

Training Manual

# Climate Change and Hydropower Development

Network for Sustainable Hydropower Development in the Mekong Countries (NSHD-M)





Training Manual

# **Climate Change and Hydropower Development**



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## INTRODUCTION

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Hydropower is an important resource in the Mekong basin as well as in many other developing regions. It is also a complex resource, as its development presents multiple issues and trade-offs over long periods of time. Climate change will make it even more complex. This training manual is designed to introduce trainers and trainees to hydropower under climate change, help them to navigate the complexities, and ultimately, contribute to better decisions on hydropower siting, design and operations.

There is now broad scientific consensus about climate change, and it is well summarized in the 5<sup>th</sup> Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) which is being released while this manual was drafted, and was used as much as possible for references.<sup>1</sup>

The manual is part of a series of manuals commissioned by GIZ to support building capacity on hydropower in the Mekong region. These cover economic, social, environmental, water resource and governance aspects of hydropower. Climate change will often modify existing issues with hydropower. For example, where a reservoir serves as storage both for hydropower and for flood control, even without climate change decisions have to be made about allocating storage space. In the future, existing reservoirs may be operated differently, and new reservoirs may be built with different designs. As this manual can be used as a stand-alone tool for trainings, there are some overlaps with the other manuals. Where this manual is used in a series of trainings, it should come towards the end of the series, and overlapping parts may be skipped. The training manuals are not cross-referenced; it is recommended that trainers familiarize themselves with the contents of the entire series.

A full delivery of the material in this manual should take up to 5 days. This would allow fully participative development of the course material, full use of the supporting documents, and group discussions. Depending on time constraints and interests of particular audiences, trainers may want to modify course materials. There is a set of powerpoint presentations which cover all the material in the manual and which can be freely customized by trainers. It is recommended, in particular, to modify the group discussions according to the interests and background of each audience. The questions for discussions in each session should be seen as suggestions only, and trainers should be clear about objectives for group work.

Modules 1 and 2 basically provide context and background information, which may or may not be necessary for a particular audience. Modules 3 to 5 present the core material, and Module 6 discusses policy implications. If time constraints exist, it is recommended to focus on Modules 3 to 5. Even within these Modules, there is some material (for example, Session 5.2. on greenhouse gas emissions from hydropower) which are relatively specialized and not required to follow other material. The one part which appears essential and should not be dropped in a customization exercise is the question on how to deal with uncertainties in decision making, covered especially in Session 3.4. This is and will remain the core challenge from climate change.

Where possible, examples from the Mekong region have been used, where the emphasis in discussions is about building new hydropower projects. However, many examples in the manual are from existing hydropower stations and from other countries. An important part of the training will be for trainees to appreciate how the lessons from existing projects can be applied to new investment. There is often better documentation from projects from

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<sup>1</sup> <http://www.ipcc.ch/report/ar5/>

developed countries than from the Mekong region, particularly for a fairly new issue like climate change. However, it could be feasible to link the training to a basin or a project in the Mekong region, and to discuss all the issues in that context. For example, there is relatively good documentation publicly available on the Nam Theun 2 project in Laos, including many issues related to climate change, and the project could be used as a case study. A hypothetical example could also be created and followed throughout the training. In some cases, an audience may be interested in a particular level of analysis (regional, country, basin, or project level), and the training could be customized for that level of interest.

At the core of the relationship between hydropower and climate change are ongoing and expected changes in hydrology. This manual therefore puts some emphasis on understanding hydrology and its implications for siting, design and operations. Trainees with a non-technical background may find the level of the sessions with an emphasis on hydrology to be relatively advanced. In principle, there are several ways of dealing with this: making sure participants understand that there will be some technical requirements, or selecting them accordingly; requiring some preparatory reading before the training course; going through the technical material particularly slowly and methodically, and/or in smaller groups; skipping or simplifying some material. One way to do this is to drop the parts of Sessions 2.3. and 3.2. which cover Flow Duration Curves and optimization of plant design; although these graphical tools are generally considered a very intuitive way to understand the linkages between hydrology, engineering, and environmental flows.

It may be possible in the future to provide a basic and an extended version, one which is designed more for a general audience and those with a social sciences background, and another which is designed for trainees with a technical background and direct planning and decision-making responsibilities.

# 1 MODULE 1. BACKGROUND

## 1.1 Session 1.1 Global and Regional Hydropower Development

Purpose and Learning Objectives	<p>This session provides an overview of current trends in hydropower development both in the Mekong basin and globally, including an overview of drivers of and problems with hydro development.</p> <p>Trainees will be able to place their own experiences with hydropower into context, and the trainer will gain an overview of existing knowledge among trainees.</p>
Key Reading	<p>Item 1.1.1 - IEA (2012) Key Findings, in Technology Roadmap Hydropower (p. 5).</p> <p>Item 1.1.2 - BP (2013) Section 36 (Hydroelectricity) in Statistical Review of World Energy.</p> <p>Item 1.1.3 - MRC (2013) Section 3.2 (Opportunities and Risks of Water Resources Development) in Basin Development Strategy (pp. 18-22).</p>
Content	<p>Where is hydropower today?          Where will hydropower be in the future?          What makes hydropower attractive?          What are the development challenges?</p> <p>optional: How is hydropower developed and who is engaged in it (developers, contractors, funders)?</p>
Key Aspects	<p>Key drivers of hydropower development are low operational costs, operational flexibility, domestic energy and water security, export potential, and climate change policies and incentives.</p> <p>The most dynamic regions for hydropower development are developing countries with appropriate hydrology and topography, demand growth, and availability of investment capital.</p> <p>Hydropower can be a sustainable source of energy and contribute to sustainable development if developed properly.</p>
Discussion Topics and Exercises	<p>Depending on group size, in plenary or groups:</p> <ul style="list-style-type: none"> <li>• Review trainee's personal experiences with and opinions about hydropower</li> <li>• Discuss why countries generate more or less hydropower (two handouts: BP world generation statistics and graphic of regional undeveloped potential)</li> <li>• Discuss how global drivers of hydro development apply to the Mekong basin</li> <li>• Optional: Discuss how and by whom hydropower is developed in Mekong countries</li> </ul>
Additional Resources	<p>for an up-to-date overview of regional and national electricity issues and the role of hydropower:</p> <p>Item 1.1.4 - ADB (2013) Assessment of the Greater Mekong Subregion energy sector development: Progress, prospects, and regional investment priorities.</p>

Hydropower is a clean and renewable energy technology that may provide additional benefits such as water supply, flood control, and recreation. The top 10-hydropower producing nations, as of 2010, are indicated in Table 1 (IEA 2012). Generation in terawatt-hours (TWh) in a given country and year depends on: (a) installed capacity, (b) hydrology, and (c) operations. It is possible to have high installed capacity with relatively little generation; for example, where hydropower is used for peaking purposes (periods of high energy demand) or when a bad hydrological year occurs. An example for the latter would be the nation-wide blackouts in Brazil in 2001. Of note, the European countries in the list above are gradually being replaced by emerging economies.

<b>Country</b>	<b>Hydro electricity (TWh)</b>	<b>Share of electricity generation (%)</b>
China	694	14.8
Brazil	403	80.2
Canada	376	62.0
United States	328	7.6
Russia	165	15.7
India	132	13.1
Norway	122	95.3
Japan	85	7.8
Venezuela	84	68
Sweden	67	42.2

*Table 1: Top ten hydropower producing nations*

World hydroelectric consumption can be examined in more detail by region in Figure 1 (BP 2013). The Asia-Pacific region consumes the largest amount of electricity generated by hydropower, a lead that has accelerated since 2003, while the Europe-Eurasia and North America markets remained stable. South America continues to steadily increase its consumption due to abundant runoff, while the Middle East and Africa show slow growth due to lack of water and lack of effective demand and capital, respectively.

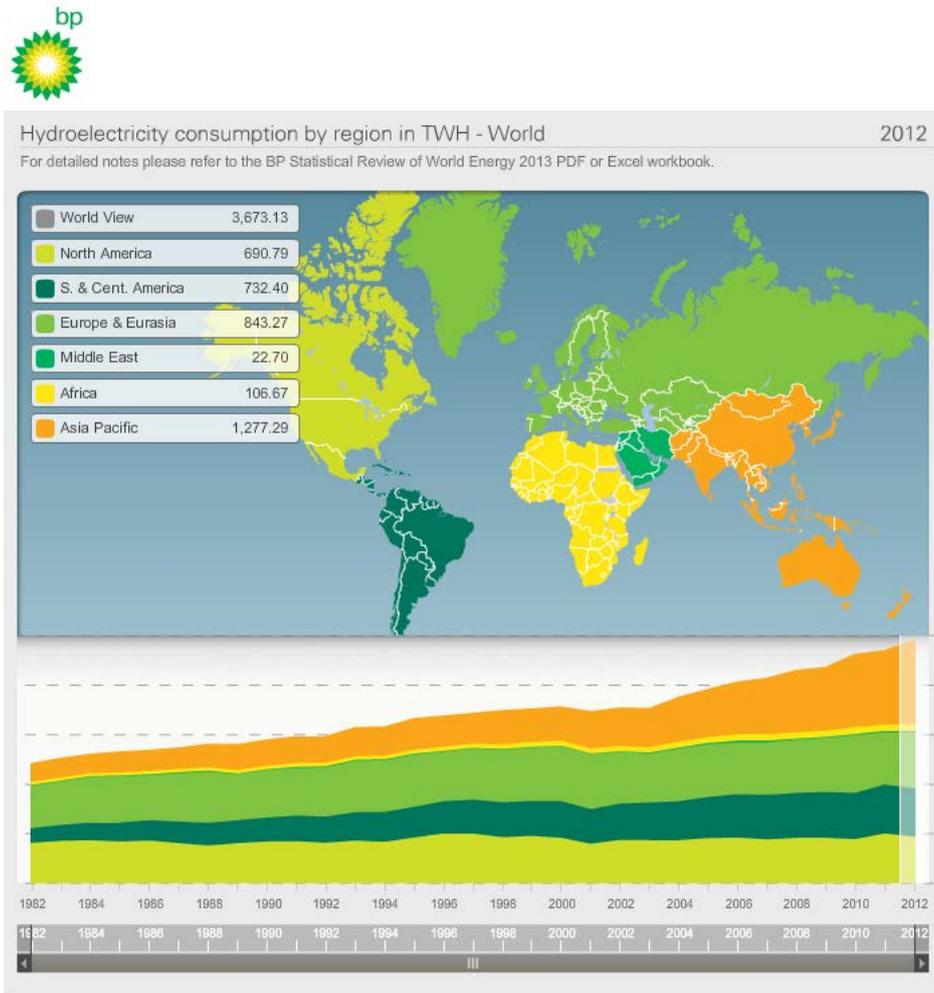


Figure 1: Hydroelectricity consumption by region

The orange trend line in Figure 2 (BP 2013) more clearly shows the sudden increase of hydroelectric generation in Asia. This figure also shows that the impact of hydrology can even be felt at the continental scale. A significant dip in generation is noted in North America around 2000. The dip must be an effect of hydrology changes, and not for example, of a recession. The reason is that hydroelectric systems are operated continuously as long as there is water available, compared to fossil fuel plants that would be turned off first in a recession.

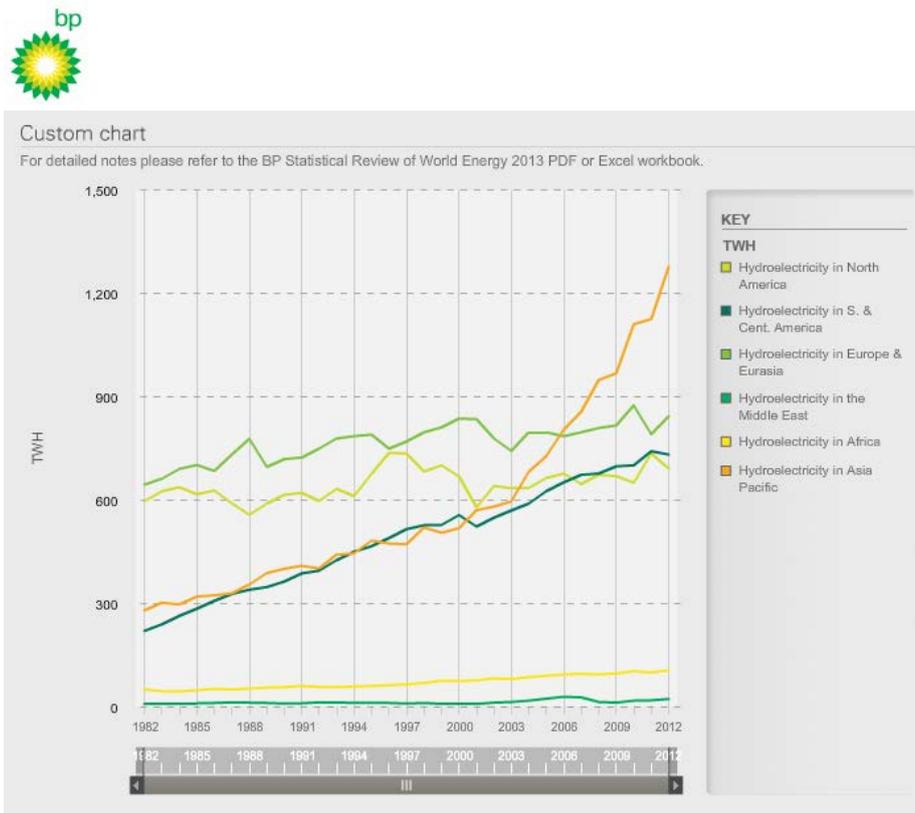


Figure 2: Hydroelectricity generation by region

Where will hydropower be in the future? Figure 3 (IEA 2012) depicts the world hydropower technical potential by region (note that the regions here are not identical to those in Figures 1 and 2), and how much of it had already been developed by 2009.

Between 74% and 92% of the potential in developing regions is not yet built. Even in North America and Europe, significant potential remains. For a sense of scale: in 2012, the global generation of hydropower was 3,670 TWh. The global technical potential is about four times that amount.

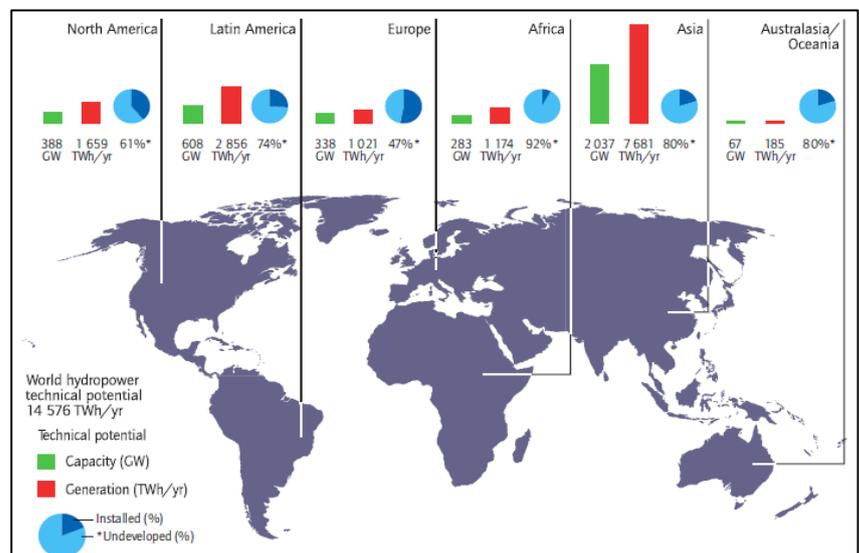


Figure 3: World hydropower potential by region

While the technical potential is possible to estimate based on surveys of feasible sites, only sub-sets of those sites are economically feasible. The economic potential is more of a moving target, because it depends on multiple and constantly changing factors, such as fossil fuel prices.

According to the IEA (2012, Figure 4), hydropower generation may double by 2050, achieving a global capacity of ca. 2,000 GW and global electricity generation of over 7,000 TWh. Other scenarios exist from the IEA and from other organizations such as the World Energy Council, with higher or lower growth rates for the hydropower sector; however, current growth of ca. 30 GW/year is consistent with the 2012 growth scenario. This scenario also predicts pumped storage hydropower capacities would be multiplied by a factor of three to five.

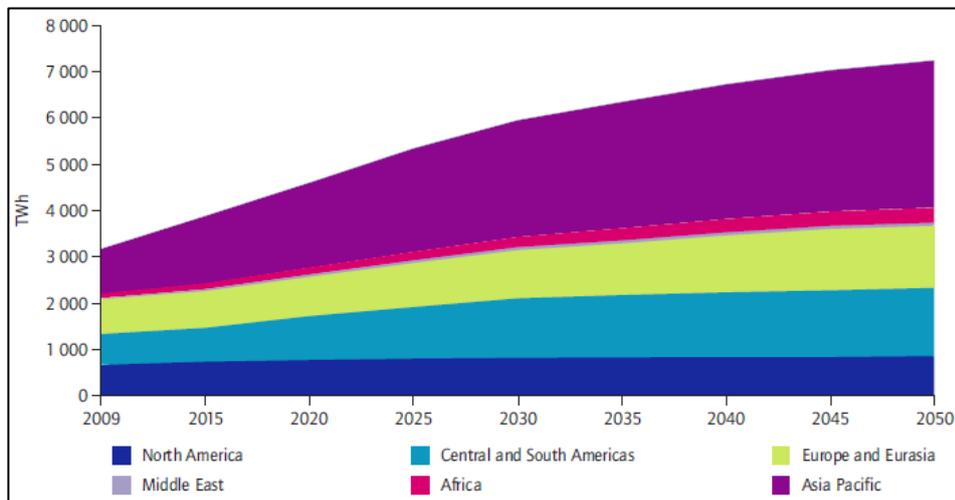
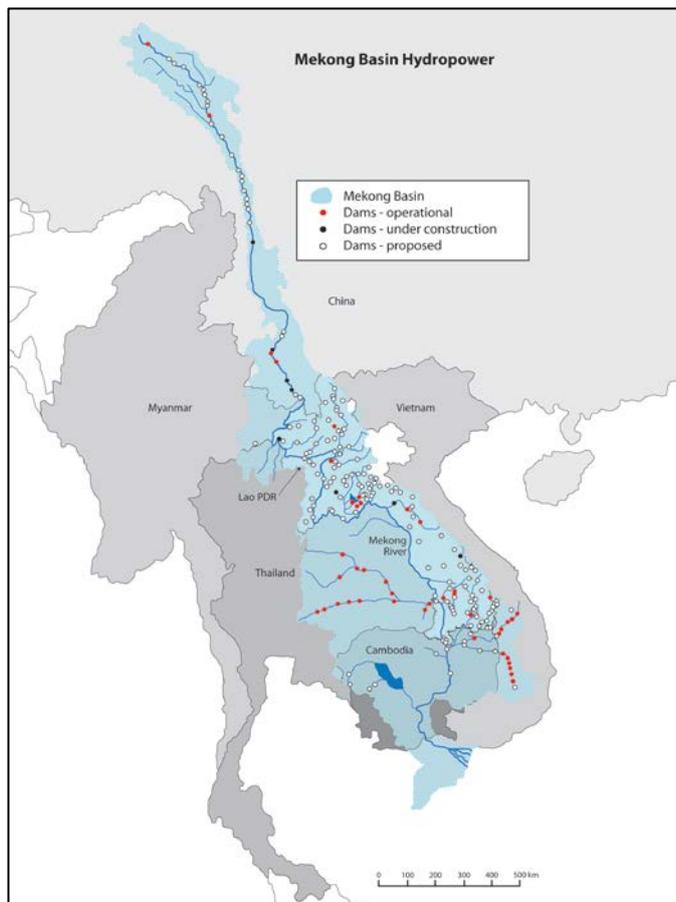


Figure 4: Future global hydropower generation projection



The Lower Mekong Basin (LMB; Figure 5)<sup>2</sup> is one of the regions with significant undeveloped hydropower potential.

Table 2 lists current and potential future hydropower generation statistics for the LMB countries (as of 2008).<sup>3</sup>

Figure 5: Lower Mekong Basin hydropower projects

<sup>2</sup> <http://nagahouse.net/wp-content/uploads/CPWF-Mekong-Basin-Hydropower-all-dots-July11.jpg>

<sup>3</sup> <http://www.intpow.com/index.php?id=487&download=1>

	Lao PDR	Cambodia	Vietnam	Thailand
Theoretical hydro potential (GWh/year)	232,500	87,660	300,000	17,746
Technically feasible hydro potential (GWh/year)	18,000 MW	34,400	123,000	16,292
Economically feasible hydro potential (GWh/year)	--	1,500 MW	100,000	<15,186
Installed hydro capacity (MW)	673	12	5,500	2,924
Generation from hydro in 2008 / most recent year (GWh)	3,777	55	5,314	24,000
Generation from hydro in 2008 / most recent year (%)	98%	7%	5%	20%
Hydro capacity under construction (MW, 2009)	2,655	193	7,534	92
Planned hydro capacity (MW)	<13,406	<1,194	14,066	<281

Table 2: Lower Mekong Basin hydropower

In the short run, the International Hydropower Association (IHA) reports annually on added capacity (pure hydro and pumped storage). Figure 6 shows that in 2012, China added 15,900 MW of capacity, or 53% of total global added capacity.

The remainder of Asia, outside of China, added 9,074 MW of capacity, 30% of the global share. The rest of the world combined added 5,051 MW of capacity, or 17% of the global capacity.<sup>4</sup>

Although remarkable, this concentration in China will be temporary, a growth spurt resulting from policy decisions made 10 years ago.

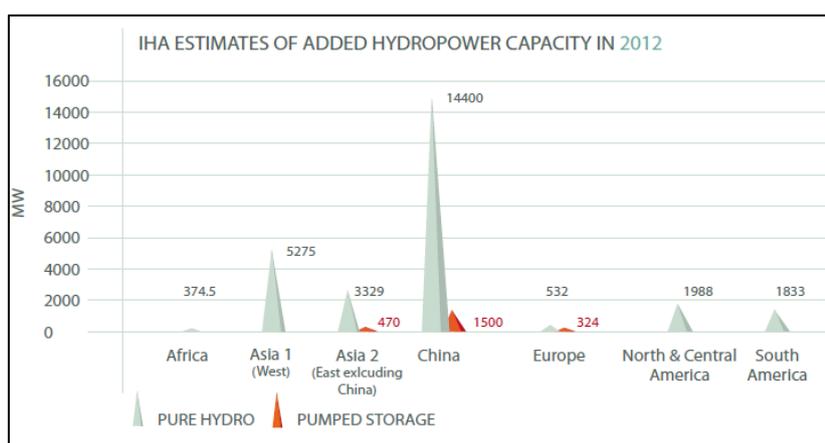


Figure 6: Added hydropower capacity in 2012

The intense interest and growth of the hydropower sector may be attributed to several factors. First, hydropower is the least expensive source of electricity in many countries. Thus, its implementation can facilitate access to electricity for the ca. 1.4 billion people who are still without access to electricity. Hydropower also offers economic development

<sup>4</sup> IHA (2013) Hydropower Report.

opportunities; exports of its power or of power-intensive products, such as aluminum, may be possible. It is also an indigenous source of power that reduces the requirements for fuel imports and increases national energy security. Hydro is also a high-value, dispatchable source, meaning that it can enable energy storage, and allow the integration of wind and solar. It is also a low-carbon source of energy. If hydropower replaced all of coal, CO<sub>2</sub> emissions would be reduced by ca. 3.8 billion tons per year. This is equivalent to USD 152 billion at a social cost of carbon of USD 40/t.<sup>5</sup>

Despite the attraction of hydropower, several barriers remain, and environmental and social concerns represent perhaps the largest challenges to further deployment (Table 3; IEA 2012, Kumar et al 2011).

Barriers	Enabling Factors
Environmental Issues	Development based on following internationally accepted approaches or protocols; integrated river basin approach
Socio-Economic Issues	Valuation of benefits, market reforms
Public Acceptance	Expanded scope of hydropower to include multi-purpose benefits
Financing	Innovative financing schemes with public-risk mitigating instruments
Cost Competitiveness	Favorable movement in relative prices of technologies and fuels, as well as taxes and subsidies for different sources
Water Availability	Effective control of competition for water and land use changes, and mitigation of climate change

*Table 3: Barriers to and enabling factors for hydropower development*

One of the environmental concerns is the rapid loss of biodiversity and wilderness. The rapid growth of the hydropower sector is paralleled by the decline of large free-flowing rivers around the world from ca. 175 down to 50 (Figure 7).<sup>6</sup> The most dramatic change was recorded during the dam-building boom from the 1950s to the 1980s. Construction slowed down in the latter part of the century; however, forecasts for 2006-2020 indicate an increase in construction of dams, and a loss of 1/3 of the remaining large free-flowing rivers.

<sup>5</sup> Own calculation. Social Cost of Carbon: <http://www.epa.gov/climatechange/EPAactivities/economics/scc.html>. This cost is for an average discount rate of 3% and for emissions in 2015.

<sup>6</sup> WWF Global Freshwater Program. "Free-flowing rivers: Economic luxury or ecological necessity?" <http://awsassets.panda.org/downloads/freeflowingriversreport.pdf>

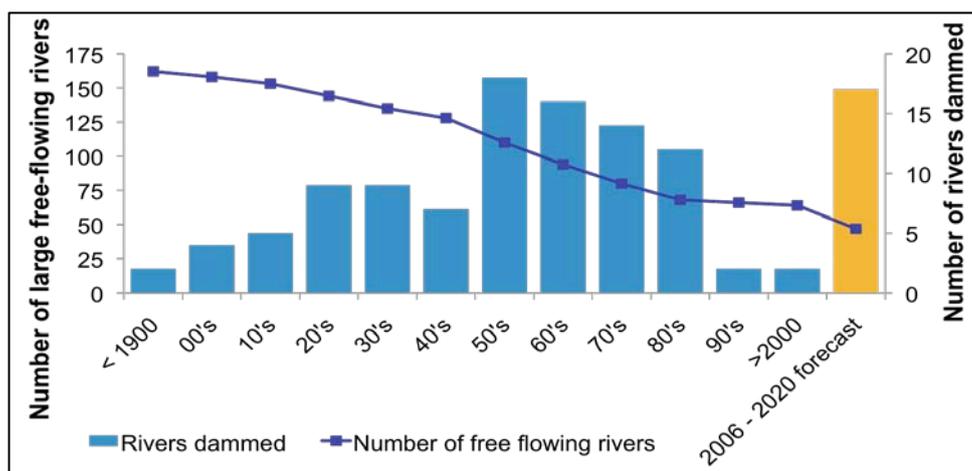


Figure 7: Rates of first dam installation on large free flowing rivers globally

Table 4 details the technical, environmental, social, economic/financial, and integrative sustainability issues that should be considered in the development of hydropower projects (IHA 2010). There is broad consensus over this list, which has been developed through a multi-stakeholder process.

Technical	Environmental	Social	Economic and Financial	Integrative
Siting and design	Downstream flows	Project affected communities and livelihoods	Economic viability	Demonstrated need and strategic fit
Hydrological resource	Erosion and sedimentation	Resettlement	Financial viability	Communications and consultation
Reservoir planning, filling and management	Water quality	Indigenous peoples	Project benefits	Governance
Infrastructure safety	Biodiversity and invasive species	Cultural heritage	Procurement	Integrated project management
Asset reliability and efficiency	Waste, noise and air quality	Public health		Environmental and social issues management

Table 4: Sustainability issues

### Optional part of session: The Hydropower Development Process

The development of hydropower is a complex process involving numerous entities including government agencies, developers, contractors, and funders. The roles, responsibilities, and assumptions of risk by these groups varies within national and regional contexts. They are important to understand as well when discussing the response to climate change.

