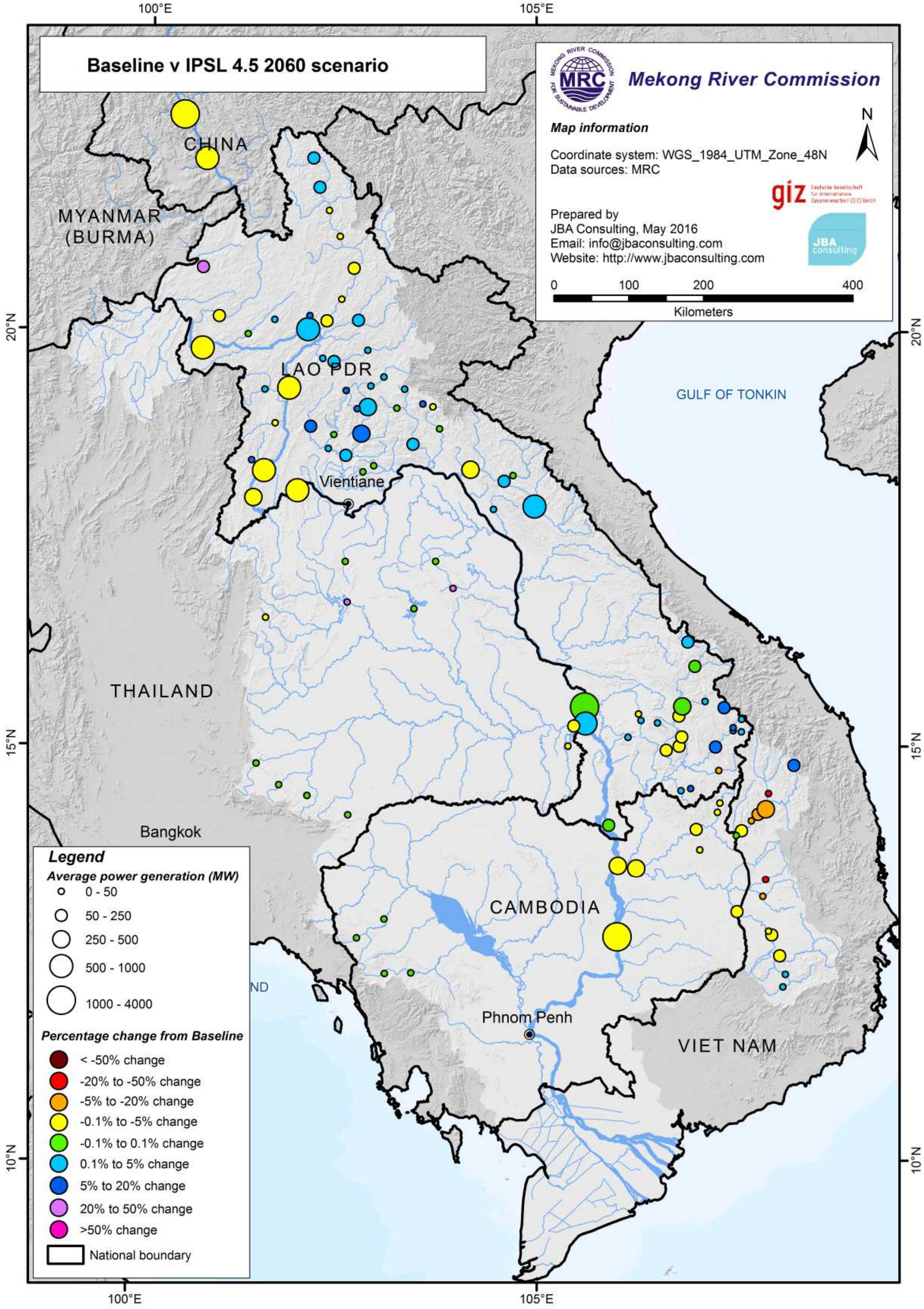
THAILAND
Bangkok
CAMBODIA
Phnom Penh
VIET NAM
ND
Legend
Average power generation (MW)
0 - 50
50 - 250
250 - 500
500 - 1000
1000 - 4000
Percentage change from Baseline
< -50% change
-20% to -50% change
-5% to -20% change
-0.1% to -5% change
-0.1% to 0.1% change
0.1% to 5% change
5% to 20% change
20% to 50% change
>50% change
National boundary


Baseline v IPSL 4.5 2060 scenario
Mekong River Commission
MRC
MEKONG RIVER COMMISSION
FOR SUSTAINABLE DEVELOPMENT
Map information
Coordinate system: WGS_1984_UTM_Zone_48N