Three models that involve different combinations of these groups are commonly seen in the planning and development of hydropower. They can be illustrated here with examples from Latin America. In the first model, the government prepares and implements the project. Mexico's Comisión Federal de Electricidad (CFE) is an example of this model. The CFE prepares 15-year masterplans and prepares, implements (with funds from the Ministry of Finance), and operates almost all projects. In the second model, the government prepares the projects and industry then implements them. In Brazil, public agencies prepare almost all projects, basin by basin, up to the point (including environmental licenses) of auctioning development licenses off to private or public developers. In the third model, the utility prepares, finances, and implements projects while the government only permits them. Chile is an example of this model. A national hydropower masterplan does not exist. Private developers obtain water rights and prepare projects for environmental approval; funding is received from private banks and private equity.

Globally, the largest hydropower utilities are all state-owned (e.g., Hydro Québec - Canada, RusHydro - Russia, Itaipu - Brazil, Three Gorges Corporation - China, Huaneng - China, US Army Corps of Engineers - USA, Statkraft - Norway, CFE Mexico, Eletrobras - Brazil). This is primarily due to the political risks and financial commitments; hydropower projects are among the most expensive infrastructure projects. Most of these state-owned utilities are domestically oriented and are implementing their governments' development agenda. Smaller projects in developing countries are often prepared and built by domestic companies with little experience. Power companies that are developing projects abroad (e.g., Brookfield, SN Power, AES, Origin, GDF Suez, Sithe, E.ON, Endesa) are mostly from the private sector and from developed countries. Some companies from emerging markets are starting international engagements, often in neighboring countries.

Hydropower infrastructure is large, complex and specialised. A large part of it is built by international active contractors.<sup>7</sup> Examples of such hydro contractors include:

- Odebrecht (private, Brazil) across South America, Angola, Mozambique etc. (USD 15bn revenues in 2012)
- Sinohydro (state-owned, China) across Asia, Africa, Ecuador etc. (USD 20bn revenues in 2012)

Civil and general contractors sometimes develop projects, but are rarely interested in operating them. Equipment suppliers do not take on an active role, but just follow the market. The current top ten international contractors in some regional and sectoral markets are shown in Figure 8. Hydropower-specific data is not available but is contained within either the water or power sector (i.e., depending on multi-purpose character of projects; whether a contract is for civil works, equipment or general contractor; and other variables).

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<sup>7</sup> The source for data on contractors including Figures 8 and 9 is Engineering News Record (2013) <http://enr.construction.com/toplists/Top-International-Contractors/001-100.asp>

1		ASIA	
RANK		Top 10 Revenue: \$74,214.8 Mil.	
2013		Sector's Revenue: \$138,814.2 Mil.	
2013	2012		
1	1	HOCHTIEF AG	
2	2	GRUPO ACS	
3	3	BECHTEL	
4	5	FLUOR CORP.	
5	4	CHINA COMMUNICATIONS CONSTR. GROUP	
6	6	LEIGHTON HOLDINGS LTD.	
7	7	SAIPEM	
8	**	BOUYGUES	
9	8	CHINA STATE CONSTRUCTION ENG'G CORP.	
10	**	HYUNDAI ENGINEERING & CONSTR. CO. LTD.	

6		AFRICA	
RANK		Top 10 Revenue: \$23,003.6 Mil.	
2013		Sector's Revenue: \$56,864.9 Mil.	
2013	2012		
1	1	SAIPEM	
2	2	CHINA COMMUNICATIONS CONSTR. GROUP	
3	4	SINOHYDRO GROUP LTD.	
4	3	VINCI	
5	6	CHINA RAILWAY GROUP LTD.	
6	10	CITIC CONSTRUCTION CO. LTD.	
7	9	CHINA STATE CONSTRUCTION ENG'G CORP.	
8	8	BOUYGUES	
9	**	CONSTRUTORA NORBERTO ODEBRECHT	
10	**	CHINA NATIONAL MACHINERY INDUSTRY CORP.	

5		POWER	
RANK		Top 10 Revenue: \$25,504.7 Mil.	
2013		Sector's Revenue: \$51,902.3 Mil.	
2013	2012		
1	2	ABEINSA SA	
2	1	GRUPO ACS	
3	3	CHINA NATIONAL MACHINERY INDUSTRY CORP.	
4	**	HYUNDAI ENGINEERING & CONSTR. CO. LTD.	
5	4	SINOHYDRO GROUP LTD.	
6	5	VINCI	
7	6	SEPCOIII ELECTRIC POWER CONSTR. CORP.	
8	7	SEPCO ELECTRIC POWER CONSTR. CORP.	
9	**	SAMSUNG C&T CORP.	
10	**	GRUPO ISOLUX CORSAN SA	

6		WATER	
RANK		Top 10 Revenue: \$9,411.0 Mil.	
2013		Sector's Revenue: \$15,406.9 Mil.	
2013	2012		
1	6	SALINI SPA	
2	2	GRUPO ACS	
3	1	HOCHTIEF AG	
4	4	CONSTRUTORA NORBERTO ODEBRECHT	
5	10	SINOHYDRO GROUP LTD.	
6	**	STRABAG SE	
7	7	CHINA INT'L WATER & ELECTRIC CORP. (CWE)	
8	8	VINCI	
9	**	SACYR VALLEHERMOSO	
10	**	CHINA GEZHOUBA GROUP CO. LTD.	

Figure 8: Top ten international contractors for some regions and sectors

Chinese companies have the largest market share worldwide; those from other emerging markets (e.g., Korea, Turkey, Brazil) are also very active (Figure 9).

DESIGNER NATIONALITY	# OF FIRMS	INT'L REVENUE		MIDDLE EAST		ASIA		AFRICA		EUROPE		UNITED STATES		CANADA		LAT. AMER / CARIB.	
		\$ MIL.	%	\$ MIL.	%	\$ MIL.	%	\$ MIL.	%	\$ MIL.	%	\$ MIL.	%	\$ MIL.	%	\$ MIL.	%
AMERICAN	33	71,516.9	14.0	11,932.4	13.1	22,691.8	16.3	2,652.2	4.7	8,127.0	7.9	NA	NA	18,889.7	68.7	7,223.9	14.4
CANADIAN	3	1,237.0	0.2	181.4	0.2	70.4	0.1	286.2	0.5	296.8	0.3	193.4	0.4	NA	NA	208.7	0.4
EUROPEAN	58	254,989.8	49.9	26,305.6	28.8	58,158.2	41.9	17,962.8	31.6	83,111.0	81.3	38,027.7	86.2	7,117.7	25.9	24,306.9	48.6
BRITISH	3	12,177.3	2.4	1,743.6	1.9	3,363.7	2.4	837.5	1.5	2,008.2	2.0	3,974.6	9.0	132.5	0.5	117.2	0.2
GERMAN	4	43,496.0	8.5	1,871.4	2.0	22,476.4	16.2	695.8	1.2	6,919.7	6.8	10,008.2	22.7	1,169.2	4.3	355.3	0.7
FRENCH	4	43,244.5	8.5	2,064.1	2.3	5,990.2	4.3	5,062.6	8.9	20,454.7	20.0	4,047.0	9.2	2,755.5	10.0	2,870.5	5.7
ITALIAN	17	30,934.5	6.1	8,689.3	9.5	3,808.7	2.7	7,400.7	13.0	5,468.3	5.3	608.2	1.4	671.2	2.4	4,288.3	8.6
DUTCH	2	7,444.0	1.5	362.6	0.4	811.0	0.6	165.9	0.3	5,905.3	5.8	0.0	0.0	50.6	0.2	148.7	0.3
SPANISH	12	72,889.3	14.3	4,429.7	4.9	20,426.1	14.7	1,457.6	2.6	16,028.8	15.7	13,802.7	31.3	1,960.8	7.1	14,783.6	29.6
OTHER	16	44,804.2	8.8	7,145.0	7.8	1,282.2	0.9	2,342.7	4.1	26,326.1	25.7	5,587.0	12.7	377.9	1.4	1,743.3	3.5
AUSTRALIAN	4	10,197.0	2.0	1,190.8	1.3	4,649.3	3.3	61.6	0.1	934.6	0.9	2,133.3	4.8	1,017.8	3.7	209.7	0.4
JAPANESE	15	21,016.7	4.1	2,339.8	2.6	14,118.5	10.2	654.4	1.2	506.7	0.5	2,310.3	5.2	307.1	1.1	780.0	1.6
CHINESE	55	67,065.3	13.1	9,311.1	10.2	24,003.2	17.3	25,487.4	44.8	1,622.5	1.6	592.1	1.3	1.0	0.0	6,048.0	12.1
KOREAN	15	41,389.7	8.1	26,700.9	29.2	9,782.3	7.0	2,732.0	4.8	309.9	0.3	598.4	1.4	111.8	0.4	1,154.4	2.3
TURKISH	38	16,804.3	3.3	5,210.1	5.7	3,002.6	2.2	2,316.1	4.1	6,104.7	6.0	2.6	0.0	0.0	0.0	168.3	0.3
BRAZILIAN	4	11,898.9	2.3	26.3	0.0	0.0	0.0	2,304.7	4.1	427.3	0.4	235.7	0.5	0.0	0.0	8,904.9	17.8
ALL OTHERS	25	14,759.9	2.9	8,119.7	8.9	2,337.9	1.7	2,407.6	4.2	822.5	0.8	13.0	0.0	47.8	0.2	1,011.4	2.0
ALL FIRMS	250	510,875.5	100.0	91,318.1	100.0	138,814.2	100.0	56,864.9	100.0	102,262.9	100.0	44,106.4	100.0	27,492.8	100.0	50,016.1	100.0

Figure 9: Top 250 international contractors in 2012

Funding of hydropower projects was traditionally from national budgets and multilateral development banks; but now sources of funding are increasingly diversifying (Figure 10).<sup>8</sup>

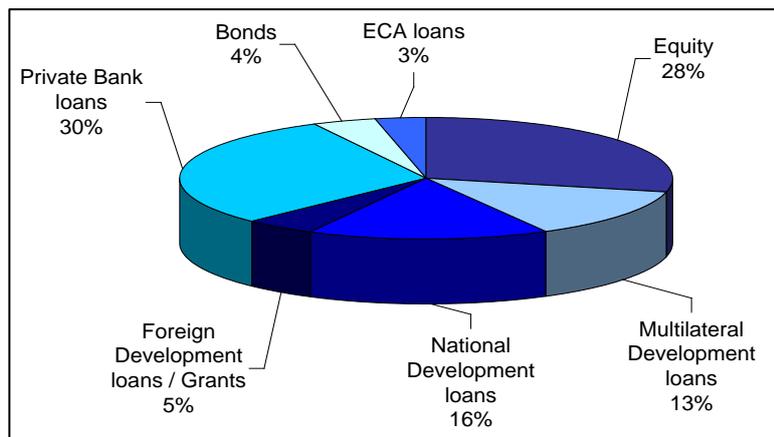


Figure 10: Financing of a sample of projects in developing countries, 2008

Examples of funding sources include:

- Brazil – almost exclusively through BNDES, the national development bank
- Malaysia – Islamic bonds marketed both to local savers and to Middle Eastern investors
- Myanmar – loans from China Development Bank and China Exim Bank
- Chile – equity from Western investors (Spain, Australia, US, etc.) and project finance from Equator Principles banks

Bank safeguard policies and knowledge management can be an important contribution to sustainability. It is generally believed that more than 50% of international project finance transactions are subject to bank safeguards, although there is a lack of data in this regard.

## 1.2 Session 1.2 Climate Change Mitigation

Purpose and Learning Objectives	<p>The session provides an introduction to climate policy frameworks internationally and in the Mekong region. The role of electricity generation in greenhouse gas emissions, and the role of hydropower in electricity systems will be reviewed.</p> <p>Trainees will gain a sense of scale of the mitigation challenge and the potential contribution of hydropower.</p>
Key Reading	<p>Item 1.2.1 - Bruckner et al (2013) Executive Summary of Chapter 7 (Energy Systems) in Climate Change 2014: Mitigation of Climate Change. Draft Working Group III contribution to the 5th Assessment Report of the IPCC.</p> <p>Item 1.2.2 - Kumar et al (2011) Executive Summary of Chapter 5 (Hydropower) in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (pp. 441-442).</p>

<sup>8</sup> Profundo (2008) New trends in the financing of dams. A research paper prepared for International Rivers, BankTrack and WWF Germany (unpublished).

Content	<p>Where do most GHG emissions come from?</p> <p>What international agreements exist for mitigation?</p> <p>How are these agreements brought into national policy frameworks?</p> <p>What options are there for mitigation?</p> <p>What are the emissions from various electricity sources?</p>
Key Aspects	<p>Fossil fuels in electricity generation are a major source of GHG, and therefore an important option for mitigation measures.</p> <p>Hydropower is a low-GHG footprint energy source.</p> <p>Current and historic emissions per capita vary drastically between countries, and climate policy frameworks such as the Kyoto Protocol are based on the principle of common but differentiated responsibilities.</p>
Discussion Topics and Exercises	<p>discuss in plenary:</p> <p>Do the LMB countries have a responsibility (moral? legal?) to participate in climate change mitigation? Even if they do not have a responsibility, do they have a self-interest?</p>
Additional Resources	<p><a href="http://www.carbonmap.org/">http://www.carbonmap.org/</a>: Explore the LMB countries' contribution to global current fossil fuels extraction and fossil fuel reserves, current and historical CO<sub>2</sub> emissions, and carbon footprint. Compare to other regions.</p>

The greenhouse effect is the process by which some of the heat that is released as infrared radiation from the Earth's surface is absorbed by greenhouse gases. This absorption results in an elevation of the atmospheric temperature. The more greenhouse gases are present, the higher the temperature will rise. A number of these additional greenhouse gases are carbon molecules. Carbon is the fourth most abundant element and is stored in rocks, in the ocean, atmosphere, plants, soil, and fossil fuels. The movement of carbon between these storage areas is called the carbon cycle. It has slow components, such as geological reservoirs, medium speed components such as the ocean sink, and fast components such as the biosphere (Figure 11).<sup>9</sup>

<sup>9</sup> <http://www.carboncyclescience.gov/what-is-carbon-cycle>

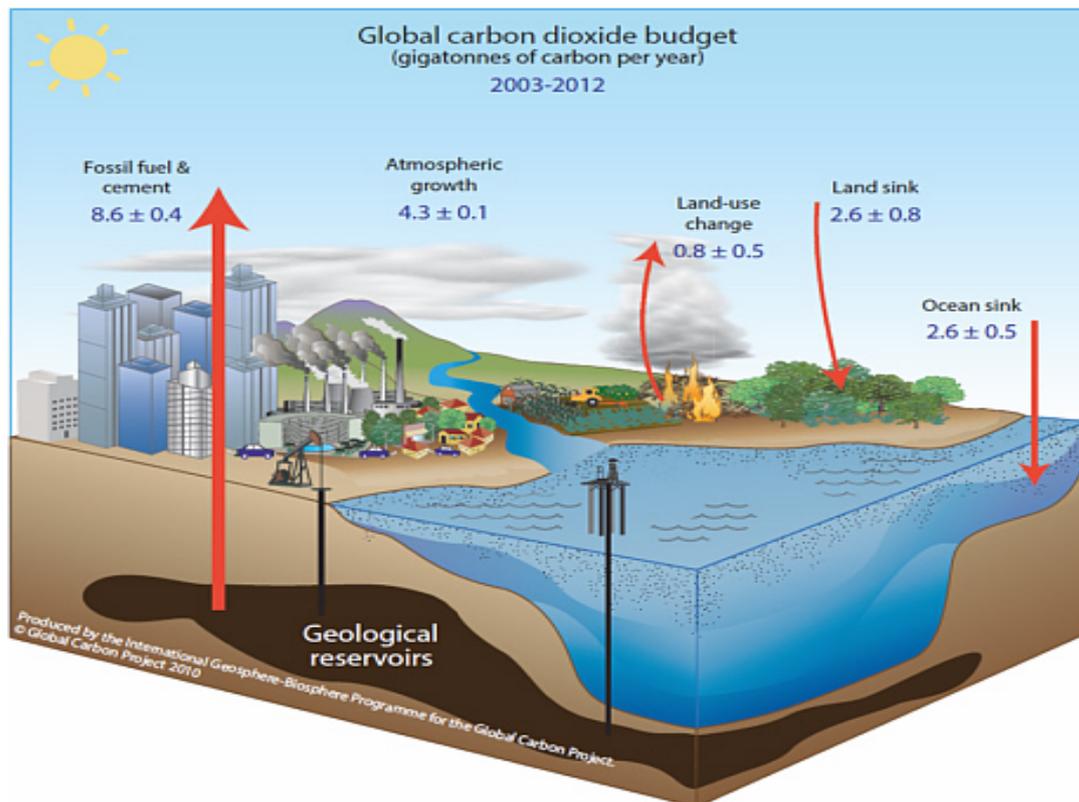


Figure 11: Global carbon cycle

Carbon dioxide (CO<sub>2</sub>) is the most important greenhouse gases the quantity of which has increased by human activity. Figure 12 shows the largest historic (1950-2003) per capita CO<sub>2</sub> emitters from land use change, fossil fuel combustion, and cement production.<sup>10</sup> In the South-East Asian region, only Laos and Malaysia belong to this group.

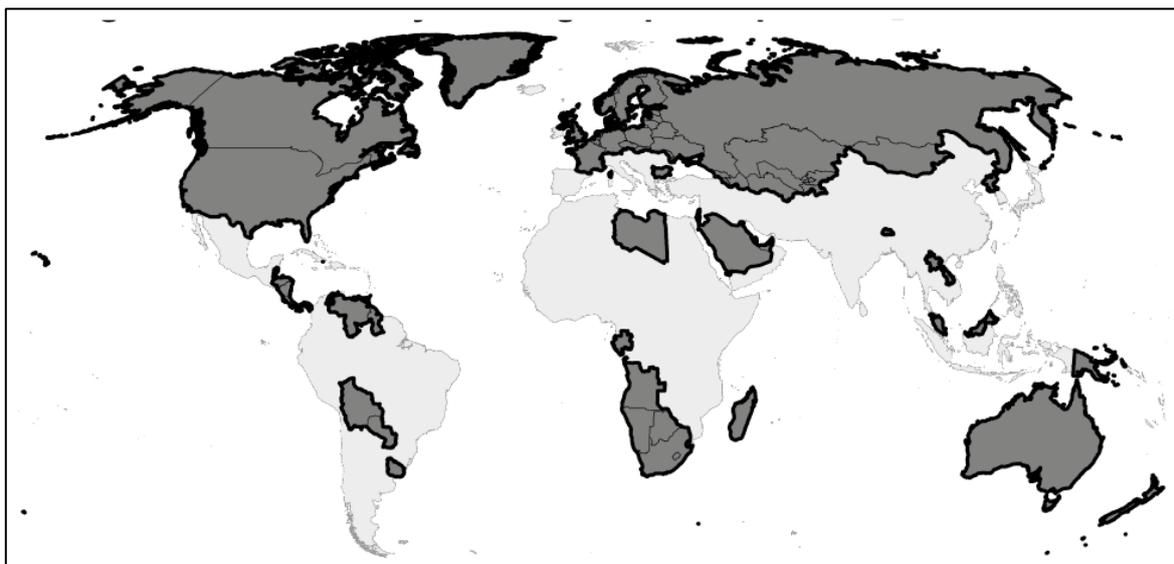


Figure 12: Largest per capita CO<sub>2</sub> emitters

<sup>10</sup> Schellnhuber (2007) Potsdam Institute for Climate Impact Research (PIK) presentation

Carbon dioxide exists naturally in the atmosphere; however, man-made sources are contributing additional quantities of CO<sub>2</sub> and other types of gases. For simplicity in calculation and analysis, quantities of these other gases are equated to a quantity of CO<sub>2</sub> that would have the same global warming potential. Figure 13 shows the quantity of CO<sub>2</sub> equivalent released through the production of electricity using various technologies.<sup>11</sup> This is usually given as a range of data because energy technologies can be quite variable depending on sites, quality of fuels, age of plants and other factors. Hydropower is generally considered a low-carbon source of power.

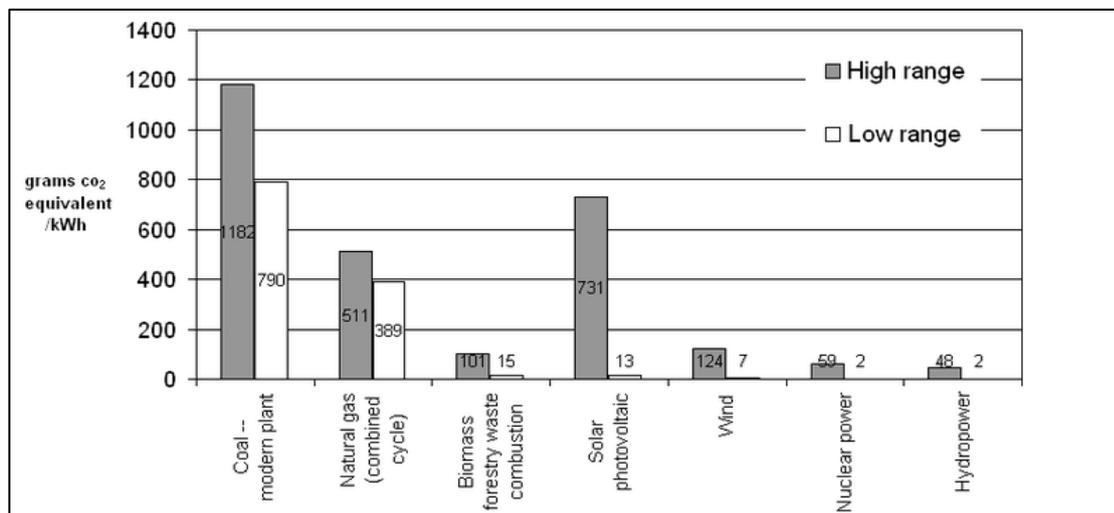


Figure 13: Greenhouse gas emissions from electricity production

Table 5 shows how different historic and current emissions are by country, comparing the LMB countries to a developed and a heavily industrialized emerging economy.<sup>12</sup> It also shows that imports and exports of fuels, other goods and services can have an important influence on the carbon balance.

	Lao PDR	Cambodia	Thailand	Vietnam	Germany	China
Population (m)	6	14	69	87	82	1338
CO <sub>2</sub> from fossil fuels extracted (m t)	15	12	139	173	196	7958
CO <sub>2</sub> from fossil fuels burned (m t)	2	5	299	160	763	8241
CO <sub>2</sub> from goods/services consumed (m t)	3	12	262	178	1015	5993
Cumulative CO <sub>2</sub> from energy use, 1850–2007 (m t)	23	51	3930	1640	81195	105915

Table 5: Mitigation responsibility and potential

<sup>11</sup> Koch (2000) Hydropower-Internalised Costs and Externalised Benefits. IEA Implementing Agreement for Hydropower Technologies and Programmes; at [http://en.wikipedia.org/wiki/Life-cycle\\_greenhouse-gas\\_emissions\\_of\\_energy\\_sources](http://en.wikipedia.org/wiki/Life-cycle_greenhouse-gas_emissions_of_energy_sources)

<sup>12</sup> <http://www.carbonmap.org/>

Reduction of CO<sub>2</sub> emissions is an essential action to limit global climate change. Mitigation is defined as “technological change and substitution that reduce resource inputs and emissions per unit of output”.<sup>13</sup> Many different social, economic and technological policies could produce a reduction in emissions. However, with respect to climate change, mitigation means implementing specific policies to reduce greenhouse gas emissions and enhance carbon sinks. (A carbon sink is, for example, a forest that absorbs carbon while growing).

The United Nations Framework Convention on Climate Change (UNFCCC) was negotiated in Rio de Janeiro at the United Nations Conference on Environment and Development in 1992 and entered into force in 1994. The treaty provides a framework for negotiating specific protocols that may set binding limits on greenhouse gases.

Principle 7 of the 1992 Rio Declaration on Environment and Development states that:

*"States shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystem. In view of the different contributions to global environmental degradation, States have common but differentiated responsibilities. The developed countries acknowledge the responsibility that they bear in the international pursuit to sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command."<sup>14</sup>*

This principle has been important in climate negotiations. The parties to the UNFCCC have met annually since 1995 at the Conferences of the Parties (COP) to assess progress in confronting climate change. In 1997, the Kyoto Protocol was adopted and it entered into force in 2005. The detailed rules for the implementation of the Protocol were adopted at COP7 in Marrakesh in 2001. During the first commitment period (i.e., 2008 to 2012), a group of countries called ‘Annex I parties’ committed to reduce greenhouse gases by an average of 5% against 1990 levels. At COP16 in Cancún, parties committed to a maximum temperature rise of 2° C. In 2012, at COP 18 in Doha, the "Doha Amendment to the Kyoto Protocol" was adopted. It includes new commitments for most Annex I parties who would participate in a second commitment period (i.e., 2013 to 2020), reducing greenhouse gases by at least 18% below 1990 levels (Figure 14).<sup>15</sup>

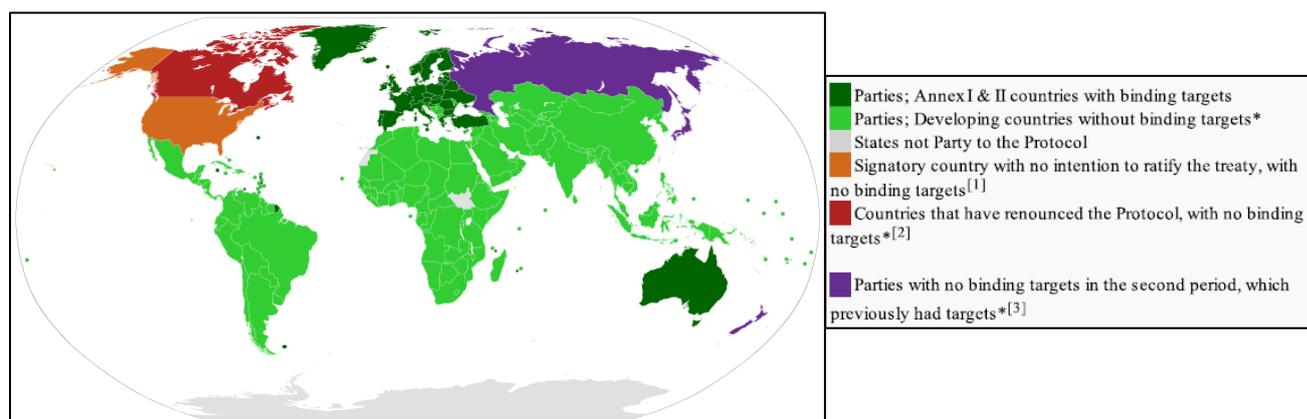


Figure 14: Participation in second commitment period

<sup>13</sup> IPCC (2007) Fourth Assessment Report: Climate Change.

<sup>14</sup> <http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm>

<sup>15</sup> [http://en.wikipedia.org/wiki/Kyoto\\_Protocol](http://en.wikipedia.org/wiki/Kyoto_Protocol)

Parties can apply mitigation measures in any sector. It would be expected that low-cost options are explored first and only if necessary, options with higher costs are adopted. Figure 15 shows the potential cost of mitigation by sector, forecasted to 2030.<sup>16</sup> For example, in the energy supply sector, if only those measures that cost less than 100 USD per ton of CO<sub>2</sub>e are taken, then global emissions could be reduced by between 2.4 and 4.7 gigatons of CO<sub>2</sub>e every year. This can be compared to the reductions potential at different cost levels in other sectors.

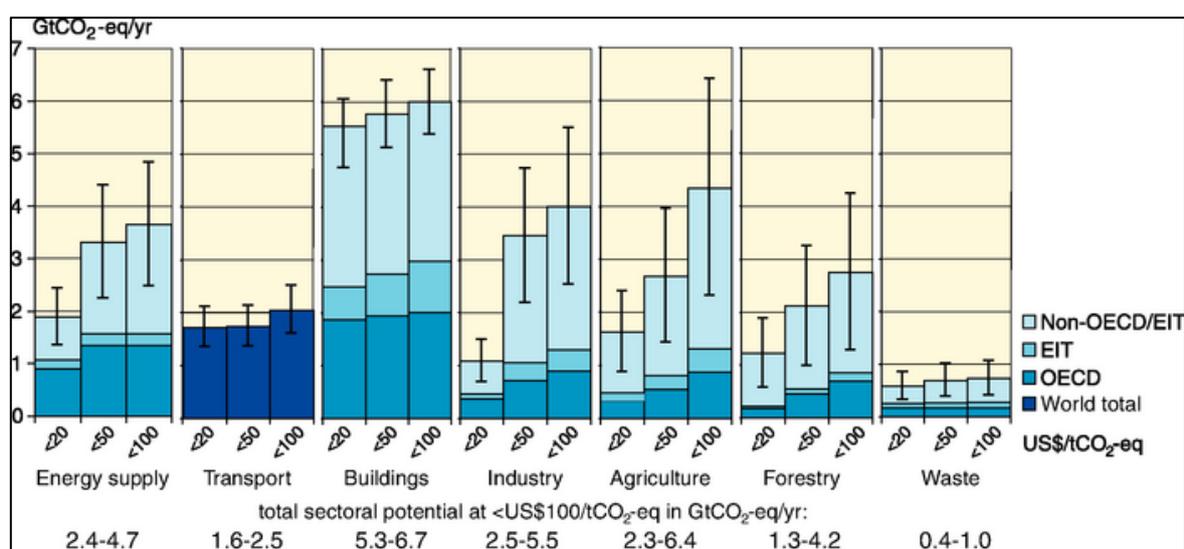


Figure 15: Economic mitigation potential by sectors in 2030

Mitigation policies vary widely between countries, and are most advanced in the countries that have taken on obligations to reduce emissions, especially in Europe. The LMB countries have started introducing relevant policies (Table 6).<sup>17</sup>

<sup>16</sup> Notes: a) Ranges for global economic potentials as assessed in each sector are shown by vertical lines. Ranges are based on end-use allocations of emissions; b) Estimated potentials have been constrained by the availability of studies particularly at high carbon price levels; c) Sectors used different baselines; d) Only global totals for transport are shown because international aviation is included; e) Categories excluded: non-CO<sub>2</sub> emissions in buildings and transport, part of material efficiency options, heat production and co-generation in energy supply, heavy duty vehicles, shipping and high-occupancy passenger transport, most high-cost options for buildings, wastewater treatment, emission reduction from coal mines and gas pipelines, and fluorinated gases from energy supply and transport. The underestimation of the total economic potential from these emissions is of the order of 10 to 15% (IPCC (2007) Fourth Assessment Report: Climate Change).

<sup>17</sup> ADB (2013)

Country	Renewable Energy Law and Policy	“Stretch” Targets	Feed-in Tariff or Other Incentives	Blending Mandates
Cambodia	No law. The REAP was conceived as a supplement to electrification.	No.	No.	No.
Lao People’s Democratic Republic	No law. There is a national strategy to 2025.	Yes. 30% by 2025.	Discussed but not in place.	No.
Myanmar	No law or policy.	No.	No.	No.
People’s Republic of China (Guangxi and Yunnan)	Well-designed law and subsequent regulation.	Yes.	Yes. For wind and solar.	Aim is 10% biofuels mandate by 2020. Nine provinces require 10% ethanol blends (but not Guangxi or Yunnan)
Thailand	No law. Detailed strategy.	Yes. 20% by 2020.	Yes. A well-designed feed-in tariff differentiated by technology and scale. Plus other support.	Voluntary for ethanol—market resistance. Mandatory for biodiesel, but shortages of feedstock. Problems in implementation.
Viet Nam	No law. The most recent strategy is for 2020 with outlook to 2050.	Partially. 5% in 2020. Very low considering the potential.	Yes, but tariffs are too low to be effective.	There are production targets, but blending mandates have been delayed.

REAP = Renewable Electricity Action Plan.  
Sources: Various country energy reports.

Table 6: LMB country mitigation policies

### 1.3 Session 1.3 Climate Change Adaptation

Purpose and Learning Objectives	<p>The session provides an overview of adaptation to climate change, with a focus on water resources and the Mekong region. It reviews the concepts of vulnerability, resilience, adaptive capacity, and the role of ‘software’ and ‘hardware’ in adaptation.</p> <p>Trainees will become familiar with adaptation terminology and start to see general implications for hydropower in Mekong countries.</p>
Key Reading	<p>Item 1.3.1 - UN Water (n.d.) Climate change adaptation is mainly about water.</p> <p>Item 1.3.2 - Jimenez et al (2013) Chapter 3 (Freshwater resources and their management) in Climate Change 2014: Impacts, Adaptation and Vulnerability. Draft Contribution of Working Group II to the 5th Assessment Report of the IPCC.</p> <p>Item 1.3.3 - Hijioaka et al (2013) Chapter 24 (Asia) in Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the 5th Assessment Report of the IPCC.</p>
Content	<p>What is the standard adaptation terminology?</p> <p>How are water resources affected both by human use and by climate change?</p>

	<p>What are some adaptation options and constraints? Can dams make adaptation more difficult?</p>
Key Aspects	<p>Large population groups in the LMB countries are vulnerable to climate change.</p> <p>Climate change is affecting people mainly through water resources, which are already stressed in many places.</p> <p>There are options to adapt to climate change, but they are not easy, cheap, and universally accepted.</p>
Discussion Topics and Exercises	<p>Group work: Discuss how climate change is used as argument for and against hydropower. (This should cover both mitigation and adaptation.)</p> <p>Divide participants into a maximum of 8 groups. All groups receive 3 handouts. Groups first separate out mitigation and adaptation arguments, then choose one argument, discuss it, and report back to plenary on their conclusions.</p> <p>Hand-outs:</p> <ul style="list-style-type: none"> <li>• Item 1.1.1 - IEA key findings page</li> <li>• Item 1.3.4 - IR graphic on dams and climate change.</li> <li>• Item 1.3.5 - IHA Congress 2013 climate session summary</li> </ul>
Additional Resources	<p><a href="http://www.carbonmap.org/">http://www.carbonmap.org/</a>: Explore the LMB countries' vulnerability in terms of people at risk from natural disasters, sea level rise, and poverty. Compare to other regions.</p> <p>Watch IR video: <a href="http://www.internationalrivers.org/campaigns/wrong-climate-for-damming-rivers">http://www.internationalrivers.org/campaigns/wrong-climate-for-damming-rivers</a></p>

The discussion of adaptation to climate change requires the use of some standard terminology:<sup>18</sup>

- **Sensitivity:** The degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).
- **Vulnerability:** The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.
- **Adaptation:** Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc.

<sup>18</sup> IPCC (2007) Fourth Assessment Report: Climate Change.

- **Adaptive capacity:** The whole of capabilities, resources and institutions of a country or region to implement effective adaptation measures.
- **Resilience:** The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change.

Nations that will potentially be most significantly affected by climate change are often not the ones most responsible for the changes happening. Figure 16<sup>19</sup> repeats the largest per-capita CO<sub>2</sub> emitters in grey (from Figure 12) but now adds the countries with the highest social or agro-economic vulnerability in orange. Only a few of the nations, annotated with orange/grey strips, are identified as being high emitters and highly vulnerable. Green areas denote areas of highest ecological vulnerability, often seen to be drylands.

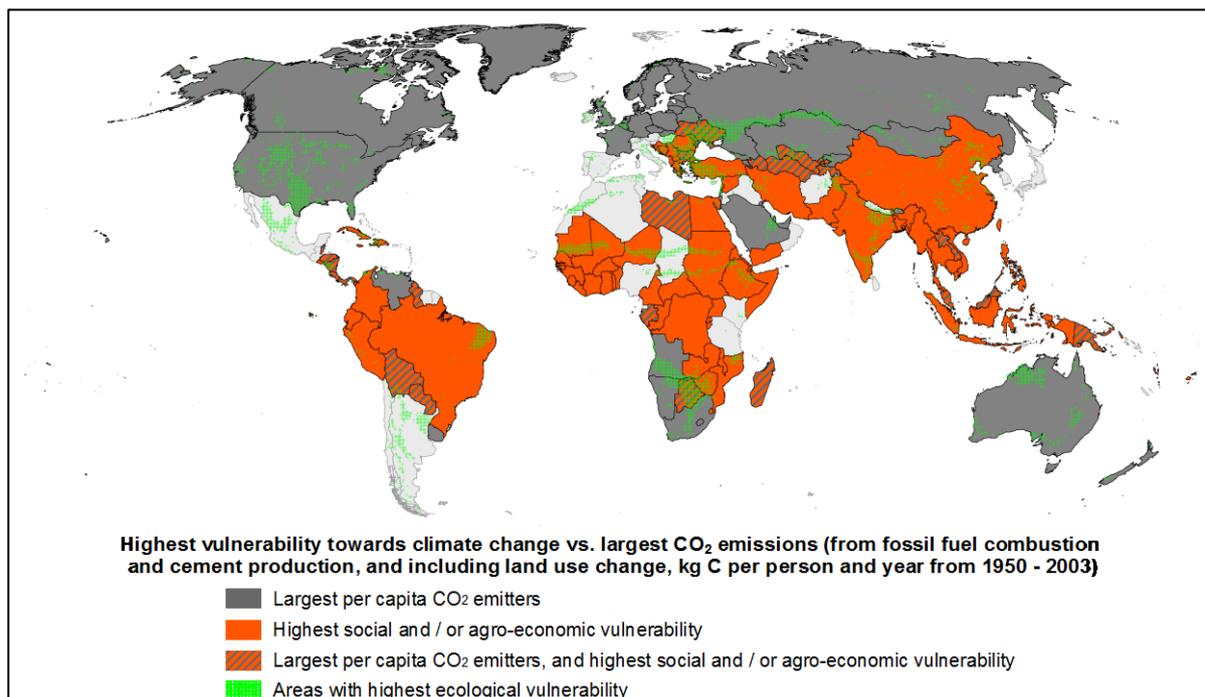


Figure 16: Emissions and vulnerability

Millions of people around the world are highly vulnerable to the current and expected effects of climate change. Often the poor, who are the most vulnerable, are also the ones mostly likely to be affected. Table 7 gives some indication of the numbers of people potentially exposed to climate change.<sup>20</sup>

<sup>19</sup> Schellnhuber (2007) Potsdam Institute for Climate Impact Research (PIK) presentation

<sup>20</sup> <http://www.carbonmap.org>

	Lao PDR	Cambodia	Thailand	Vietnam	Germany	China
Population (m)	6	14	69	87	82	1338
Population already suffering from droughts, floods or extreme temperatures (m)	0.2	0.9	2.6	1.4	0.03	106.4
Population living less than 5m above sea level (m)	0	1	10	37	4	108
People living on less than 1.25 dollars a day (m)	1.9	2.9	0.2	13.4	0.0	160.0
GDP at PPP (billion USD)	16	31	591	279	3040	10200

Table 7: Vulnerability in LMB region in a comparative perspective

In order to reduce this vulnerability, individuals, communities, businesses, sectors, and entire countries can apply adaptation strategies. Table 8 shows adaptation options for various sectors.<sup>21</sup> These may require supportive policy frameworks and may be subject to barriers, but also present new opportunities.

Sector	Adaptation option/strategy	Underlying policy framework	Key constraints and opportunities to implementation (Normal = constraints; <i>italics</i> = opportunities)
<b>Water</b>	Expanded rainwater harvesting; water storage and conservation techniques; water re-use; desalination; water-use and irrigation efficiency	National water policies and integrated water resources management; water-related hazards management	Financial, human resources and physical barriers; <i>integrated water resources management; synergies with other sectors</i>
<b>Agriculture</b>	Adjustment of planting dates and crop variety; crop relocation; improved land management (e.g., erosion control and soil protection through tree planting)	R&D policies; institutional reform; land tenure and land reform; training; capacity building; crop	Technological and financial constraints; access to new varieties; markets; <i>longer growing season</i>

<sup>21</sup> IPCC (2007) Fourth Assessment Report: Climate Change.

		insurance; financial incentives (e.g., subsidies and tax credits)	<i>in higher latitudes; revenues from 'new' products</i>
<b>Infrastructure/ settlement (including coastal zones)</b>	Relocation; seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of marshlands/wetlands as buffer against sea level rise and flooding; protection of existing natural barriers	Standards and regulations that integrate climate change considerations into design; land-use policies; building codes; insurance	Financial and technological barriers; availability of relocation space;  <i>integrated policies and management; synergies with sustainable development goals</i>
<b>Human health</b>	Heat-health action plans; emergency medical services; improved climate-sensitive disease surveillance and control; safe water and improved sanitation	Public health policies that recognize climate risk; strengthened health services; regional and international cooperation	Limits to human tolerance (vulnerable groups); knowledge limitations; financial capacity;  <i>upgraded health services; improved quality of life</i>
<b>Tourism</b>	Diversification of tourism attractions and revenues (e.g., shifting ski slopes to higher altitudes and glaciers or artificial snow-making)	Integrated planning (e.g., carrying capacity; linkages with other sectors);  financial incentives, (e.g., subsidies and tax credits)	Appeal/marketing of new attractions; financial and logistical challenges; potential adverse impact on other sectors (e.g., artificial snow-making may increase energy use);  <i>revenues from 'new' attractions; involvement of wider group of stakeholders</i>
<b>Transport</b>	Realignment/relocation; design standards and planning for roads, rail and other infrastructure to cope with warming and drainage	Integrating climate change considerations into national transport policy; investment in R&D for special situations, (e.g., permafrost areas)	Financial and technological barriers; availability of less vulnerable routes;  <i>improved technologies and integration with key sectors (e.g., energy)</i>

<b>Energy</b>	Strengthening of overhead transmission and distribution infrastructure; underground cabling for utilities; energy efficiency; use of renewable sources; reduced dependence on single sources of energy	National energy policies, regulations, fiscal and financial incentives to encourage use of alternative sources; incorporating climate change in design standards	Access to viable alternatives; financial and technological barriers; acceptance of new technologies; <i>stimulation of new technologies; use of local resources</i>
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Table 8: Adaptation options by sector

Water is a fundamental component of adaptation to climate change. Climate change will alter temperatures and thus impact rates of precipitation, snow and glacier melt, flows, and evaporation, ultimately also affecting water quality. The natural water cycle is already affected by human activities through various direct and indirect pathways (Figure 17).<sup>22</sup> All these activities determine the complexity of water resource management (i.e., the planning, developing, distributing and managing for optimum use of water resources). Ideally, water resource management regards all competing demands for water and seeks to allocate water on an equitable basis to satisfy all uses and demands, including environmental water needs.

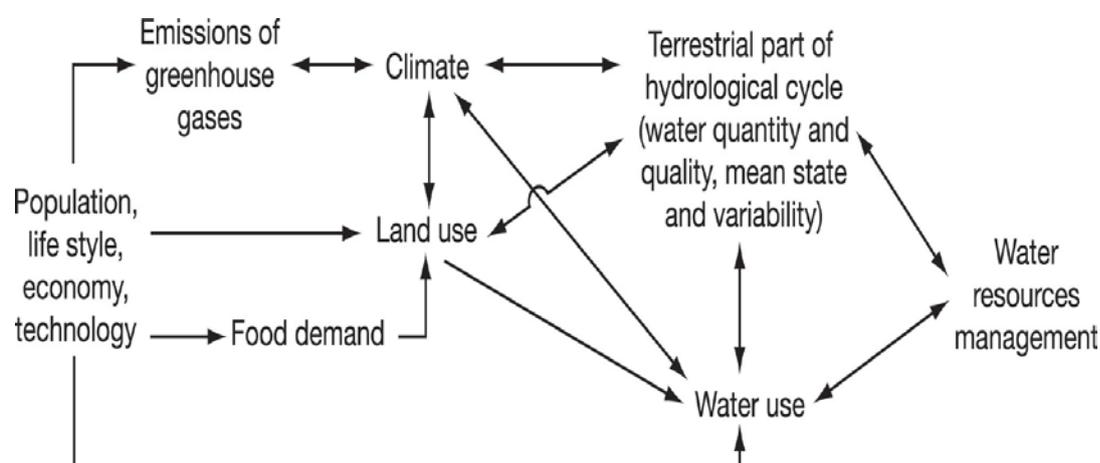


Figure 17: Impact of human activities on freshwater resources and their management

Even before climate change was recognized, water resource management was subject to different regional climates that cause water stress, and natural climate variability that results in temporary disturbances such as floods and droughts. Figure 18 shows some examples.<sup>23</sup> Many pre-existing water resource management challenges are made more difficult by climate change, but attribution of the incremental impact of climate change is difficult.

<sup>22</sup> IPCC (2007) Fourth Assessment Report: Climate Change.

<sup>23</sup> IPCC (2007) Fourth Assessment Report: Climate Change.

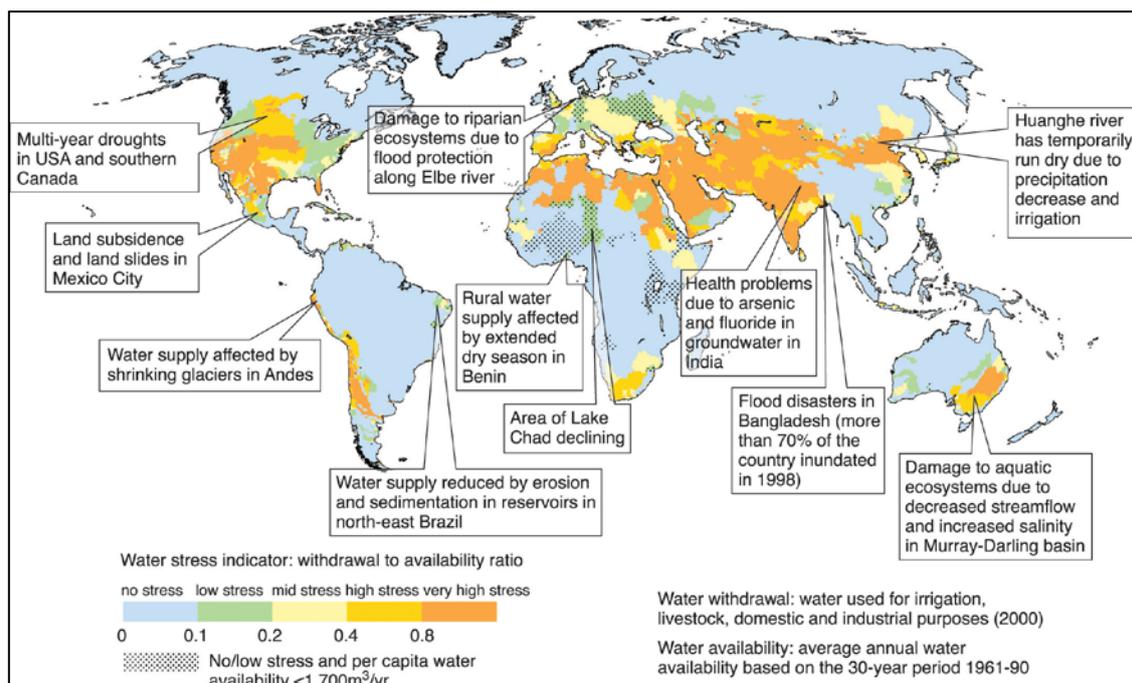


Figure 18: Water resource management challenges

Adaptation is a necessary and enduring feature of human societies. We have always adapted and keep adapting to multiple structural changes in our environment. Adaptation requires creative planning and often, the implementation of multi-faceted strategies; all options must be considered. Table 9 shows that many water resource management options can equally be seen as adaptation options.<sup>24</sup>

Supply-side	Demand-side
Prospecting and extraction of groundwater	Improvement of water-use efficiency by recycling water
Increasing storage capacity by building reservoirs and dams	Reduction in water demand for irrigation by changing the cropping calendar, crop mix, irrigation method, and area planted
Desalination of sea water	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water
Expansion of rain-water storage	Promotion of indigenous practices for sustainable water use
Removal of invasive non-native vegetation from riparian areas	Expanded use of water markets to reallocate water to highly valued uses
Water transfer	Expanded use of economic incentives including metering and pricing to encourage water conservation

Table 9: Adaptation strategies

The ability to implement adaptation strategies in a timely manner may however be limited by physical, economic, political, social, and institutional factors. Physical factors include constraints such as the design of existing water resource infrastructure. Large infrastructure projects or the relocation of a community due to sea level rise may not be economically practical. Some strategies may not be politically or socially acceptable; for example, the construction of a storage reservoir or the reduction in reliability of public services. Institutional barriers also exist due to a lack of attention, capacity, coordination, or knowledge of the issues.

<sup>24</sup> ibid

Some opponents of dams emphasize that dams have multiple drawbacks as an adaptation and mitigation option (Figure 19).<sup>25</sup> These drawbacks need to be considered as well as the drawbacks of other adaptation and mitigation options.

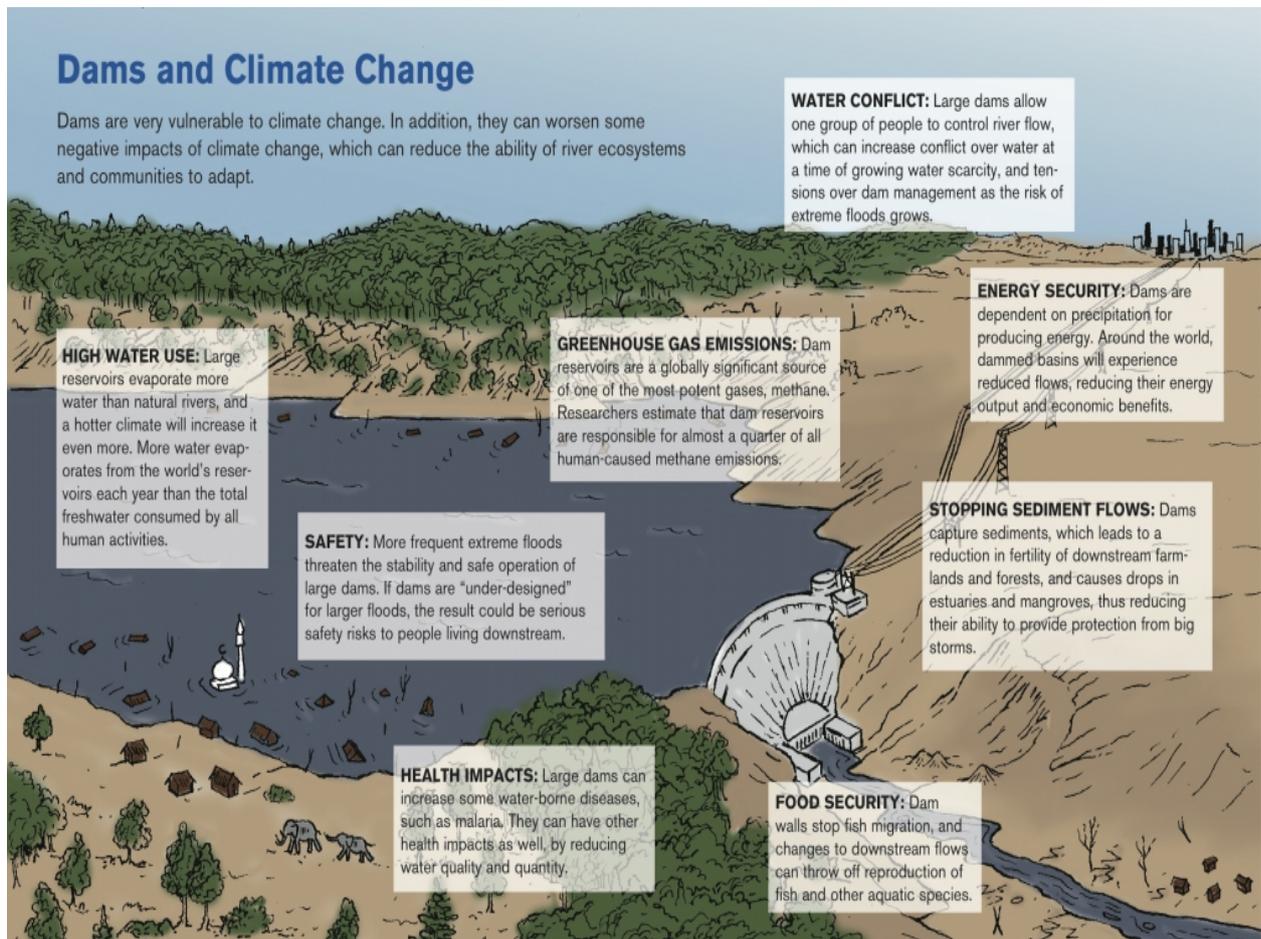


Figure 19: Drawbacks of dams under climate change

<sup>25</sup> <http://www.internationalrivers.org/campaigns/wrong-climate-for-damming-rivers>

## 2 MODULE 2. BASIC CONCEPTS

### 2.1 Session 2.1 Basic Climate Concepts

Purpose and Learning Objectives	This session provides an overview of weather and climate definitions. It will review climate systems, classifications, variability, and forecasting/modelling, globally and for the Mekong region.  Trainees will be able to refresh their understanding of basic climate issues and become confident users of climate terminology.
Key Reading	Item 2.1.1 - Climate article from <a href="http://en.wikipedia.org/wiki/Climate">http://en.wikipedia.org/wiki/Climate</a>
Content	What is the difference between weather and climate? How is weather forecasted and how is the climate modelled? How can we describe and classify the climate in the Mekong region? How variable is the climate?
Key Aspects	The weather is the short-term variable and the climate the long-term average state of the atmosphere. Weather and climate are forecasted through similar models.  The Mekong region has a tropical/sub-tropical climate with a strong Monsoon influence.  The climate is highly variable on various timescales, including long-term trends.
Discussion Topics and Exercises	Explore and discuss the current weather forecast for the LMB region at <a href="http://www.weather-forecast.com/maps/VietNam">http://www.weather-forecast.com/maps/VietNam</a>
Additional Resources	Online courses on climate science at <a href="http://www.climate.be/textbook/index.html">http://www.climate.be/textbook/index.html</a> <a href="https://www.e-education.psu.edu/meteo469/node/31">https://www.e-education.psu.edu/meteo469/node/31</a>

The climate system includes external mechanisms (principally, the sun) that ‘force’ or influence its components (Figure 20).<sup>26</sup> The non-living components consist of the lithosphere (solid Earth), atmosphere (gaseous envelope), hydrosphere (liquid water) and cryosphere (frozen water) – together the geosphere. The living components are the biosphere. Climate variations result from changes in the components of the climate system.

<sup>26</sup> Baede, A.P.M, E. Ahlonsou, Y. Ding, D. Schimel (2001) The Climate System: an Overview. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.