Data sources: MRC
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Prepared by
JBA Consulting, May 2016
Email: info@jbaconsulting.com
Website: http://www.jbaconsulting.com
JBA consulting
N
0
100
200
400
Kilometers
100°E
105°E
20°N
15°N
10°N
CHINA
MYANMAR (BURMA)
LAO PDR
Vientiane
GULF OF TONKIN
THAILAND
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20% to 50% change
>50% change
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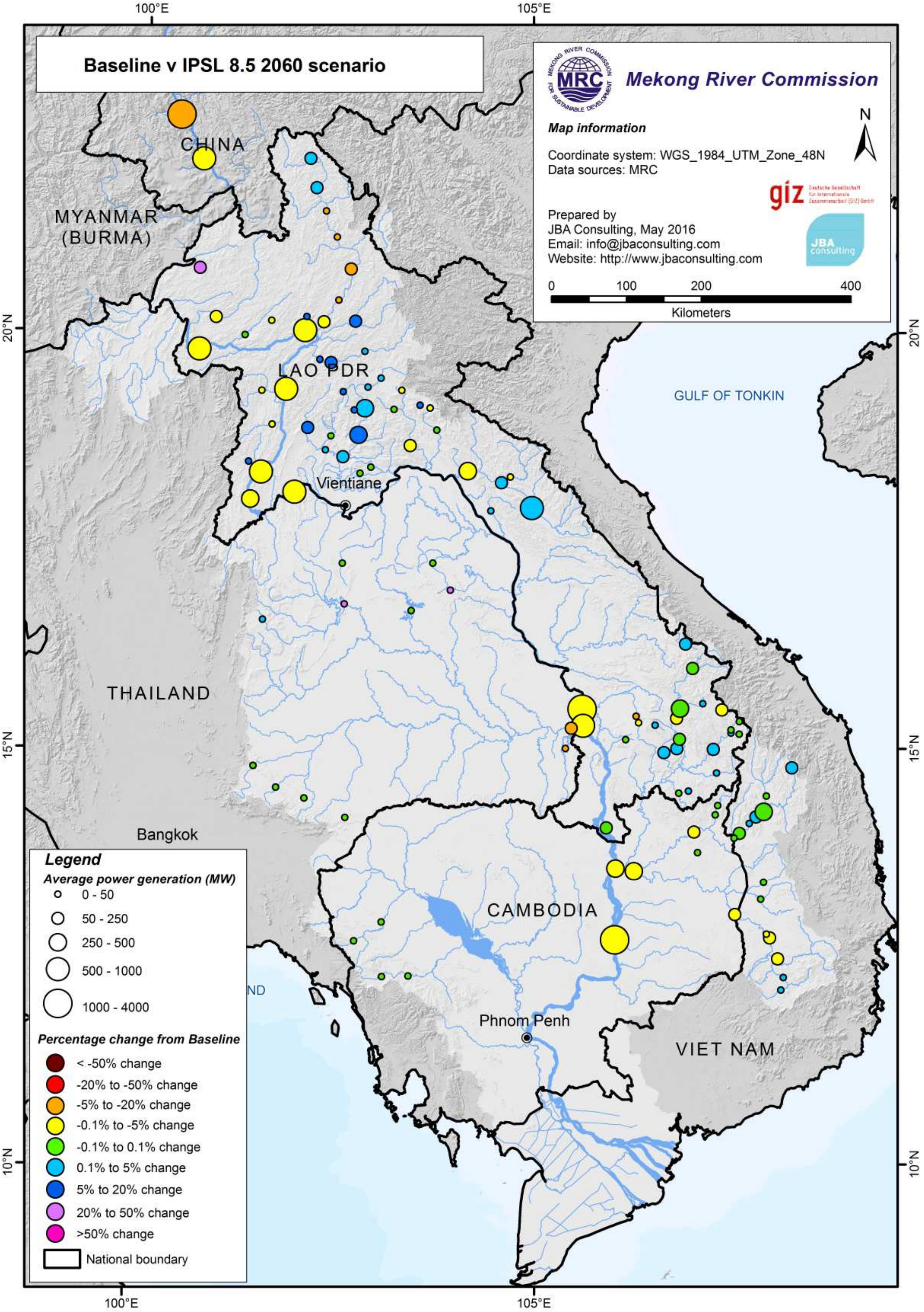
Baseline v IPSL 8.5 2060 scenario
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