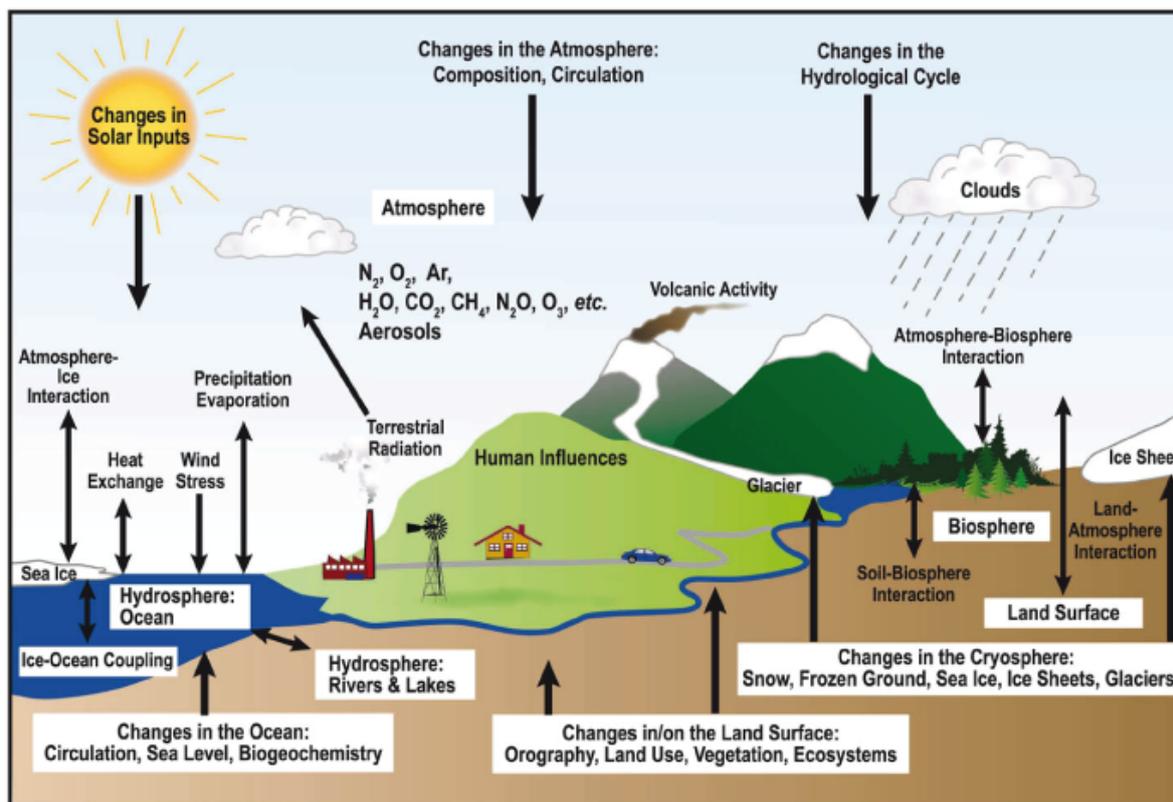


Figure 20: Components of the climate system, their processes, and interactions

Weather refers to the fluctuating state of the atmosphere. Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description of the mean and variability of relevant quantities over a period ranging from months, to thousands or millions of years. These quantities are most often surface variables such as temperature, precipitation, and wind. In a broader sense, climate is the state (statistically described) of the climate system.<sup>27</sup>

Weather	Climate
instantaneous atmospheric condition	average atmospheric condition
can change rapidly, within less than an hour	over a period of 30 years, as defined by the World Meteorological Organization (WMO)
prevails over a small area	prevails over a large region
has only limited predictability beyond a few days (chaotic nature of atmosphere)	almost constant
depends primarily on density differences (temperature and moisture) between places	depends on latitude, distance to sea, vegetation, presence of mountains, and geographical factors

Table 10: Weather versus climate

<sup>27</sup> IPCC (2007) Fourth Assessment Report: Climate Change. Also, for example, see [http://www.nasa.gov/mission\\_pages/noaa-n/climate/climate\\_weather.html](http://www.nasa.gov/mission_pages/noaa-n/climate/climate_weather.html).

Weather forecasts such as in Figure 21<sup>28</sup> are made by collecting quantitative data about the current state of the atmosphere and using scientific understanding of atmospheric processes to project how the weather will evolve. The chaotic nature of the atmosphere, error involved in measuring the initial conditions, and an incomplete understanding of atmospheric processes mean that forecasts become less accurate as their time range increases. Recent improvements mean that a five-day weather forecast of today is as reliable as a two-day weather forecast 20 years ago.<sup>29</sup>

Climate models use quantitative methods to simulate the interactions within the atmosphere, land, oceans, and ice. They are used to study the dynamics of the climate system and project future climates. As knowledge and computing power have increased, climate models have become much more complex and coupled over time (Figure 22). Climate models divide the earth into spatial grids and interrelated cells and compute changes in time-steps. Generally, fewer details are included than in weather forecasts, in order to minimize computational intensity (Figure 23).<sup>30 31</sup>

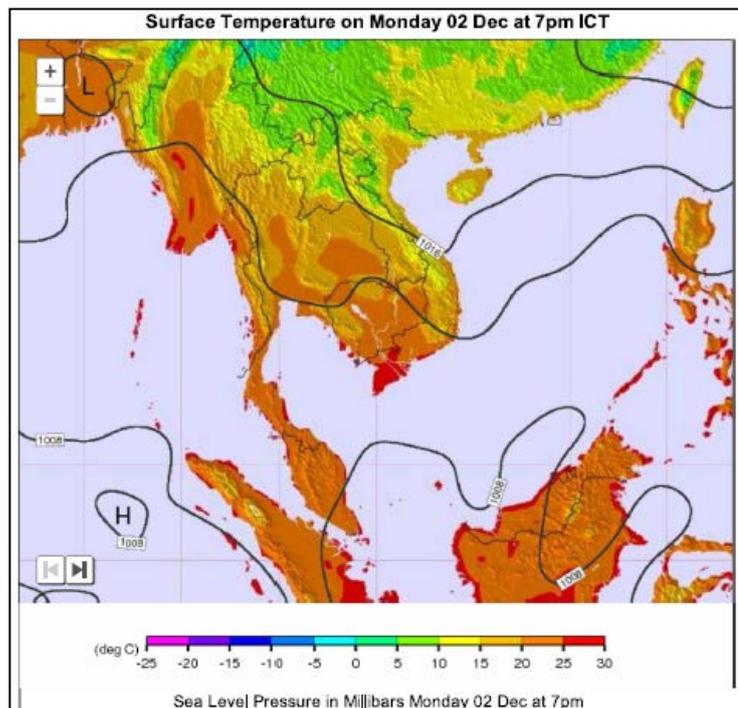


Figure 21: Weather forecast

<sup>28</sup> <http://www.weather-forecast.com/maps/VietNam>

<sup>29</sup> World Meteorological Organization [http://www.wmo.int/pages/index\\_en.html](http://www.wmo.int/pages/index_en.html)

<sup>30</sup> IPCC Third Assessment Report, Technical Summary of Working Group I Report, 2001; <http://www.gfdl.noaa.gov/climate-modeling>, [http://www.wmo.int/pages/themes/climate/climate\\_models.php](http://www.wmo.int/pages/themes/climate/climate_models.php)

<sup>31</sup> <http://www.metoffice.gov.uk/climate-guide/science/science-behind-climate-change/hadley>

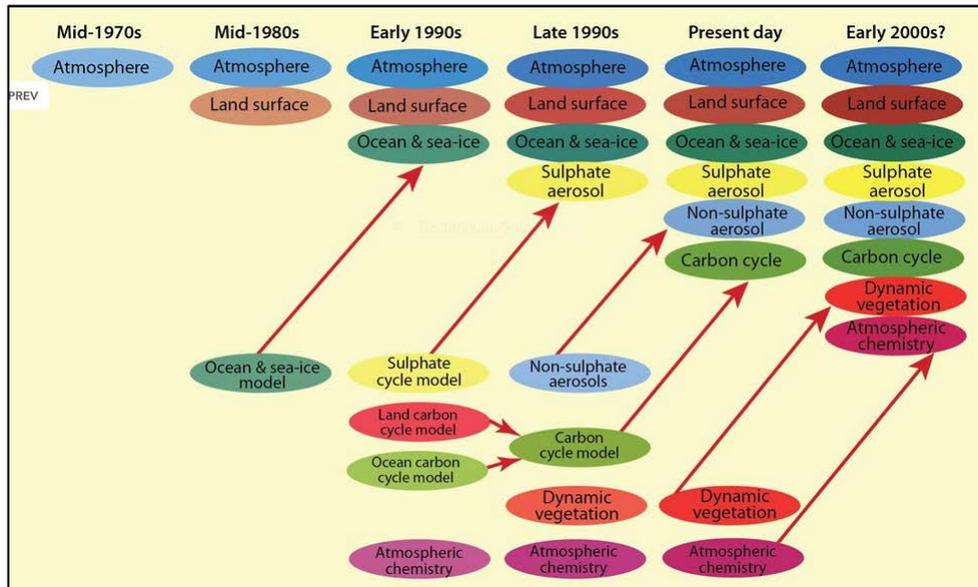


Figure 22: Evolution of climate models

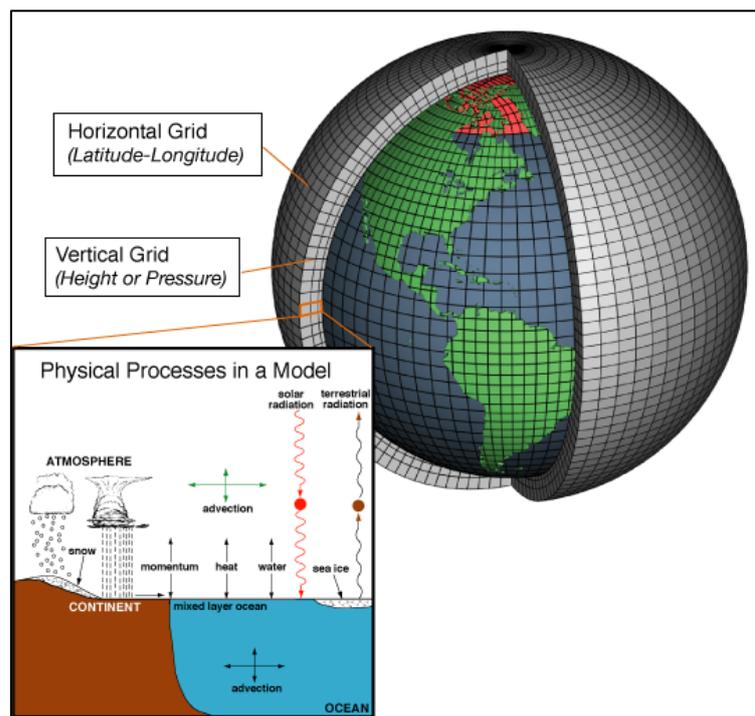


Figure 23: Schematic for global atmospheric model

Climate zones are spatial regions with generally similar climate patterns. Various classification systems exist including the Köppen climate classification system (Figure 24).<sup>32</sup> It is based upon the principle that vegetation is the best expression of climate. The Köppen system incorporates data sets of mean annual temperature, mean annual precipitation, and seasonal precipitation.

<sup>32</sup> Peel et al (2007) at <http://hal.archives-ouvertes.fr/docs/00/30/50/98/PDF/hess-11-1633-2007.pdf>

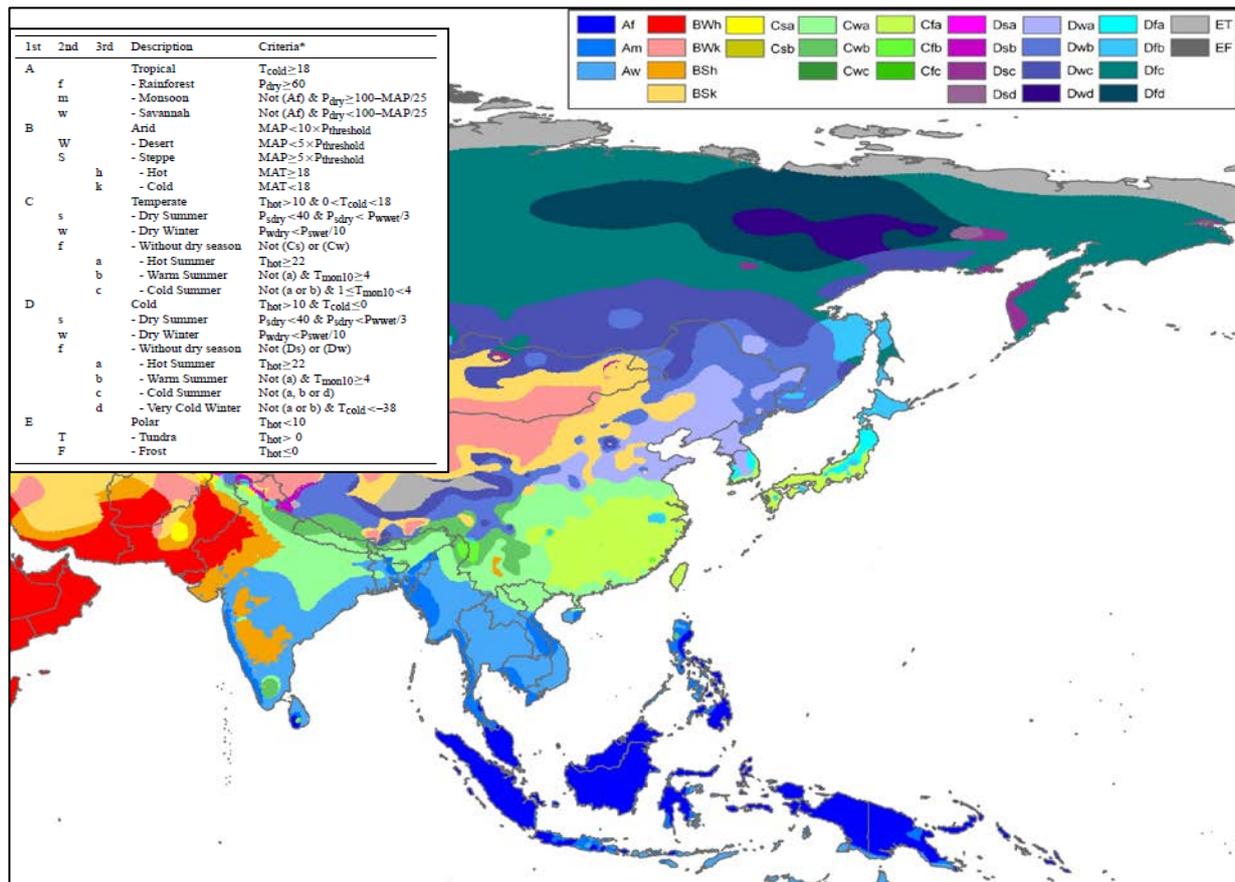


Figure 24: Köppen climate classification system

According to the climate zone definitions used in Figure 25, the LMB mostly consists of tropical wet and dry (Vietnam, Cambodia, Thailand) and humid subtropical (Laos). The tropical zone is defined as the region between the Tropics of Cancer and Capricorn ( $23.45^\circ$  north and south latitude) and described by a generally humid climate in which all twelve months have mean temperatures of at least  $18^\circ\text{C}$ . The sub-tropical zone is defined as the region between the tropics and  $35^\circ$  north or south latitude with generally at least eight months with a mean temperature of at least  $10^\circ\text{C}$ , and generally arid on the west side of continents and humid on the east side.

As previously mentioned, weather refers to the short-term (i.e., daily) change in factors and climate refers to the longer-term (i.e., typically 30-year) change in factors. Weather of course is variable from day to day, but the climate is also variable. Climate variability is the way climate fluctuates above or below the long-term average value. This variability can be seen, for example, in long-term precipitation records (Figure 26).<sup>33</sup> There are also various long-term cycles that have been identified in historic weather data.

<sup>33</sup> Uhlenbrook, <http://ocw.tudelft.nl/courses/watermanagement/>

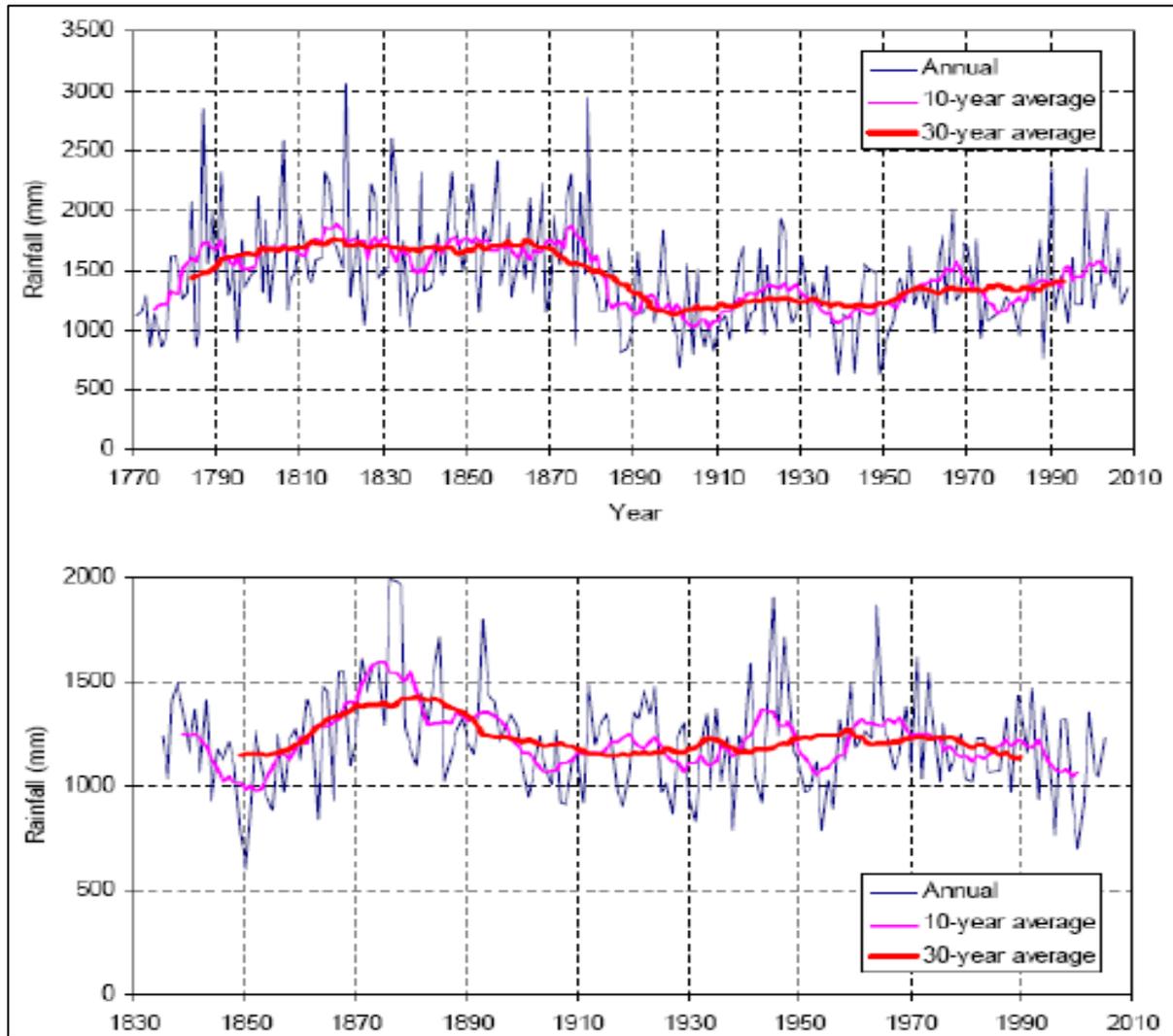


Figure 25: Annual precipitation at Seoul, Korea (upper) and Charleston, USA (lower)

## 2.2 Session 2.2 Basic Hydrology Concepts

Purpose and Learning Objectives	The session provides an introduction to the hydrological cycle, and reviews other basic concepts such as variability, basins and catchments, surface and groundwater, and rainfall-runoff relationships. The hydrology of the Mekong river system will be discussed.  Trainees will learn to understand and work with flow duration curves as a key tool.
Key Reading	Item 2.2.1 - MRC (2009) The Flow of the Mekong. Management Information Booklet Series No. 2.
Content	How can we describe the water cycle and water balances? How does the watershed influence the runoff? How do we build and interpret flow duration curves?
Key Aspects	The hydrological cycle is complex and different for each watershed.  The Mekong basin is characterized by high evapotranspiration and a pronounced flood season.  Runoff can be described and analyzed with the help of hydrographs and flow duration curves.
Discussion Topics and Exercises	Construct a flow duration curve from monthly Mekong flow data. Work either in groups or individually. Requires Excel. Use Item 2.2.2. (Excel file) with stepwise explanations if necessary.
Additional Resources	Online courses on hydrology at <a href="http://ocw.unesco-ihe.org/course/view.php?id=7">http://ocw.unesco-ihe.org/course/view.php?id=7</a> <a href="http://www.youtube.com/watch?v=wIL2wVpOMC0">http://www.youtube.com/watch?v=wIL2wVpOMC0</a>

The water cycle, or hydrological cycle, describes the continuous movement of water on, above, and below the earth's surface (Figure 27).<sup>34</sup> The mass of water in these regions stays fairly constant over time. The largest stocks of water are in the oceans, glaciers and snow, groundwater, permafrost, lakes, soil moisture, wetlands, atmosphere, rivers, and organisms – in this order.

Human activities have both direct and indirect impacts on the water cycle and subsequent water resource management. Direct impacts result from altered flows for irrigation, industry, and domestic uses. Reservoirs store a volume of 6,000 km<sup>3</sup>. Indirectly, land use changes result in changes in soil moisture, evapotranspiration, and rainfall (over large areas). The water cycle will also be impacted by anthropogenic climate change. Warmer air holds more moisture, and thus accelerates the cycle.

<sup>34</sup> Oki and Kanae (2006) Global Hydrological Cycles and World Water Resources. Science.

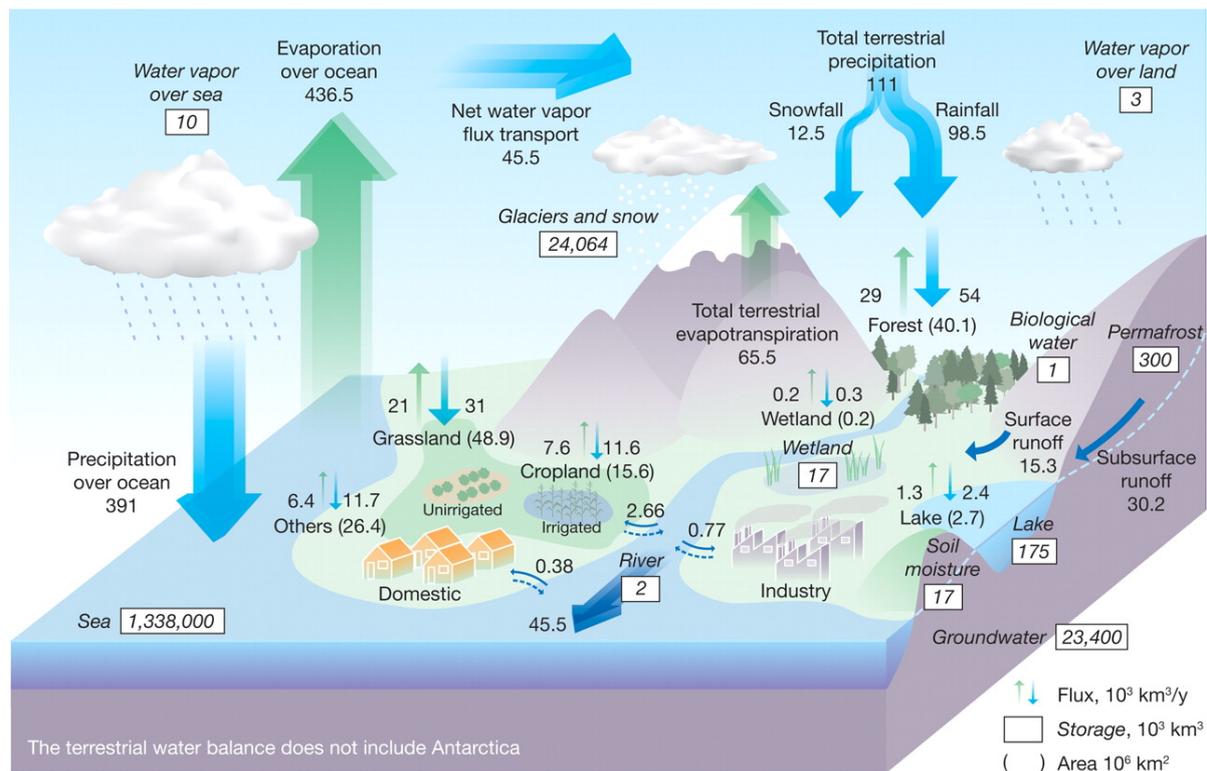


Figure 26: Fluxes and stocks of water

A water balance equation is used to describe the flow of water into and out of a system. The water balance of a river basin is<sup>35</sup>

$$P = R + E + dS/dt$$

$P$	:	precipitation [mm a <sup>-1</sup> ]
$R$	:	runoff [mm a <sup>-1</sup> ]
$E$	:	evaporation [mm a <sup>-1</sup> ]
$dS/dt$	:	storage changes per time step [mm a <sup>-1</sup> ]

The terms of transpiration and of infiltration may also be included in this equation. Applying sample data from Table 11 to the equation, the water balance of the Mekong River Basin is:

$$970 = 625 + 345 +/- 0 \text{ (mm/a)}$$

<sup>35</sup> Much of this session is based on Uhlenbrook, <http://ocw.tudelft.nl/courses/watermanagement/>

River	Catchment size	Rainfall		Evapo-transpiration		Runoff		Runoff Coefficient
	10 <sup>3</sup> km <sup>2</sup>	mm/a	10 <sup>9</sup> m <sup>3</sup>	mm/a	10 <sup>9</sup> m <sup>3</sup>	mm/a	10 <sup>9</sup> m <sup>3</sup>	%
Nile	2803	220	620	190	534	30	86	14
Mississippi	3924	800	3100	654	2540	142	558	18
Parana	975	1000	980	625	610	382	372	38
Orinoco	850	1330	1150	420	355	935	795	70
Mekong	646	1500	970	1000	645	382	325	34

Table 11: Hydrologic data of sample river basins

*The principles of water balances can be applied to a sample problem:*<sup>36</sup>

In a given year, a catchment with an area of 2,500 km<sup>2</sup> received 1.3 m of precipitation. The average rate of flow measured in a river draining the catchment was 30 m<sup>3</sup>/s.

- How much total river runoff occurred in the year (in m<sup>3</sup>)?
- What is the runoff coefficient?
- How much water is lost due to the combined effects of evaporation, transpiration, and infiltration (expressed in m)?

Solutions:

- Total runoff volume = number of seconds in a year \* average flow rate

$$31,536,000 * 30 \text{ m}^3/\text{s} = \underline{946,080,000 \text{ m}^3}$$

- Runoff coefficient = Runoff volume/ precipitation volume

$$\begin{aligned} &= 946,080,000 \text{ m}^3 / (1.3 \text{ m} * 2,500 \text{ m}^2 * 1,000,000) \\ &= 946,080,000 \text{ m}^3 / 3,250,000,000 \text{ m}^3 \\ &= \underline{0.29} \text{ or } 29 \% \end{aligned}$$

- Total water lost due to evaporation, transpiration, and infiltration:

After a little rearrangement, the water balance equation becomes:

$$E + T + F = P - R - \Delta S$$

where: P = 3,250,000,000 m<sup>3</sup>, R = 946,080,000 m<sup>3</sup>, ΔS = 0 (no change in storage), T = transpiration, and F = infiltration

$$\begin{aligned} E + T + F &= 3,250,000,000 \text{ m}^3 - 946,080,000 \text{ m}^3 \\ &= 2,303,920,000 \text{ m}^3 \end{aligned}$$

Divided by number of m<sup>2</sup> in catchment:

$$2,500 \text{ km}^2 * 1,000,000 = 2,500,000,000 \text{ m}^2$$

$$2,303,920,000 \text{ m}^3 / 2,500,000,000 \text{ m}^2 = \underline{0.92 \text{ m}}$$

A graphical representation of the water balance in the Mekong basin is given in Figure 28.<sup>37</sup>

<sup>36</sup> Based on <http://www.aboutcivil.org/hydrology.html>

<sup>37</sup> MRC (2009)

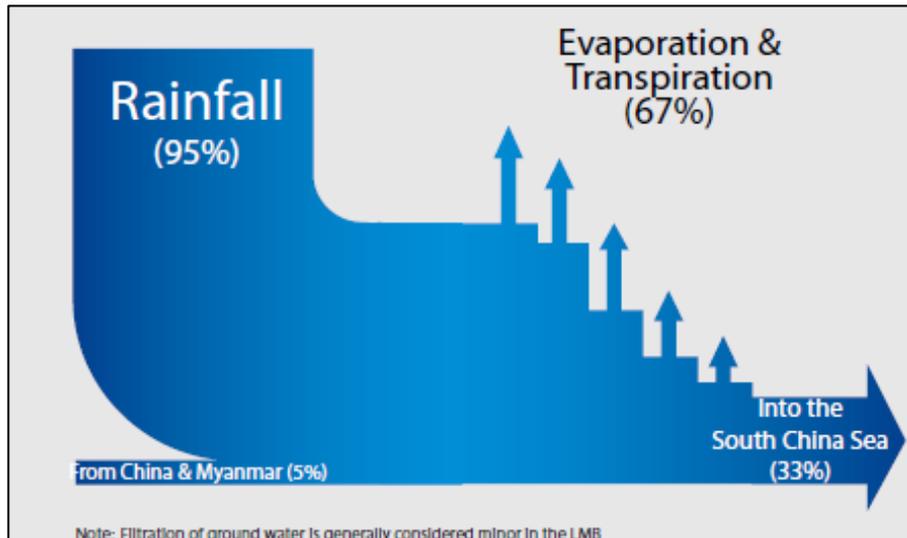


Figure 27: Water balance in the LMB

Land cover does not perceptibly influence precipitation, except in special cases such as:

- where a large enough open water area such as a reservoir is located in an arid region, it may change the micro-climate and increase humidity and precipitation,
- a cloud forest may capture precipitation from the clouds,
- a large contiguous forest, like the Amazon, creates its own internal hydrological cycle, and reducing evapotranspiration through deforestation may reduce rainfall.

However, land use always has both direct and indirect influences on hydrology through runoff, evaporation, and transpiration. Typical water balances for two different land uses in the same climate zone are given in Table 12.

P = Precipitation

$E_{total} = E_S + E_I + E_T$

R = Runoff

$E_S$  = Soil evaporation

$E_I$  = Interception evaporation

$E_T$  = Transpiration

	P	$E_{total}$	R	Expressed in % of $E_{total}$		
				$E_S$	$E_I$	$E_T$
<b>Forests</b>	100	52	48	29	26	45
<b>Open land</b>	100	42	58	62	15	23

Table 12: Typical water balance for forested and open land

In the previous water balance sample problem, the total or average runoff over a period of time was used in calculations. Time-dependent runoff is generated by precipitation events (i.e., rainfall, snowfall); its occurrence and quantity are dependent on the characteristics of

the event (i.e., intensity, duration and distribution). Runoff is also influenced by characteristics of a watershed such as its size, shape, topography, soils, and routing, and by human interferences such as stormwater drainage, abstraction, and inter-basin transfers. Discharge peaks in downstream rivers follow high volume precipitation events, or a series of smaller volume events. As an example, Figure 29 shows a discharge peak after a high volume precipitation event (black bars on top represent precipitation in mm and the blue lines along the bottom represent discharge in cumecs). The figure also shows that discharge is continuous, even during periods without precipitation due to the base flows in the system.<sup>38</sup>

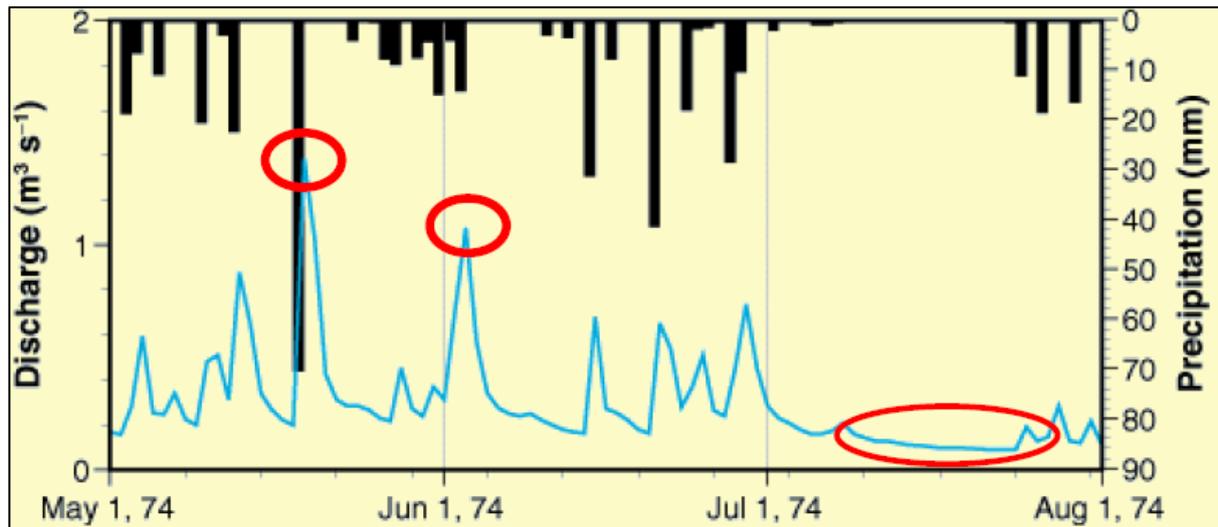


Figure 28: Relationship of precipitation and discharge

In a large basin, discharge is generally 'flatter' than in a small basin because floods and low flows in different tributaries may arrive at different times and cancel each other out. Only if there is similar weather over a large region, will there be a large difference between low and high flows. This is the case, for example, in regions with monsoon-driven weather patterns, such as the Mekong (Figure 30; MRC 2009). There, the onset of the flood season is when mean daily discharge exceeds the long-term mean annual discharge (3,600 cumecs at Luang Prabang). The end of the season is when the mean daily discharge is less than the long-term mean.

<sup>38</sup> Uhlenbrook, <http://ocw.tudelft.nl/courses/watermanagement/>

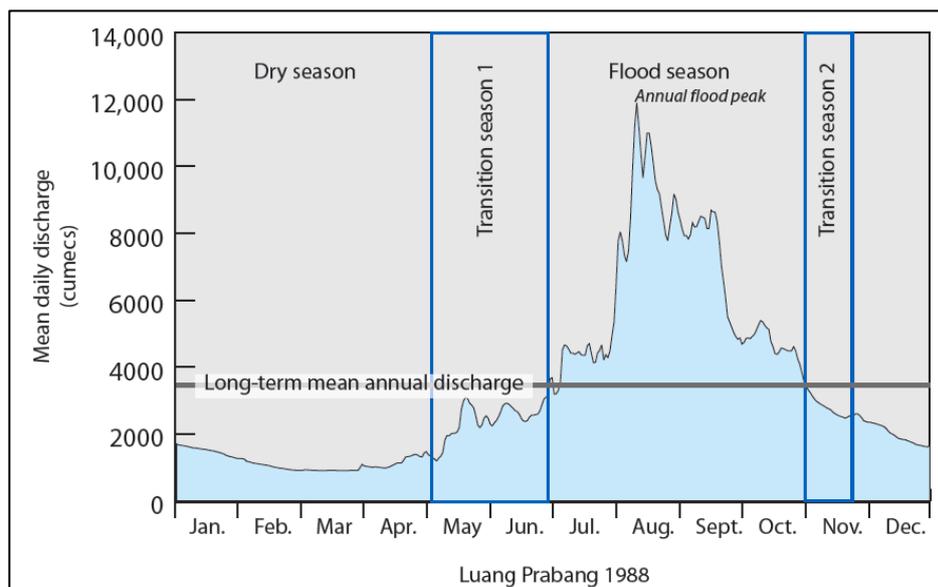


Figure 29: Typical hydrograph of the Mekong River

A reservoir is a natural (e.g., groundwater, forest soils, lakes, wetlands, glaciers, snow) or artificial area for the storage, regulation, and control of water. Reservoirs influence hydrology; for example, natural reservoirs absorb and slowly release water and artificial reservoirs can capture and slowly release floods. On the river represented in Figure 31, a reservoir was built in 1940 and there have been no major floods since its construction.<sup>39</sup>

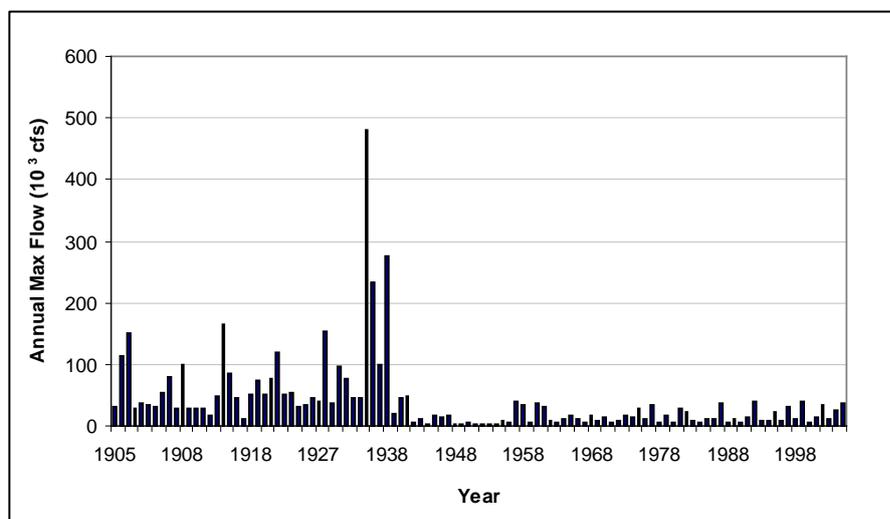


Figure 30: Annual maximum discharge for 106 years on Colorado River near Austin

A “return period” is the average recurrence interval between two events, for example between two floods. In the example above, this river’s maximum flow reached values greater than 200,000 cfs three times over 106 years. Various probabilities of events can be calculated from this information.

Note, however, that even if all the data in Figure 31 (the ‘period of record’) will be considered for these examples, there are actually two distinct hydrologies in these data. For predictions of future events, only the period after 1940 should be considered.

<sup>39</sup> University of Texas, Austin. <http://www.cae.utexas.edu/prof/maidment/GradHydro2008/gradhydro2008.htm>

## Example 1:

Annual maximum flow =  $x_T = 200,000$  cfs

Number of occurrences in 106-year record = 3

Therefore, 2 recurrence intervals in 106 years

Return period =  $T = 106/2 = 53$  years

## Example 2:

Annual maximum flow =  $x_T = 100,000$  cfs

Number of occurrences in 106-year record = 8

Therefore, 7 recurrence intervals in 106 years

Return period =  $T = 106/7 = 15.2$  years

## Example 3:

Probability of the annual maximum flow to be equal to or exceed 100,000 cfs at least once in the next five years

$P(X \geq 100,000 \text{ cfs at least once in the next } n \text{ years})$

$$= 1 - (1-1/T)^n$$

$$= 1 - (1-1/15.2)^5 = 0.29$$

While figures such as this are useful, care must be taken to not over interpret hydrologic data. For example, more floods could be hidden within the years of high flows.

Hydrologists use models to understand complex environmental systems. In the LMB, hydrologists divided the basin area into zones based on hydrology, physiography, land use and existing, planned and potential resource developments. Along the Mekong River, the contributions to the mainstream flow from the catchments on the left and right banks differ depending on their size, precipitation, evaporation (as a function of land cover and climate), and infiltration (due to soil texture, structure, and moisture content; Figure 32; MRC 2009).

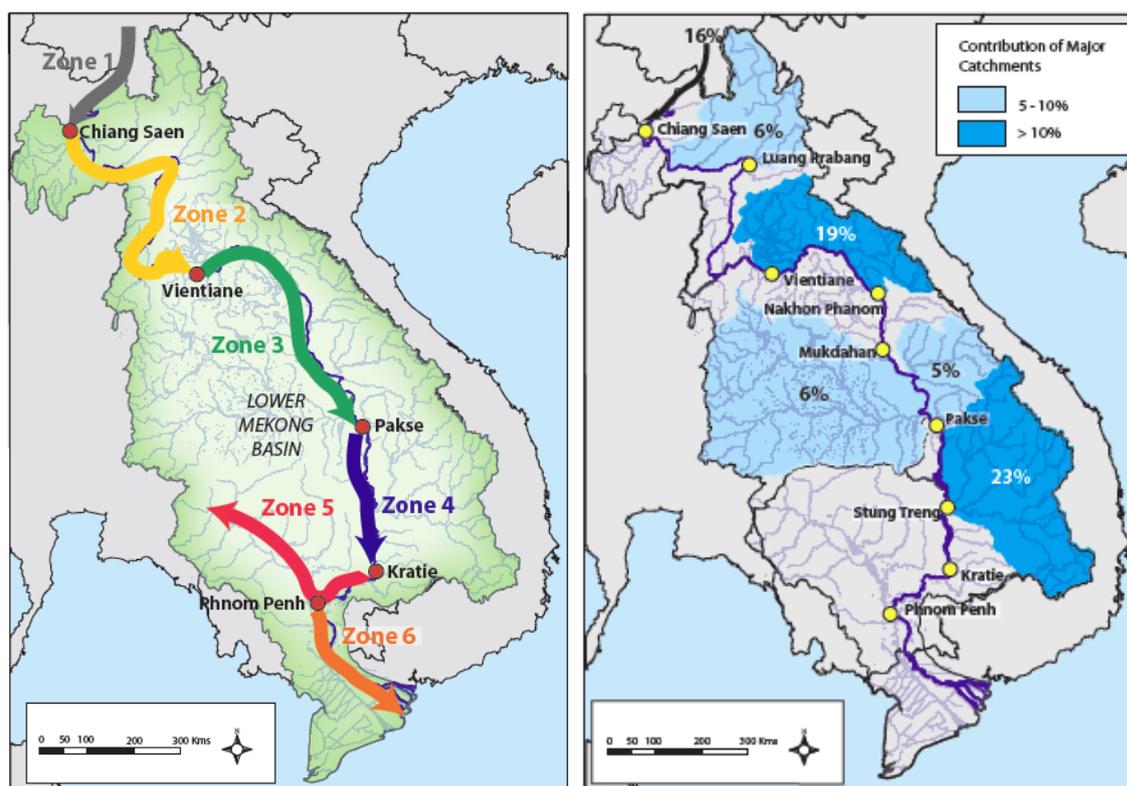


Figure 31: Major hydrologic zones and catchments of LMB

Extreme flood events occurred on the Mekong River in the Cambodian floodplain and the Viet Nam Mekong delta in 2000 and 2011 (Figure 33).<sup>40</sup> A scatterplot of the joint distribution of the annual flood peak (cumecs) and of the annual flood volume (km<sup>3</sup>) at Kratie on the Mekong mainstream shows the quantity and flow of water in these two events. The shaded 'boxes' indicate one (1 $\sigma$ ) and two (2 $\sigma$ ) standard deviations for each variable above and below their respective means (red lines). Events outside of the 1 $\sigma$  box might be defined as significant flood years, with an annual recurrence interval greater than 10 years, and those outside of the 2 $\sigma$  box as historically extreme flood years, with an annual recurrence interval greater than 20 years.

<sup>40</sup> MRC (2011) Annual Mekong Flood Report 2010, Mekong River Commission, 76 pages

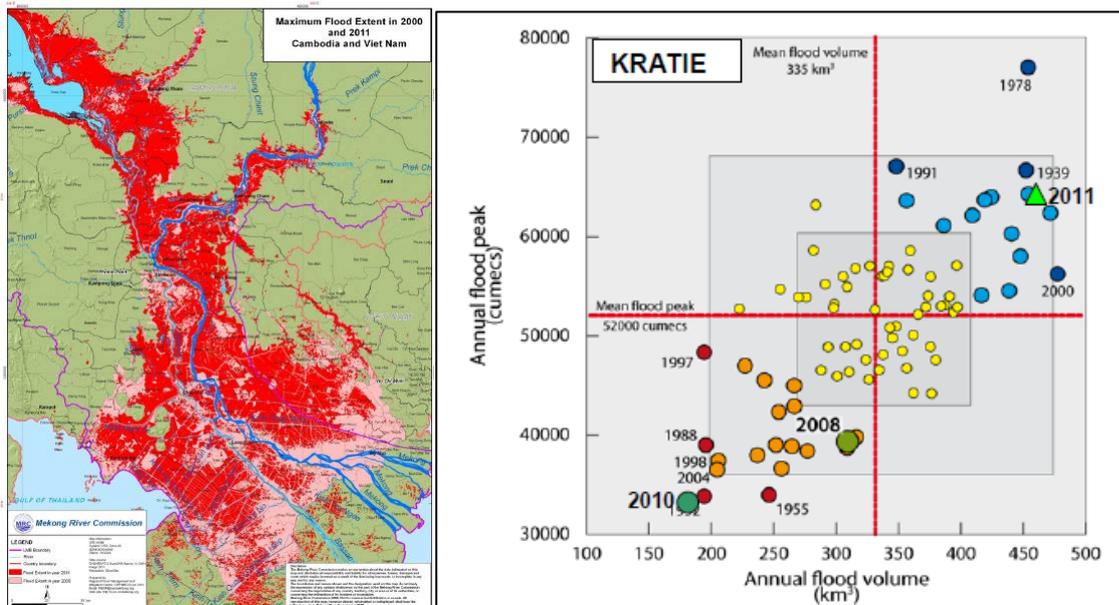


Figure 32: Mekong flood events of 2000 and 2011

A key task of hydrology is to predict the probability of flows. One of the tools that hydrologists use is a flow duration curve (FDC), a graphical representation of the cumulative exceedance probabilities of flows. The flow is represented on the y-axis, usually as a daily mean or total, but other periods are used as well. The percentage of time a given flow is equaled or exceeded, the cumulative exceedance probability, is represented on the x-axis. For example, in Figure 34, about 10% of the time the flow is higher than 10 m<sup>3</sup>/s.<sup>41</sup> The axes are on logarithmic scales.

This figure shows data from a catchment in South Africa. Low or base flows were higher in the virgin (natural) state than in the present (developed) state. This suggests that in the natural state water was released slowly from natural reservoirs, such as primary forest soils or wetlands. These reservoirs were later damaged by development and thus lost their ability to retain water.

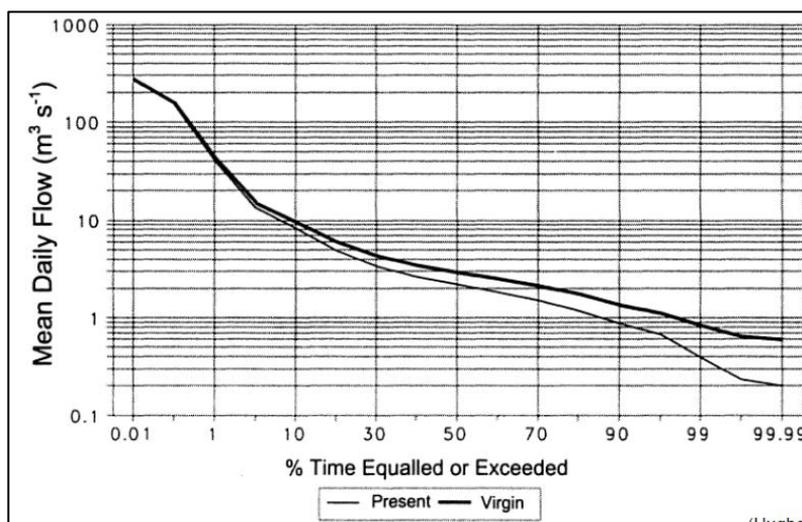


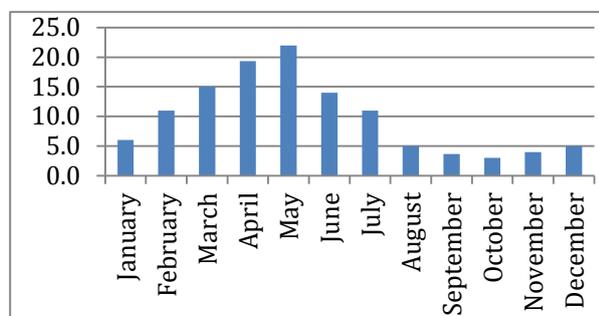
Figure 33: Flow duration curve of present (developed) and virgin (natural) states

<sup>41</sup> Uhlenbrook. Engineering Hydrology, <http://ocw.tudelftnl/courses/watermanagement/>

Flow duration curves are essential tools in hydrology and are very helpful in illustrating and analyzing changes in flow. Thus they will be constructed here step-by-step, and used in this Training Manual in different sessions. The following steps are required:<sup>42</sup>

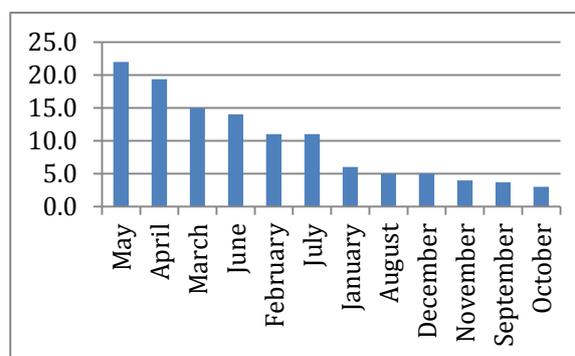
1. Collect flow data over a period of time (monthly in this example).

	Average Flow (m <sup>3</sup> /s)			
	3-year monthly averages	2013	2012	2011
January	6,0	5	6	7
February	11,0	10	11	12
March	15,0	15	14	16
April	19,3	20	20	18
May	22,0	22	26	18
June	14,0	15	13	14
July	11,0	10	11	12
August	5,0	5	6	4
September	3,7	2	3	6
October	3,0	2	3	4
November	4,0	5	4	3
December	5,0	5	5	5



2. Rank the months highest to lowest flow:

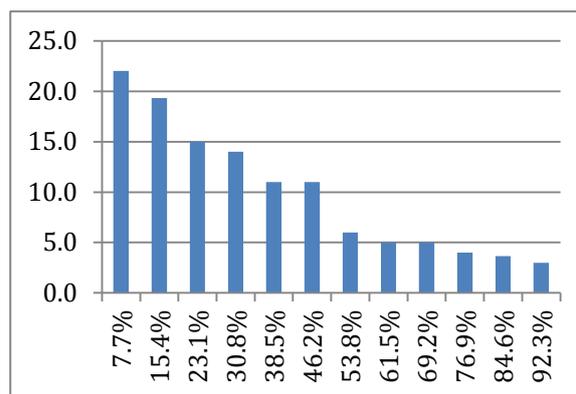
	3-year monthly averages	Rank
May	22,0	1
April	19,3	2
March	15,0	3
June	14,0	4
February	11,0	5
July	11,0	6
January	6,0	7
August	5,0	8
December	5,0	9
November	4,0	10
September	3,7	11
October	3,0	12



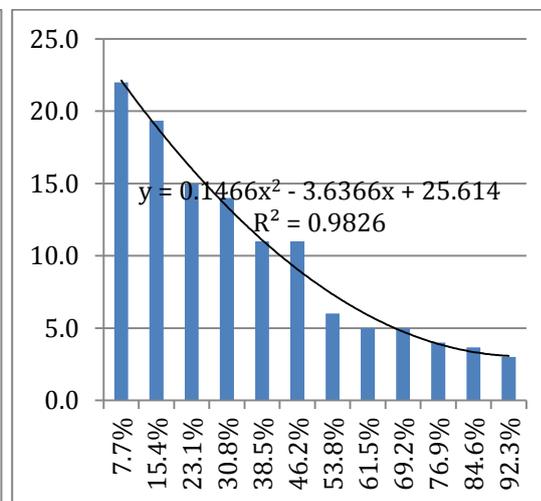
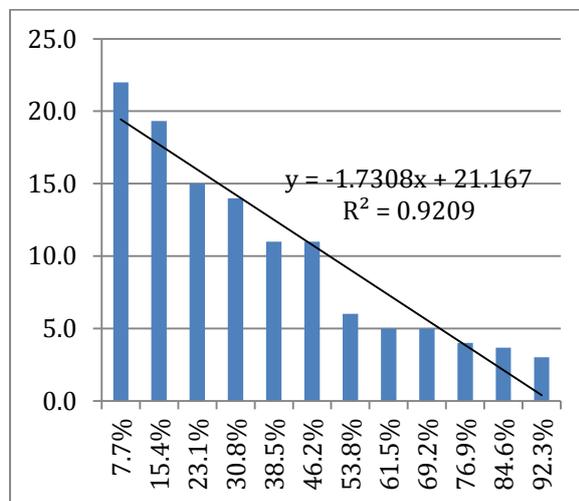
<sup>42</sup> This is also shown in the accompanying excel file (item 2.2.2)

3. Calculate and display exceedance probabilities ( $p = m/(n+1)$ ) for ranked flows, with  $m =$  rank and  $n =$  number of observations:

	Exceedance Probability	3-year monthly averages
May	7,7%	22,0
April	15,4%	19,3
March	23,1%	15,0
June	30,8%	14,0
February	38,5%	11,0
July	46,2%	11,0
January	53,8%	6,0
August	61,5%	5,0
December	69,2%	5,0
November	76,9%	4,0
September	84,6%	3,7
October	92,3%	3,0



4. Predict future flows by analyzing trends. More samples and finer resolution (weekly, daily, or even hourly data) allow smoother fits as the discrete data approaches continuous data. In the left figure, a linear trend line is fit to the data and in the right figure a polynomial trend line is applied.



Care must be taken when fitting models. Normal distribution of data is often assumed as the easiest and most familiar model, but hydrological data are not generally normally distributed. In addition, extreme values – floods and low flows – are the parts of a FDC that are often the most interesting. However, they are less frequent in samples and most difficult to fit to a statistical model.

Like in climate data, variability exists in the hydrological data. There are many sources of uncertainty associated with defining and managing hydrologic variability. The degree of variability is different all over the world. Information is often lacking on how to properly define and predict it. The known natural factors (e.g., runoff) with known variability will most likely change in the future, due to climate change.

## 2.3 Session 2.3 Basic Hydropower Engineering Concepts

Purpose and Learning Objectives	<p>The session provides an overview of the project cycle and the water-related aspects of hydropower: available flows, head, storage, installed capacity, load factor, generation, residual flows, spilling. It will explain how hydrological data are used for design and operational decisions in hydropower engineering. Examples from projects on the Mekong will be discussed.</p> <p>Trainees will learn how flow duration curves and other hydrological information are related to hydropower.</p>
Key Reading	Item 2.3.1 – Principles of Hydropower Engineering. Module 5.1 of Water Resources Engineering Course. Indian Institute of Technology Kharagpur.
Content	<p>What are the stages in the hydropower project development cycle?</p> <p>What are the key technical options?</p> <p>How is water managed in a reservoir?</p> <p>How can a flow duration curve be used to plan hydropower design and operations?</p>
Key Aspects	<p>Hydrological information plays a key part in hydropower development.</p> <p>The main design and operational options depend on the flow duration curve.</p> <p>Optimal solutions may change if the flow duration curve changes.</p>
Discussion Topics and Exercises	Read and discuss article on flow alterations from hydropower in the Sekong/ Sesan/ Sre Pok basin (Item 2.3.2. - Piman et al. 2013). This is a good application of hydrological and engineering concepts from this and the previous sessions.
Additional Resources	<p>Item 2.3.3 – US Army Corps of Engineers (1992) Hydrologic Engineering for Hydropower. Regulation No. 1110-2-1463.</p> <p>Additional course material on Water Resources Engineering at <a href="http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT%20Kharagpur/Water%20Resource%20Engg/New_index1.html">http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT%20Kharagpur/Water%20Resource%20Engg/New_index1.html</a></p>

The hydropower project development cycle typically includes three stages: project planning, project implementation, and project operation (Figure 35).<sup>43</sup> Hydrological and climate information are most relevant during preparation studies and during project operations.

<sup>43</sup> Altinbilek, Dogan (2014) Course CE 571 Handout, Middle Eastern Technical University

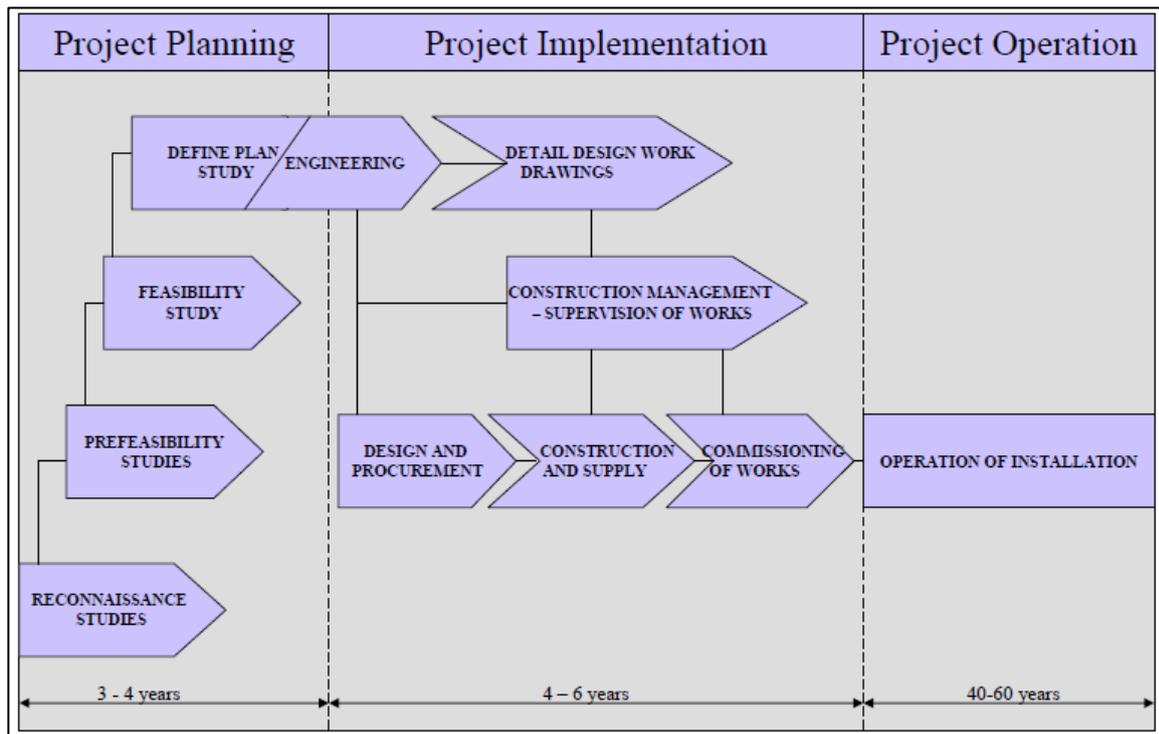


Figure 34: Hydropower project development cycle

In hydropower generation, the amount of power extracted from the water is proportional to the volume of water and the head, the difference in level between the source and the outflow. Two types of hydropower designs are being constructed – run-of-river and reservoir. Run-of-river projects have little or no storage capacity (generally less than one day) and the amount of electricity generated is proportional to the inflow from the river at any one time (Figure 36).<sup>44</sup>

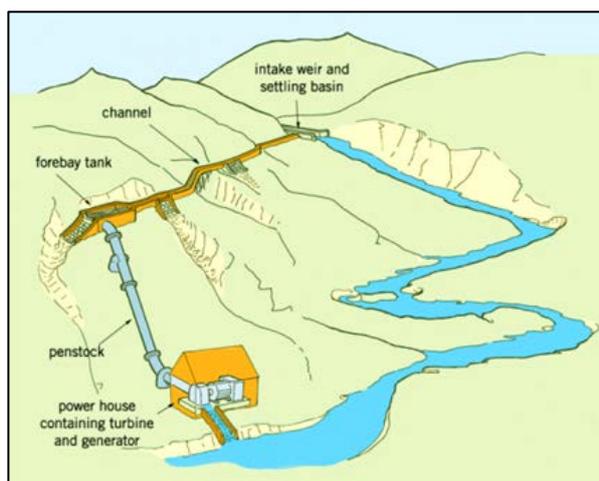
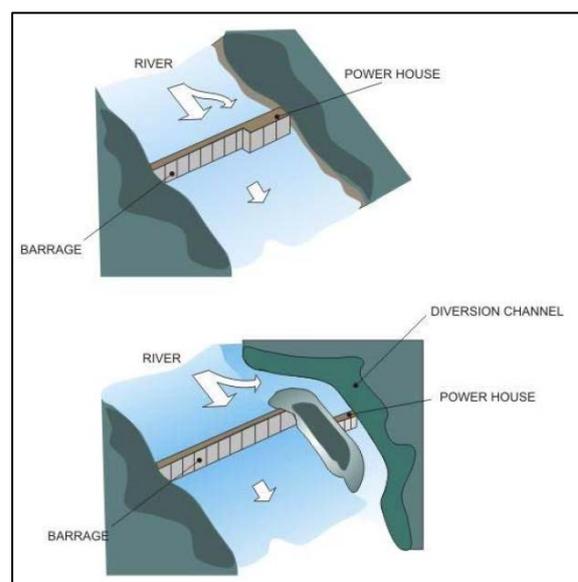


Figure 35: Run-of-river projects



<sup>44</sup> <http://www.worldwatch.org/system/files/central%20america%20hydropower-article2.png>; Item 2.3.1.

Reservoir projects use the potential energy of stored water to create electricity (Figure 37).<sup>45</sup>

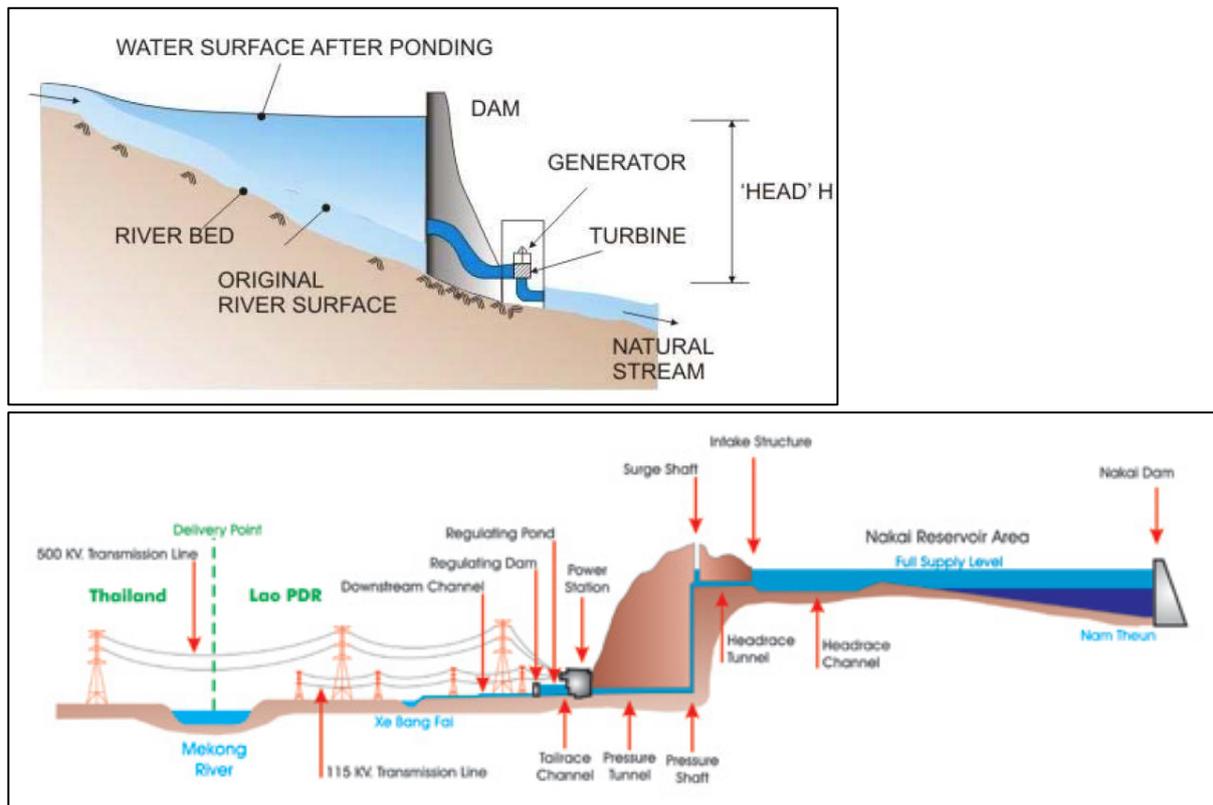


Figure 36: Reservoir projects

The water may be stored in reservoirs that generally have uncontrolled inflows but (largely) controlled outflows. The capacity of the reservoir is the maximum volume of water that can be stored, up to the maximum pool level. Reservoirs can be used to balance flows, taking in water during high flows and releasing it again during low flows. Many reservoirs substantially change flow patterns; for example on the Green River in the U.S. (Figure 38).

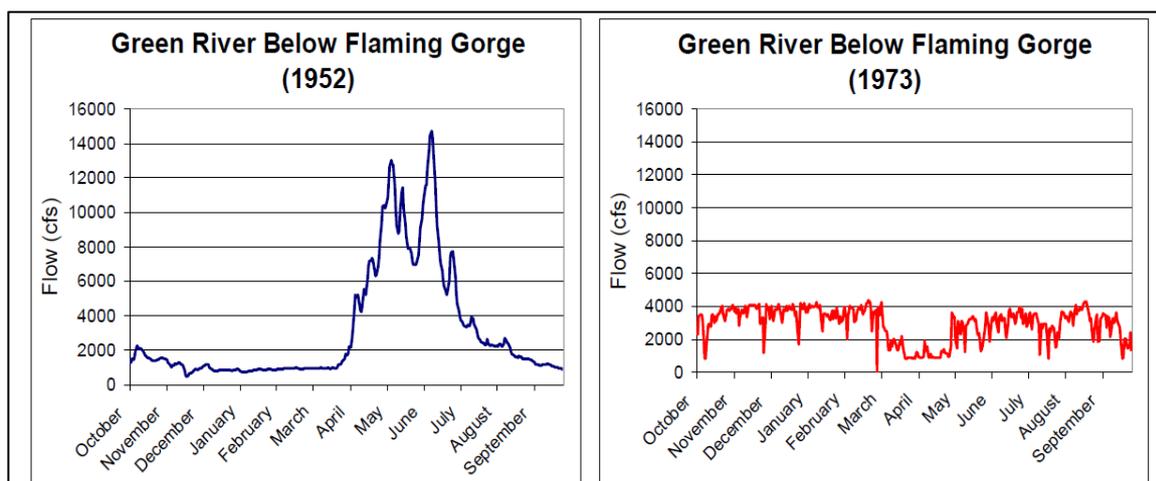


Figure 37: Green River flows prior to and after the construction of Flaming Gorge dam (1964)

<sup>45</sup> Item 2.3.1.; [http://siteresources.worldbank.org/INTLAOPRD/Resources/293582-1092106399982/492430-1092106479653/492431-1214977916515/project\\_schematics\\_web.jpg](http://siteresources.worldbank.org/INTLAOPRD/Resources/293582-1092106399982/492430-1092106479653/492431-1214977916515/project_schematics_web.jpg)

Excess water can be spilled via a spillway and/or released through other outlets (not through uncontrolled overtopping of a dam, which is generally unsafe). Dead or inactive storage refers to water in a reservoir below the level of the lowest outlet that cannot be drained by gravity and would have to be pumped out. Active or live storage is the portion of the reservoir that can be utilized. This is illustrated in Figure 39, which shows the probability of different operational curves for a reservoir in India over several years.

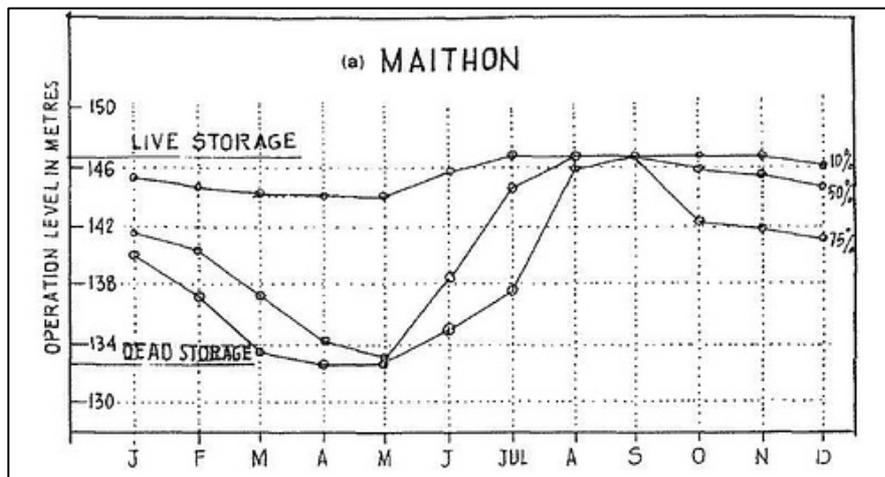


Figure 38: Regulation of a multipurpose reservoir: Damodar Valley, India

Reservoir projects require operational decision making to account for the uncontrolled inflows. For example, when a storm approaches, dam operators estimate the volume of water that the storm may add to the reservoir. If forecasted storm water would overflow the reservoir, water is slowly let out of the reservoir prior to, and during, the storm. If this is done with sufficient lead-time, the storm will not fill the reservoir and areas downstream will not experience flooding. Accurate weather forecasts are essential so that dam operators can correctly plan drawdowns prior to a high rainfall event.

The following highly simplified example will show how hydrological information is used to plan a project. In this example it is assumed that

- A sufficient flow record exists so that the data represents historic flows well;
- Future flows will follow the same distribution as historic flows (i.e., hydrology is 'stationary').

(The following Session 2.4 (Changes in Climate and Hydrology) will address why 'stationary' hydrology is not actually a good assumption, and in Module 3 (Hydropower Siting, Design and Operations in a Changing Climate) the planning approach will be modified accordingly.)

The basic principles of infrastructure planning can be shown on the basis of a stylized FDC (Figure 40). This FDC is the result of a simple optimization exercise. In this example, the relevant values are:

- Run-of-river plant with no storage
- Head of 10m
- Generation efficiency of 90%
- Runoff will exceed 80 m<sup>3</sup>/s 20% of the time, 60 m<sup>3</sup>/s 40% of the time, etc.
- Intake capacity of 40 m<sup>3</sup>/s
- Plant runs at full capacity 60% of the time
- Plant runs at average 50% capacity 40% of the time

- Load factor  $(60 \cdot 100 + 40 \cdot 50) / 100 = 80\%$
- Sales price of \$ 0.05 / KWh
- Fixed costs of \$ 300,000 and variable costs of \$ 166,667 / MW

Water infrastructure will be designed to “harness” the hydrology at a given site. A hydropower planner would design to optimize the capacity to be installed. Higher installed capacity means higher production and revenues, but it also means higher investment costs and lower load factors. As plant size is increased, economies of scale will tend to reduce the specific costs per  $\text{m}^3/\text{s}$  utilized or MW installed. The area under the red line in Figure 40 shows the total flow that can be utilized by the plant at a selected intake capacity of  $40 \text{ m}^3/\text{s}$ .

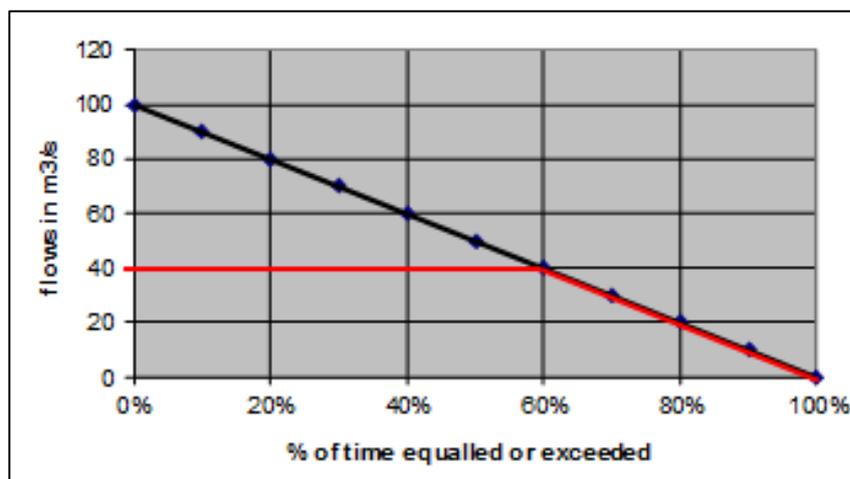


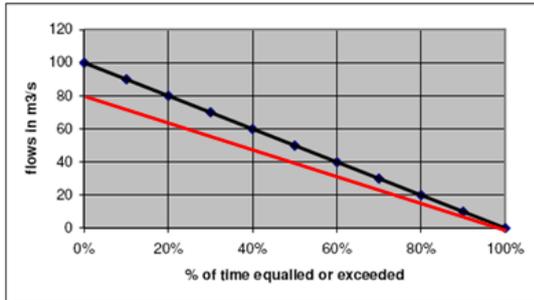
Figure 39: Example flow duration curve for optimizing plant capacity

In this base case, an installed intake capacity of  $60 \text{ m}^3/\text{s}$  and powerhouse capacity of 5.4 MW would be preferable to higher or lower capacities. While the annual cash-flow surplus is a rather crude indicator of financial efficiency (the Internal Rate of Return (IRR) or Net Present Value (NPV) would be better benchmarks), the example suffices to show that maximum capacity is not always optimal (Table 13).

Intake Capacity ( $\text{m}^3/\text{s}$ )	Installed Power Generation Capacity (MW)	Load Factor (%)	Annual Generation (MWh)	Annual Revenues (\$)	Annualized Investment and O&M costs (\$)	Annual Surplus (\$)
80	7.2	60	37,843	1,892,160	1,500,000	392,160
70	6.3	65	35,872	1,793,610	1,350,000	443,610
60	5.4	70	33,113	1,655,640	1,200,000	455,640
50	4.5	75	29,565	1,478,250	1,050,000	428,250
40	3.6	80	25,229	1,261,440	900,000	361,440
20	1.8	90	14,191	709,560	600,000	109,560

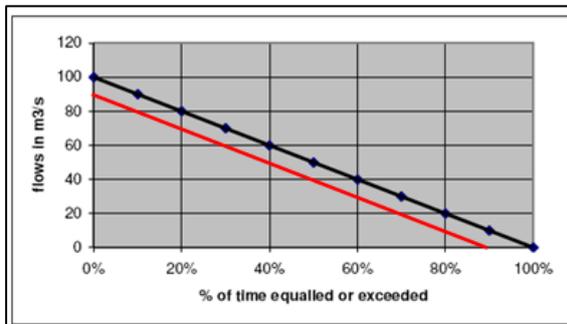
Table 13: Data for optimizing plant capacity

What role do environmental flows play in this scenario? Imagine a situation where a hydropower plant operates by diverting water from a river, but some environmental flows are guaranteed and may not be utilized. The FDC that is relevant for the hydropower planner will then not be the natural one but a modified one. Examples of modifications follow:



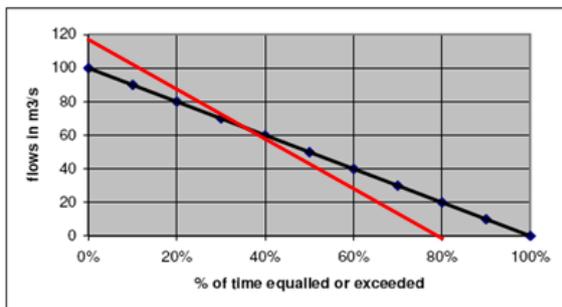
If 20% of given flows at any time may not be diverted, the relevant FDC will have a lower slope (Figure 41).

Figure 40: Baseline FDC (black) and modified FDC (red) for diversions



If a minimum environmental flow of 10 m<sup>3</sup>/s is required at all times (as long as naturally available), the slope of the relevant FDC will not change but the utilizable flow will be reduced by 10 m<sup>3</sup>/s (downward parallel shift of FDC; Figure 42).

Figure 41: Baseline FDC (black) and modified FDC (red) for minimum environmental flows



Upstream glaciers, snow packs, groundwater aquifers, wetlands, forests and other natural features that store and gradually release water will have significant effects on the slope of the FDC. The more these natural features are damaged by anthropogenic changes, the steeper the FDC becomes (Figure 43).

Figure 42: Baseline FDC (black) and modified (red) FDC for storage changes

Inter-basin transfers will reduce or increase (in this case increase) the available volume of water, thus causing an upward shift of the FDC (Figure 44).

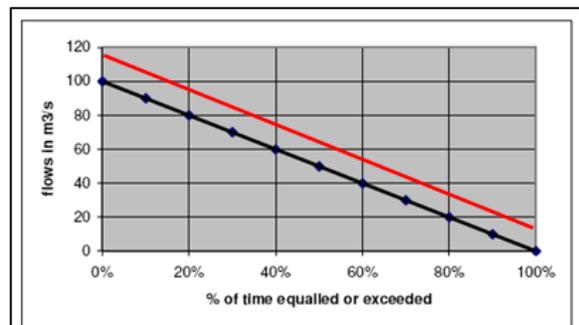
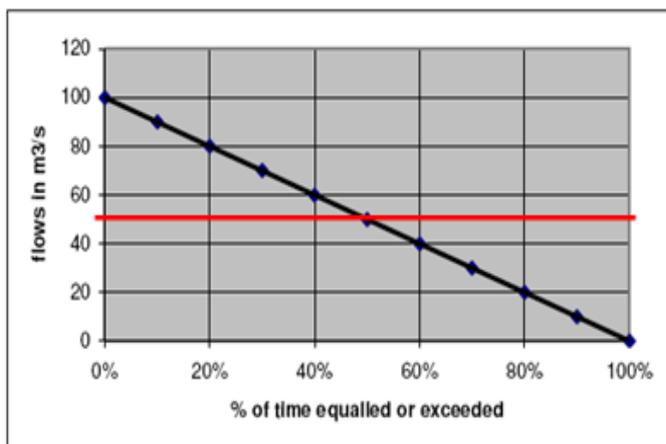


Figure 43: Baseline FDC (black) and modified (red) FDC for water quantity changes

Up to this point, we have assumed that the plant has no storage capacity. Artificial storage that can be directly controlled by the operator will change the planning context profoundly.

Depending on the storage space available and the operating rules, reservoir inflow and outflow FDCs will differ. Storage space can range from a few hours of runoff (which may



enable the operator to smooth out very short-term fluctuations and to shift some generation capacity to daily peaking hours) to huge reservoirs with inter-annual storage (such as Lake Volta in Ghana which can store almost 4 years of runoff). In an extreme case like Lake Volta, the outflow FDC could be completely manipulated by the operator to provide continuous base load at a 100% load factor, or to provide seasonal and daily peaking power.

Figure 44: Converting naturally variable into continuous flows

In this example, base-load operations with annual storage will provide a fully controlled, continuous outflow of 50 m<sup>3</sup>/s (Figure 45). Note that this example assumes no evaporation and seepage losses from the reservoir, so that the total outflow from the reservoir is identical to the total inflow.

Assuming additional annualized costs of \$400,000 for constructing and operating a reservoir with full annual storage, the above calculation is modified to that in Table 14. This surplus is higher than before; thus it is a good investment to add storage capacity to the project. Note that generation and revenues are higher even though the installed capacity is lower than previously, when the optimum intake capacity was at 60 m<sup>3</sup>/s.

Intake Capacity (m <sup>3</sup> /s)	Installed Power Generation Capacity (MW)	Load Factor (%)	Annual Generation (MWh)	Annual Revenues (\$)	Annualized Investment and O&M costs (\$)	Annual Surplus (\$)
50	4.5	100	39,420	1,971,000	1,450,000	521,000

Table 14: Optimal plant capacity with reservoir

In general, any high flows beyond the design flow that cannot be stored and need to bypass the plant (spilling) can be considered as 'wasted' from the point of view of the operator. Therefore, any way to flatten the FDC, through natural or artificial storage, is welcome as it increases the low flows that can be turned into additional energy. Figure 46<sup>46</sup> illustrates that storage can also be at a different project, higher up in the basin.

<sup>46</sup> Hydro Tasmania Consulting (2007) India River Basin Development Optimisation Study. Modelling Report.

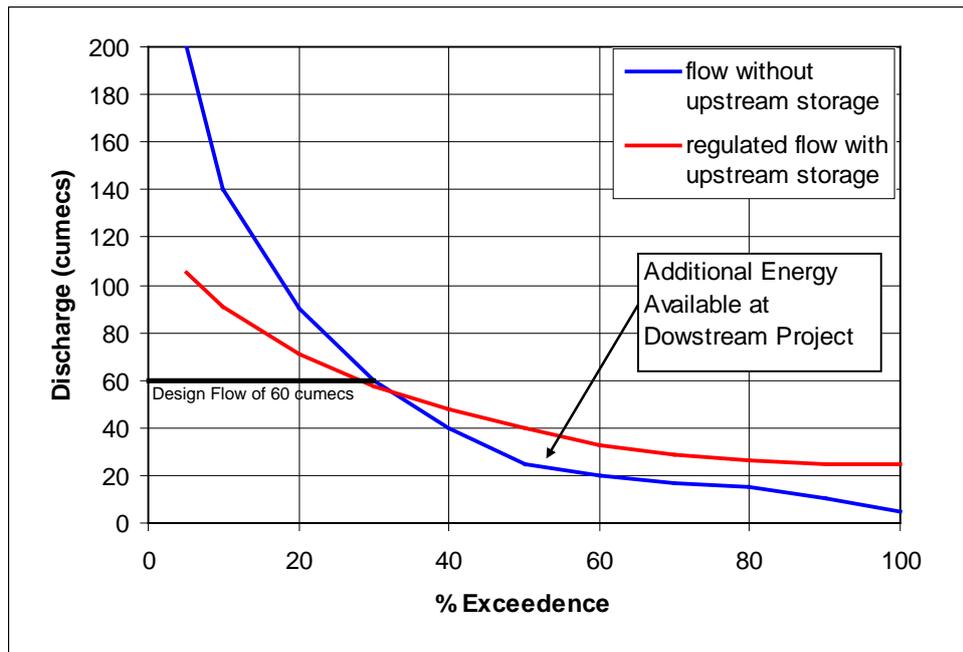


Figure 45: Influence of storage on flow duration curves

A reservoir can also allow provide more valuable peaking power. Consider a situation where the plant only runs half the time and can obtain a price of \$ 0.07 / KWh instead of \$ 0.05 / KWh (Figure 47).

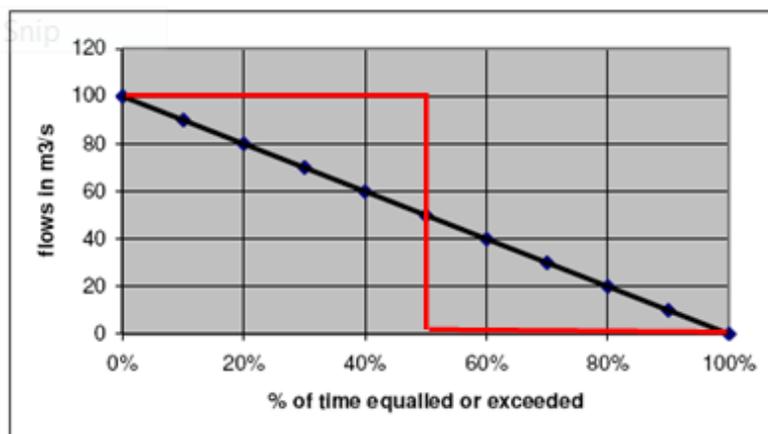


Figure 46: Using a reservoir to provide peaking power

Again, the surplus is improved even though much higher investments are required (Table 15).

Intake Capacity (m <sup>3</sup> /s)	Installed Power Generation Capacity (MW)	Load Factor (%)	Annual Generation (MWh)	Annual Revenues (\$)	Annualized Investment and O&M costs (\$)	Annual Surplus (\$)
100	9.0	50	39,420	2,759,400	2,200,000	559,400

Table 15: Optimal plant capacity with reservoir and peaking operations

In practice, full outflow control is not likely to be optimal, as storage space is costly to provide. The planner then needs to balance the costs of extra storage capacity with the benefits of higher load factors and/or peaking power generation. The optimization problem gets even more complex when the possibility of pumped storage is introduced – using low-cost power at off-peak hours to pump water into a reservoir (which may be in-stream or off-stream) and releasing that water during peak hours.

Finally, since hydrology is directly related to generation, for run-of-river projects a flow duration curve can be converted into a power duration curve, which shows the probability with which power generation exceeds certain values. In the example below, the probability is expressed in number of days per year (Figure 48).<sup>47</sup> Also, the volume that bypasses the plant as ‘residual’, or environmental flow is clearly shown.

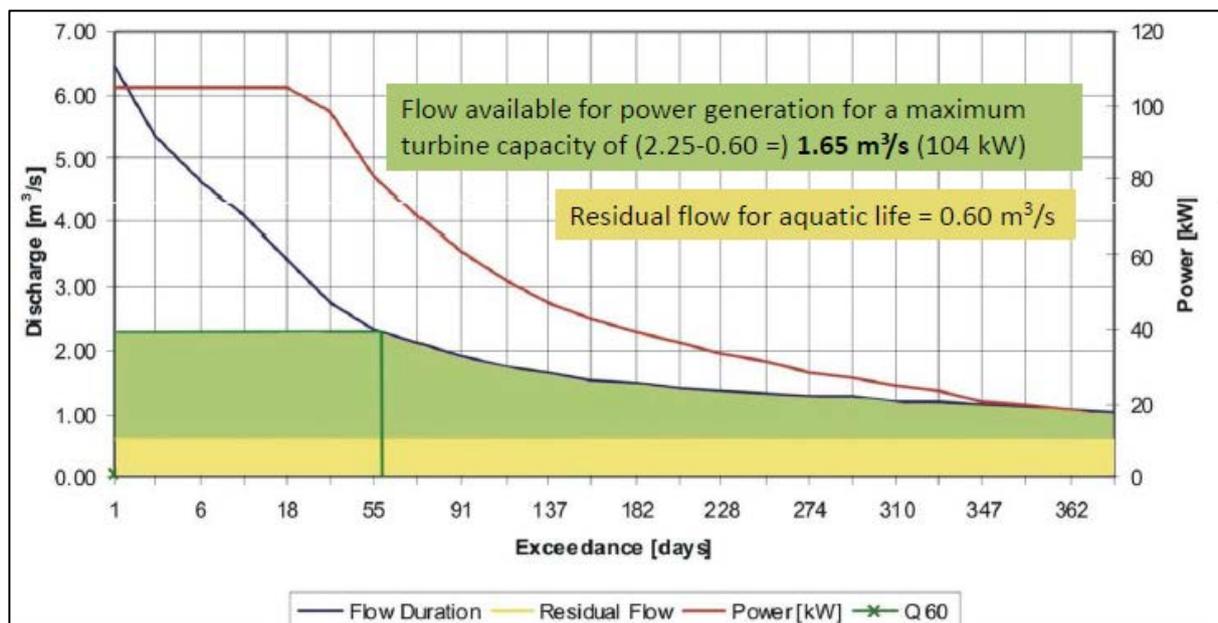


Figure 47: Power duration and flow duration curves with energy production

<sup>47</sup> Froend (2013) at [http://www.ecreee.org/sites/default/files/3.\\_assessment\\_of\\_hydropower\\_resources.pdf](http://www.ecreee.org/sites/default/files/3._assessment_of_hydropower_resources.pdf)

## 2.4 Session 2.4 Changes in Climate and Hydrology

Purpose and Learning Objectives	<p>The session provides an overview of global studies on observed and predicted climate and hydrological changes. It will also discuss downscaling and regional studies for the Mekong.</p> <p>Trainees will become familiar with different levels of confidence for different changes that are expected or are possible over time. Focus will be on the expected future trends and variability of climate and hydrology.</p>
Key Reading	<p>Item 2.4.1 - Stocker et al (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the 5th Assessment Report of the IPCC.</p> <p>Item 2.4.2 - MRC (2011) Impacts of climate change and development on Mekong flow regimes: First assessment – 2009. Management Information Booklet Series No. 4.</p>
Content	<p>What changes are being observed?          What drives these changes?          How much do we understand the climate system and its recent changes?          What future global and regional changes are projected?</p>
Key Aspects	<p>The recent 5<sup>th</sup> Assessment Report of the IPCC confirms, with more confidence, previous projections of climate change.</p> <p>Projections based on a range of Representative Concentration Pathways show a clear temperature response and a more complex precipitation response in the Mekong region.</p>
Discussion Topics and Exercises	<p>Group work:</p> <ul style="list-style-type: none"> <li>• Discuss how projected climate change may influence floods in the lower Mekong.</li> <li>• Discuss how the flow duration curve developed at the end of session 2.2. may change.</li> </ul>
Additional Resources	<p>Item 2.4.3 - MRC (2010) Impacts of climate change and development on Mekong flow regimes. First assessment – 2009. Technical Paper No. 29.</p>

The latest IPCC results show that warming of the climate system is unequivocal.<sup>48</sup> Temperatures of the atmosphere and ocean have increased, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased. Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850, as also shown in Figure 49.<sup>49</sup> In the Northern Hemisphere, the time period 1983–2012 was perhaps the warmest 30-year period of the last 1400 years (medium confidence). Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (high confidence). It is virtually certain that the upper ocean (0–700 m) warmed from 1971 to 2010, and it likely warmed between the 1870s and 1971.

<sup>48</sup> This session is largely based on Stocker et al (2013).

<sup>49</sup> Hansen, J.E., R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl, 2001: A closer look at United States and global surface temperature change. *J. Geophys. Res.*, **106**, 23947–23963, doi:10.1029/2001JD000354.

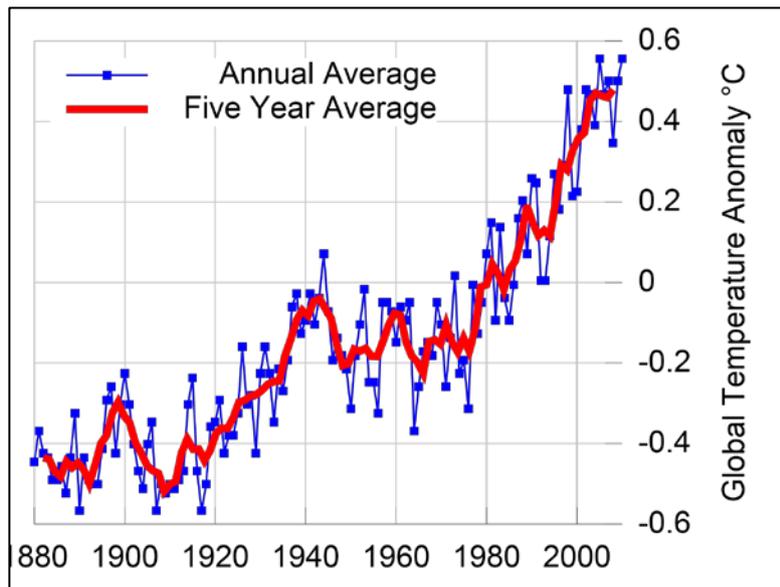


Figure 48: Global temperature trends from 1880

Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (high confidence). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (high confidence). Over the period 1901–2010, global mean sea level rose by 0.19 m.

Temperatures and atmospheric concentrations of carbon dioxide (CO<sub>2</sub>) are closely correlated and are at levels closest to the highest in at least the last 400,000 years, as shown in the ice core data from Antarctica in Figure 50.<sup>50</sup> CO<sub>2</sub> concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.

<sup>50</sup> Petit, J.C., et al. (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* 399, 429-436.

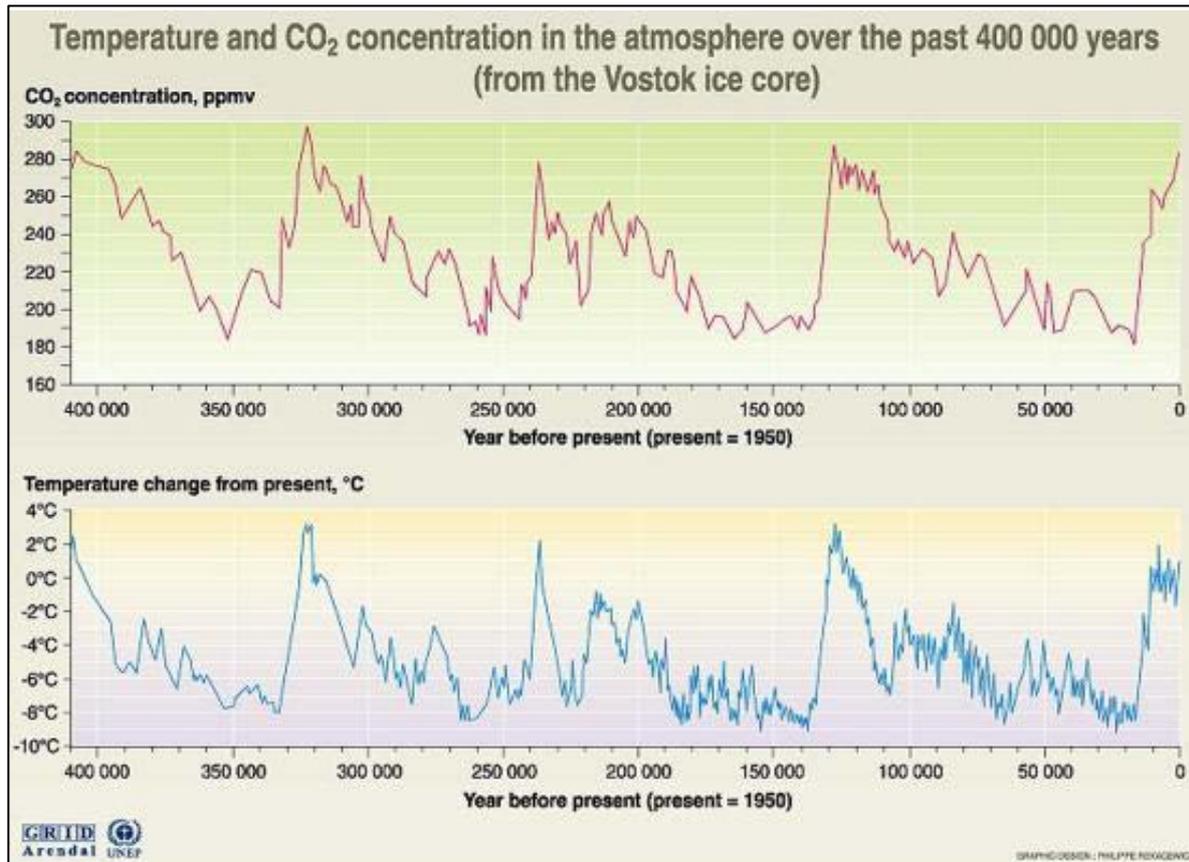


Figure 49: Temperature and CO<sub>2</sub> concentration in the atmosphere over the last 400,000 years

Total radiative forcing (i.e., the difference of radiant energy received by the earth and energy radiated back to space) is positive, and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO<sub>2</sub>, followed by Methane (CH<sub>4</sub>) and other gases and factors (Figure 51).<sup>51</sup>

<sup>51</sup> Stocker et al (2013)

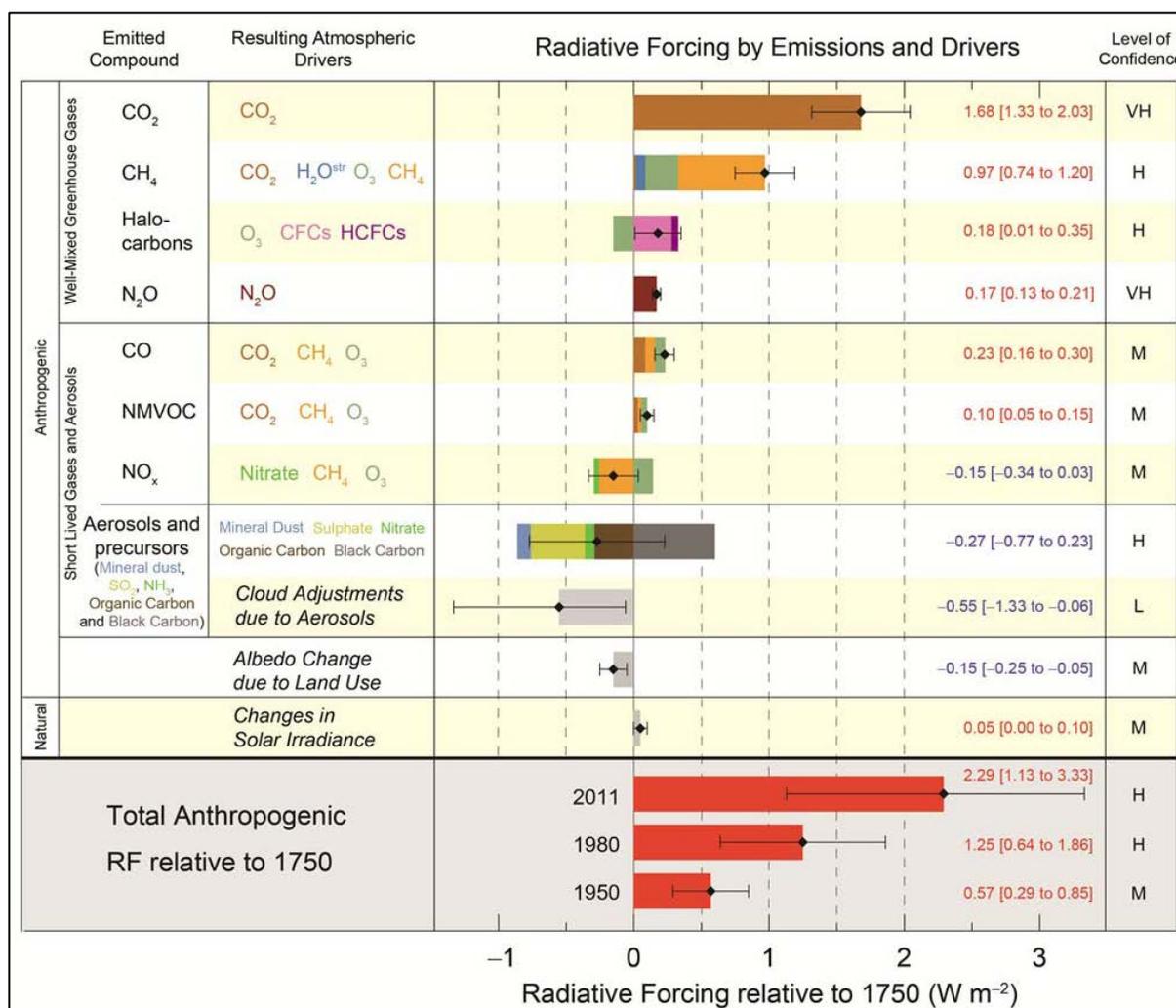


Figure 50: Radiative forcing relative to 1750

Human influence on the climate system has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century. The evidence for this has grown in recent years with new understandings and with the improvement in models of the climate system. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (very high confidence). Observational and model studies of temperature change, climate feedbacks and changes in the Earth’s energy budget together provide confidence in the magnitude of global warming in response to past and future forcing.

Projecting into the future, continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900 for all representative concentration pathways (RCP) except RCP 2.6, which

corresponds to a low-emissions scenario. Warming will continue beyond 2100 under all RCP scenarios except RCP 2.6 (Figure 52).<sup>52</sup>

RCPs are greenhouse gas concentration trajectories used for climate modeling and research. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come.

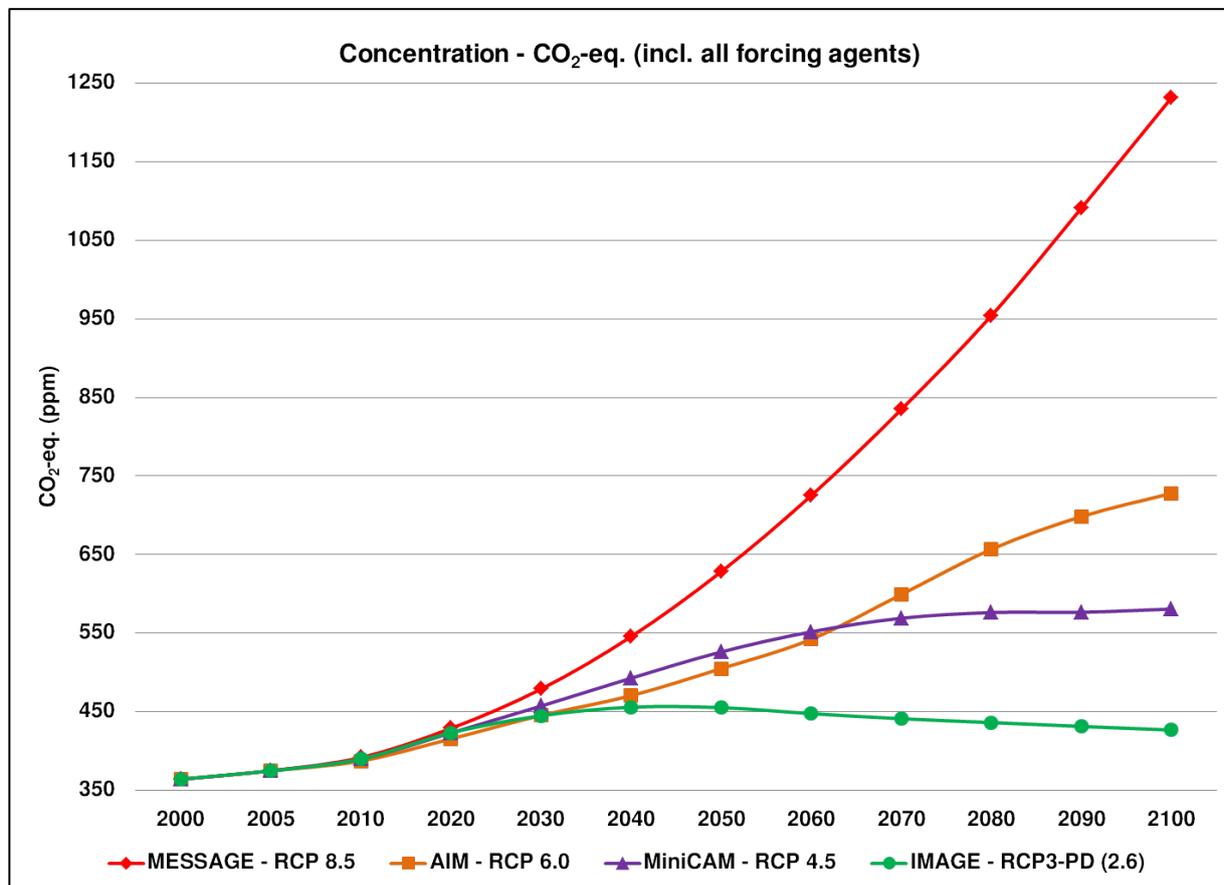


Figure 51: Four Representative Concentration Pathways (RCPs)

Warming over the 21st century will be highest in Northern latitudes and over land than over water. Changes in the global water cycle in response to the warming will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions (Figure 53).

<sup>52</sup> ibid

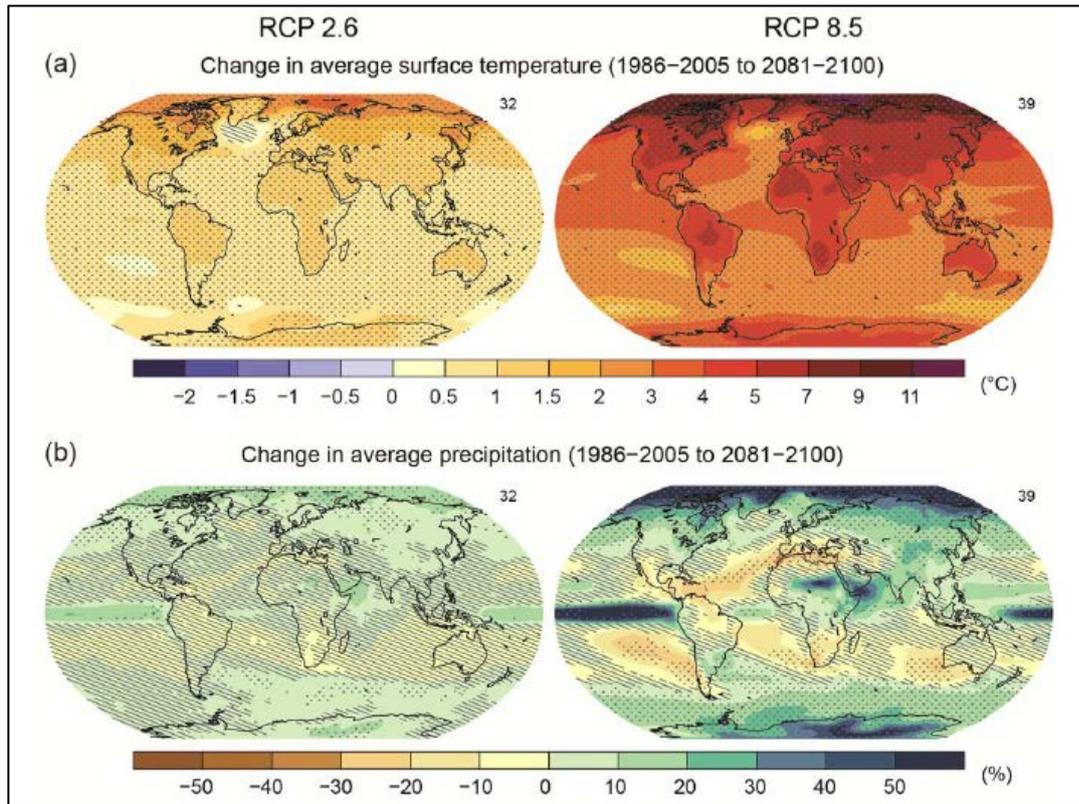


Figure 52: Projected changes in temperature and precipitation under RCPs 2.6 and 8.5<sup>53</sup>

If we turn to regional impacts, Figure 54 shows the projected temperature increases from the four RCPs in Southeast Asia. The projections range from about +1° C to +4° C. On the right-hand side the 5th, 25th, 50th (median), 75th and 95th percentiles of the distribution of 20-year mean changes are given for 2081–2100, in the four RCP scenarios.

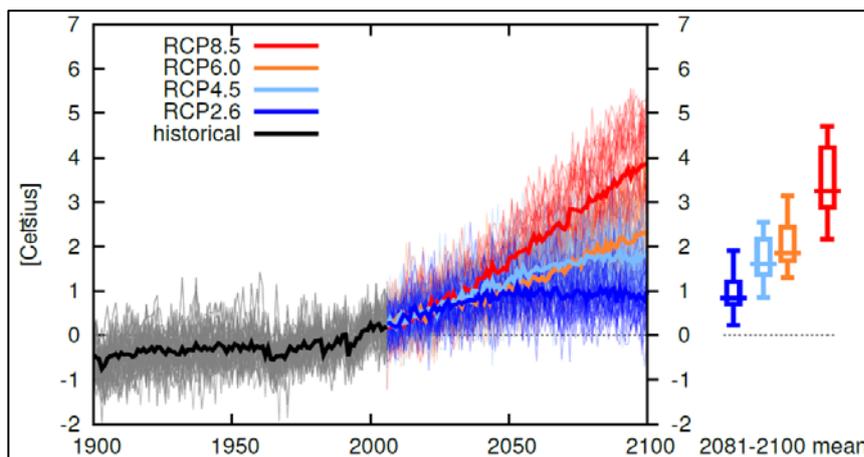


Figure 53: Temperature change predictions from RCP scenarios in Southeast Asia (land), December – February<sup>54</sup>

<sup>53</sup> Stocker et al (2013)

<sup>54</sup> IPCC (2013b) Annex 1: Atlas of Global and Regional Climate Projection. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

These temperature increases will differ according to precise geographical location, the model run, and the time period under consideration. For example, Figure 55 shows PCP 4.5 results.<sup>55</sup>

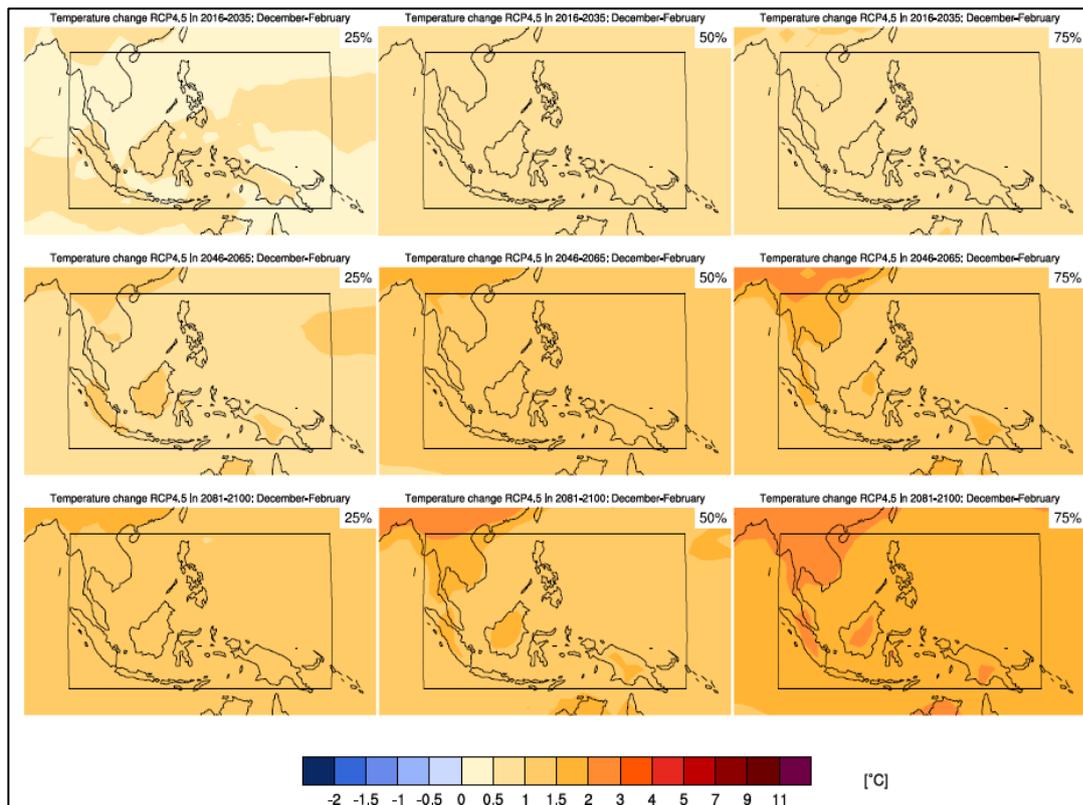


Figure 54: Regional temperature change predictions under RCP4.5 in December-February

The projected precipitation changes from the four RCPs in the Southeast Asia region are also depicted; again these differ by geographical location and other factors (Figures 56, 57).<sup>56</sup> Generally, precipitation increases of up to about 15% are expected.

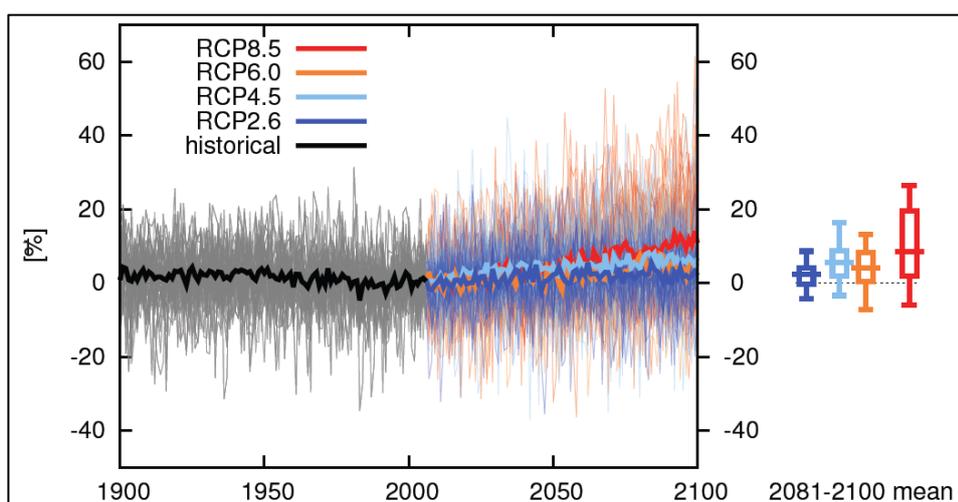


Figure 55: Precipitation change predictions from RCP scenarios in Southeast Asia (land) October-March

<sup>55</sup> ibid

<sup>56</sup> ibid

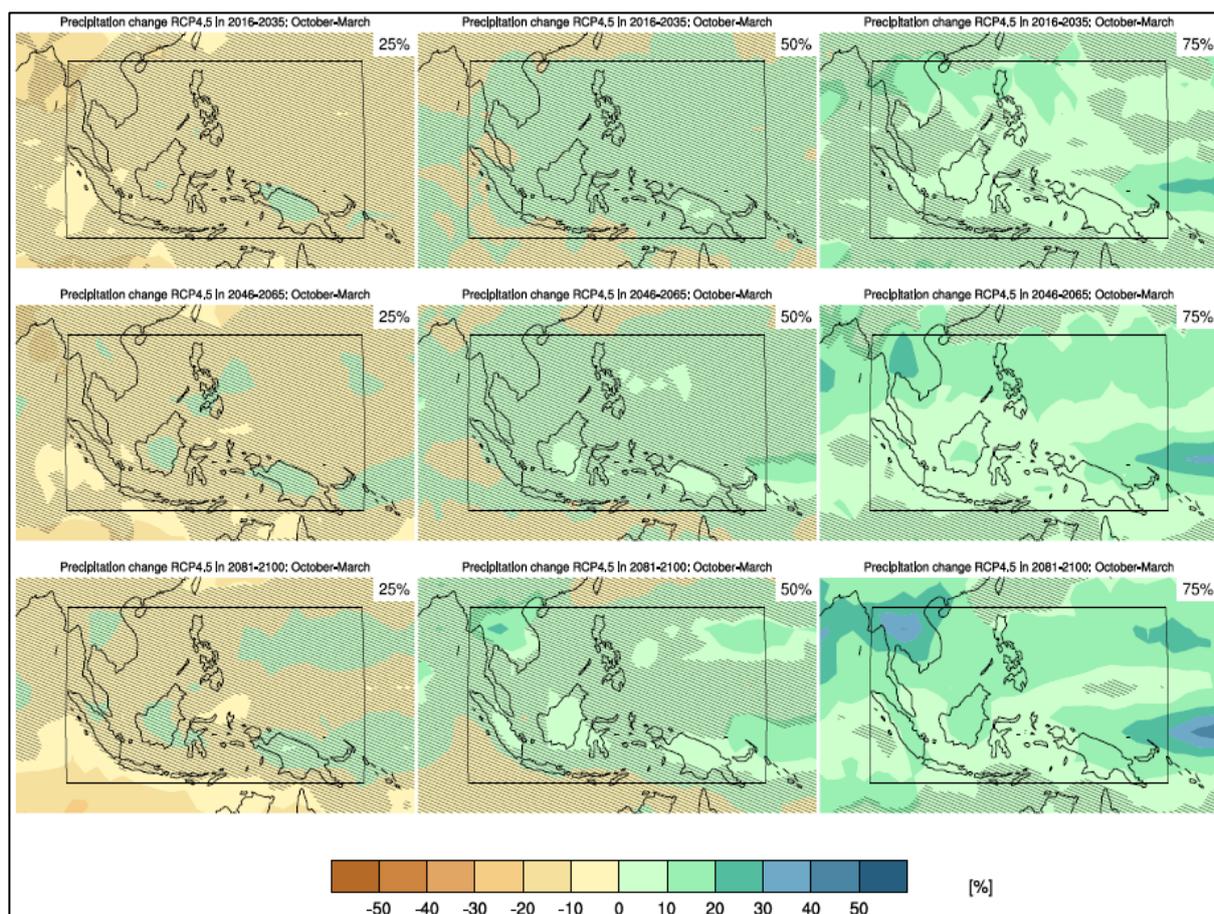


Figure 56: Regional precipitation change predictions under RCP4.5 in October-March

There are a number of other projections in the 5th IPCC report which are less relevant for hydropower:

The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation. It is very likely that the Arctic sea ice cover will continue to shrink and thin. Global glacier volume will further decrease. Global mean sea level will continue to rise during the 21st century. Under all RCP scenarios the rate of sea level rise will very likely exceed that observed during 1971–2010 due to this increased ocean warming and increased loss of mass from glaciers and ice sheets.

Climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO<sub>2</sub> in the atmosphere (high confidence). Further uptake of carbon by the ocean will increase ocean acidification. Cumulative emissions of CO<sub>2</sub> will largely determine global mean surface warming by the late 21<sup>st</sup> century and beyond. Most aspects of climate change will persist for many centuries even if emissions of CO<sub>2</sub> are stopped. This represents a substantial multi-century climate change commitment created by past, present, and future emissions of CO<sub>2</sub>.

### 3 MODULE 3. HYDROPOWER SITING, DESIGN AND OPERATIONS IN A CHANGING CLIMATE

#### 3.1 Session 3.1 Range of Siting, Design and Operations Options

Purpose and Learning Objectives	<p>This session explores how hydropower planners can harness the hydrological conditions in a basin and at project sites through various technical options (single-project and cascade arrangements; storage capacities; outlet/intake capacities and levels; base-load, peaking and pumped storage designs), medium-term (rule curves) and short-term (dispatch) operational decisions. It also explores how these siting, design and operational decisions depend on, or would benefit from, the ability to forecast future climatic conditions.</p> <p>This will help trainees to understand, improve or question (depending on their role) project siting, design and operational decisions, which are often taken without awareness of climate change.</p> <p>This session with its emphasis on discussion will prepare the more technical sessions in the rest of Module 3.</p>
Content	<p>What are the main siting options in a hydropower system?          What are the main design options for a hydropower station?          What are the main operational options for a reservoir hydropower station?          How are choices amongst these options influenced by climate change?</p>
Key Aspects	<p>Hydropower projects are highly site-specific and have long service lives, during which conditions will continue to evolve.</p> <p>Planning of hydropower projects has to take multiple aspects and objectives into account and achieve a balance between them. Future re-balancing may be constrained by initial choices.</p>
Discussion Topics and Exercises	<p>Group discussions: How are climate change issues brought into hydropower siting, design and operations in the LMB countries? Groups will discuss typical siting, design and operational considerations and review their exposure to or modification by climate change.</p> <p>Trainees should be requested to bring in examples from their own experience in the LMB countries.</p>

This session explores how hydropower planners can utilize the local hydrological conditions in a basin and at a project site through various options:

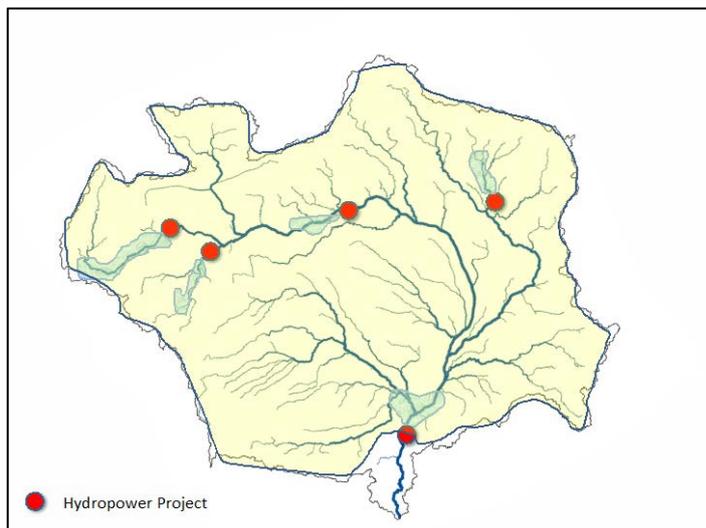
- single-project and cascade arrangements
- storage capacities
- outlet/intake capacities and levels
- base-load, peaking and pumped storage, and how this translates into medium-term (rule curves) and short-term (dispatch) decisions

It will also describe how more complex water management options depend on the ability to forecast future flows.

Prior to siting a hydropower project within a basin, typical questions that must be considered include:

- How large is the overall expected power demand? Base load or peak load?
- Which reaches or tributaries have the best conditions (e.g., large and regular flow, steep topography)?
- Are there any factors that exclude reaches or tributaries from consideration (e.g., unstable geology, lack of access, protected areas)?
- Is there a choice between building one large station instead of several small projects?
- Is there any logical sequence in which stations should be built?
- Can stations support each other in their operations?
- What other water uses besides hydropower exist in the area? How much storage space do they require? Where are the locations with storage capacities? Are their storage requirements going to be compatible with hydropower operations?

The answers to these questions will aid planners in choosing final sites and from a variety of options. The example below highlights how the same installed capacity could be sited in very different ways:



Option A: Five stations located on the mainstream and two tributaries. The highlighted area shows that almost the entire basin is upstream of the hydropower stations. Possible issues include effects on fish passage and sediment. However, this scheme enables the control of flows or floods downstream.

Figure 57: Hydropower siting Option A

Option B: Six stations located on one tributary. Only one sub-basin is upstream of the stations. This reduces the impact on sediment and fish passage but also reduces the ability to control flows/floods downstream. However, options include operating cascades with reservoirs at the top and run-of-river stations below the stations. Also, the last reservoir could release close-to-natural flows.

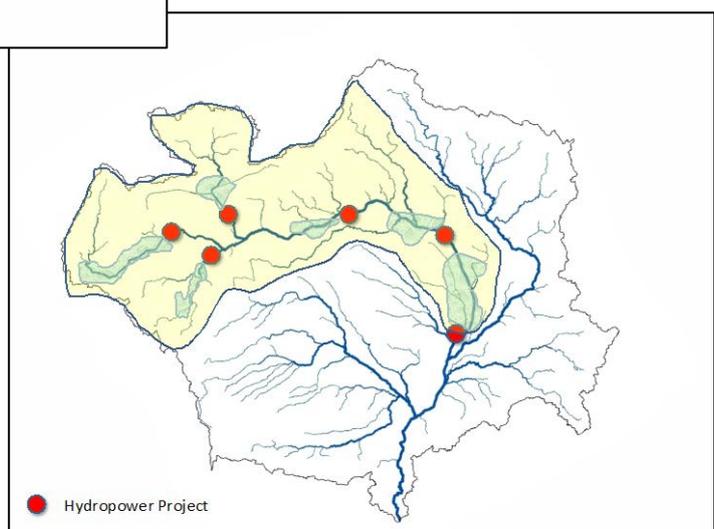


Figure 58: Hydropower siting Option B

Figure 60<sup>57</sup> shows the lower Mekong cascade as an example for sets of projects which are often planned together. There are obviously multiple siting options in a basin.

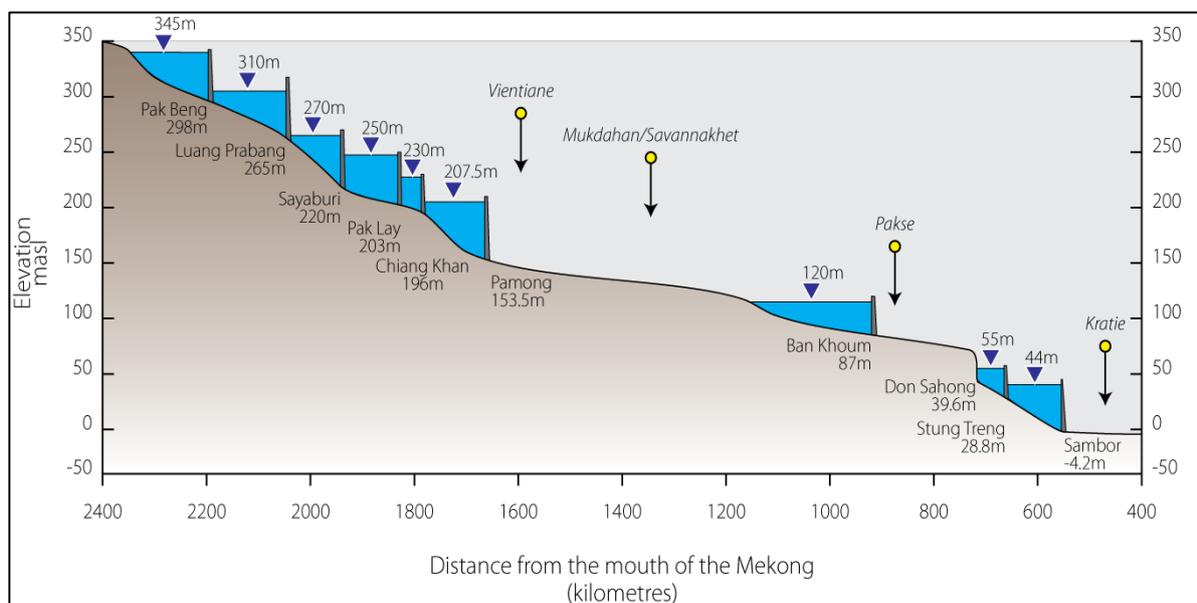


Figure 59: Example of cascade option

Which sites will be developed depends on a number of factors considered above. These factors may be modified, or their weight in decisions may be changed, when plans take climate change into account. Stations on larger tributaries may be preferred if flows are more regular on these tributaries or more storage capacity is needed. If storage will be built at the top of a cascade, then it may have to be built early to protect and help operate the downstream stations. These issues are explored in more detail in the rest of Module 3.

How many sites will be developed largely depends on the demand for hydropower. Demand is a function of overall trends in the economy (population, income per capita, energy intensity, cost of different energy sources etc.). These trends may also be modified by climate change. For example,

- a government may promote electric vehicles as a mitigation option,
- a government may promote renewable power, and more wind power requires more firm energy back-up, or
- energy intensity may increase as people use more power for cooling.

Such increases in demand would require more or larger hydropower sites to be developed. We will come back to these issues in Module 4.

Once a site is identified, the project development process moves into more detailed planning of design and operations. Economic, technical, and environmental factors must be considered in the iterative planning process, prior to a final investment assessment, as shown in Figure 61.<sup>58</sup>

<sup>57</sup> WWF presentation.

<sup>58</sup> MACS Management & Consulting Service (2012) Financing hydropower / Introduction to the Specifics of Small Hydro Power Plants in GGF Technical Workshop on Small Hydro Power at EFSE Annual Meeting. Tbilisi, Georgia.

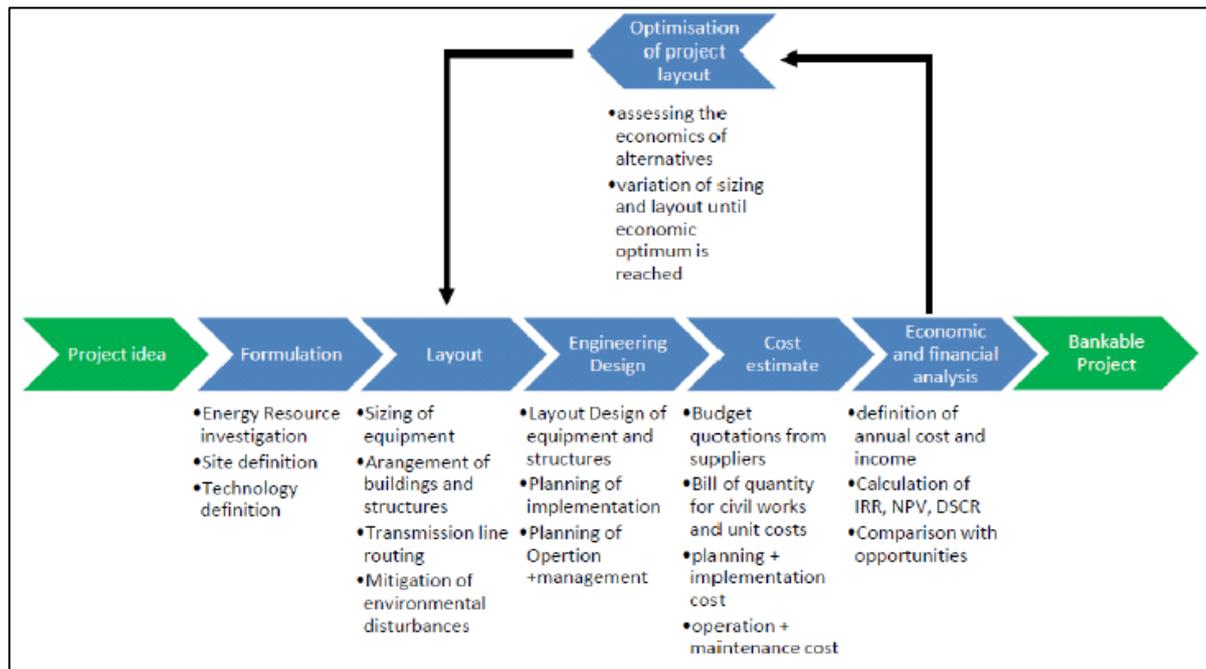


Figure 60: Design process for a single station

Engineering studies will progress from the conceptual level and will be fed by subsequent site studies, which provide more data about opportunities and constraints. Design engineering then develops a project idea in more detail:

- What kind of dam (e.g., roller-compacted concrete, arch, rockfill)?
- How much live and dead storage capacity? Both for hydro and other needs?
- How much capacity for spillways and other outlets? Where should these be located?
- What kind of powerhouse (e.g., at foot of dam or further downstream, above ground or underground, turbine type, and number of turbines)?
- Can the project be developed in stages?

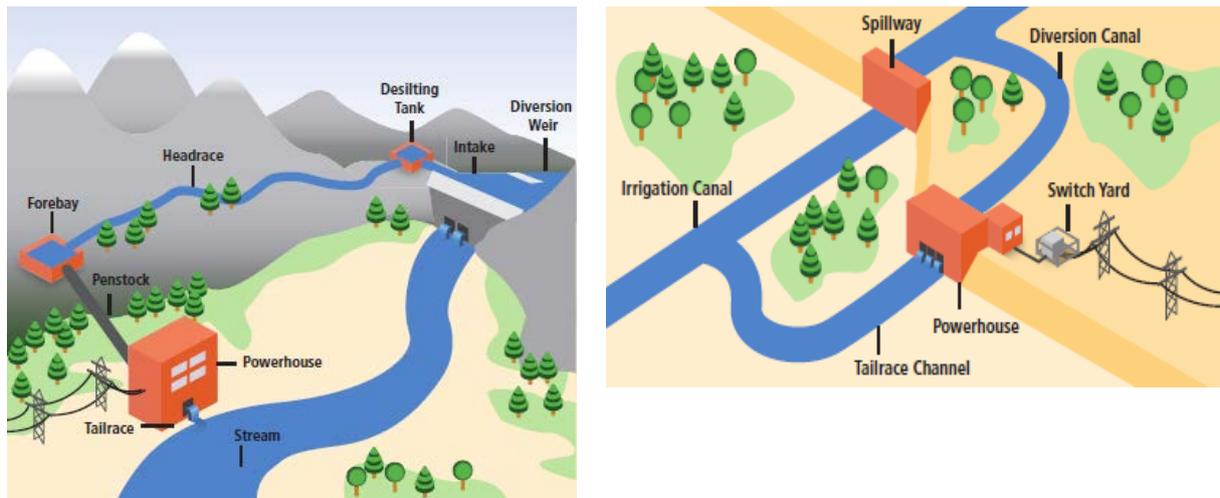


Figure 61: Design Options<sup>59</sup>

One of the fundamental questions in hydropower design is the storage capacity required to provide a given yield (or release) with a certain level of reliability. To help with this decision, a Rippl diagram (mass curve analysis) is often used (Brown et al 2010; Figure 63). The tangent lines parallel to the yield curve reveal inflection points on the inflow curve that represent points in time when the inflow is the same rate as the yield (release rate), indicating that reservoir storage is constant. Whenever the inflow curve has a greater slope than the yield curve, the storage is increasing. Whenever the inflow curve slope is smaller than that of the yield curve, storage is decreasing. The maximum vertical distance between two successive tangent lines represents the difference in volume between a full and empty reservoir, and provides the storage capacity required to provide the specified yield. This is a very simplistic model – it assumes stationary hydrology, constant outflows and 100% reliability – but can be adjusted to more realistic planning situations.

<sup>59</sup> Kumar et al (2011)

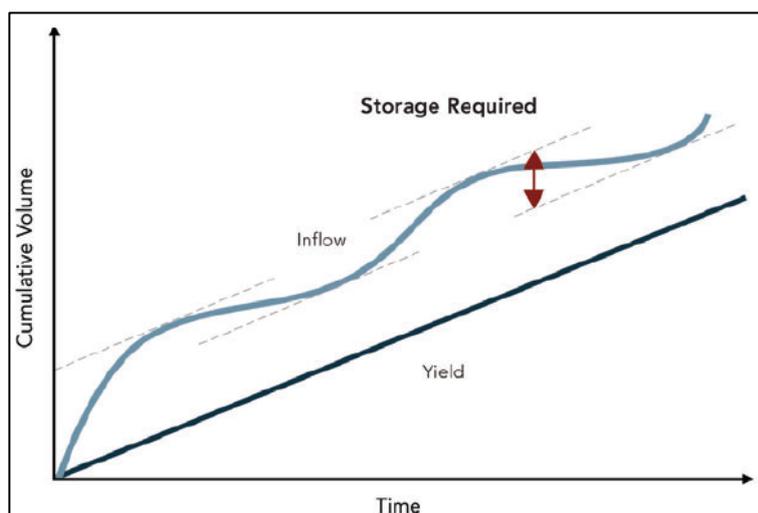


Figure 62: Design options: storage capacity required to meet a constant yield

Future demands, not just current conditions, must be considered when calculating the required storage capacity. An increase in storage requirements is visualized in Figure 64 which shows intra-annual fresh water supply (solid curves) and demand (dashed curves) for a basin that is characterized by seasonality of flows and high water demand in the dry season. Projected changes in river flow assume more pronounced seasonality, as a result of climate change. Projected changes in demand assume that dry season requirements, for example for irrigation, will increase. The shaded areas represent the current and projected storage required to meet intra-annual fresh water demand. The larger red shaded areas show the projected increased need for storage capacity.<sup>60</sup> Storage as an adaptation option is addressed in more detail in Session 4.3.

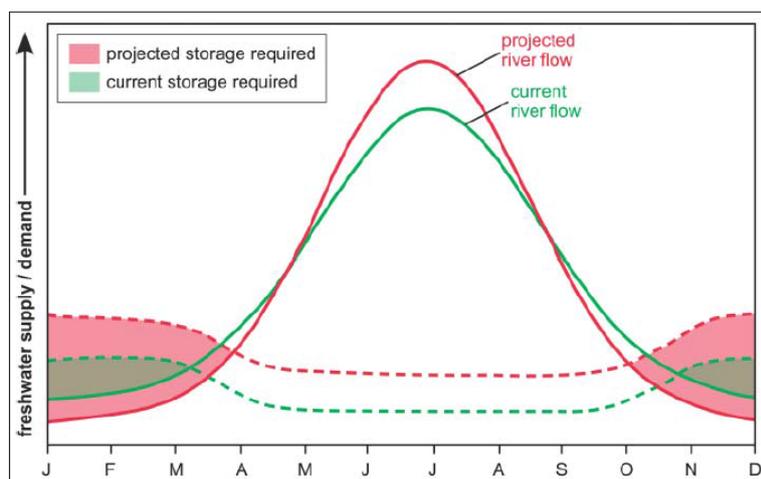


Figure 63: Design options: increasing storage capacity

Design options also exist for the choice of turbine type (e.g., Pelton, Kaplan, Francis), the numbers of units required, and their individual design. The choice depends on whether flows can be controlled to maximize efficiency, or if the flows are irregular and difficult to predict,

<sup>60</sup> Taylor (2009) Rethinking Water Scarcity: The Role of Storage. Eos, Vol. 90, No. 28

and the turbines need to be functioning under a wide range of flows. Figure 65 shows how different turbine types have different ranges of efficient functioning.<sup>61</sup>

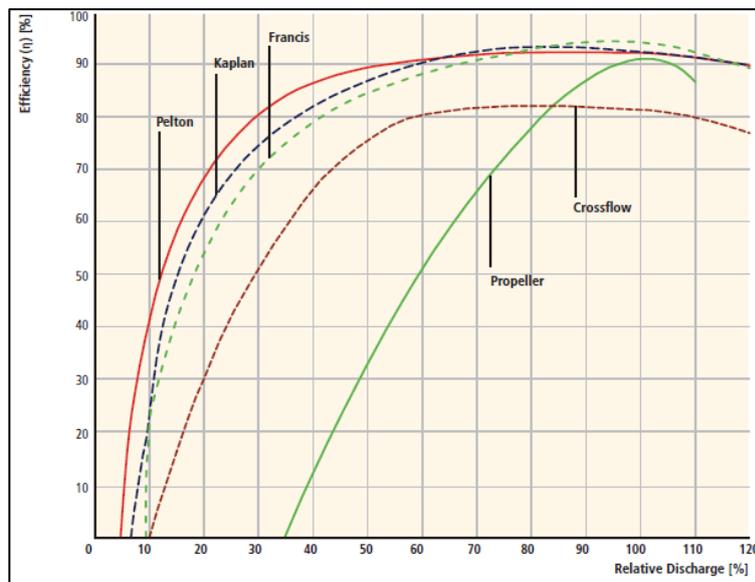


Figure 64: Design options: turbine choice and design

Additional considerations that should be addressed may be influenced to various degrees by climate change:

- How large should the installed generation capacity be?
- What is the best balance between reservoir size, costs, and environmental and social impacts?
- What is the design flood?
- Which layout of the civil works and which configuration of electro-mechanical installations will minimize construction costs?
- How can the resource be used most efficiently?
- Will there be a need to manage sediment accumulation and water quality in the reservoir?
- Will there be a need to mitigate environmental impacts on downstream flows (e.g., timing, temperature, gas content) and aquatic biodiversity?

An analysis of current practices and typical operational arrangements help to answer these questions and inform decisions. Reservoir stations operate within their storage rule curves (graphs that represent target and actual storage goals to guide operations) that reflect simplified summaries of historical experience and arrangements with stakeholders. There is often potential to re-examine and improve rule curves.

In Lake Madden, Panama, traditionally the same rule curve was used every year (Figure 66; Brown et al 2010). Through modeling, two different rule curves, chosen based on the forecast of an El Niño or La Niña event, are now suggested. These forecasts are made in May each year and the rule curves adjusted, to reflect the reservoir drawdown that is suggested based on expected inflows. The rule curves aim to ensure approximately the same reliability of refill by the end of the year. Since La Niña events lead to higher average inflows for this system, the

<sup>61</sup> Kumar et al (2011)

reservoir is drawn down to a lower level. El Niño events lead to drier than average conditions and are accompanied by a higher rule curve.

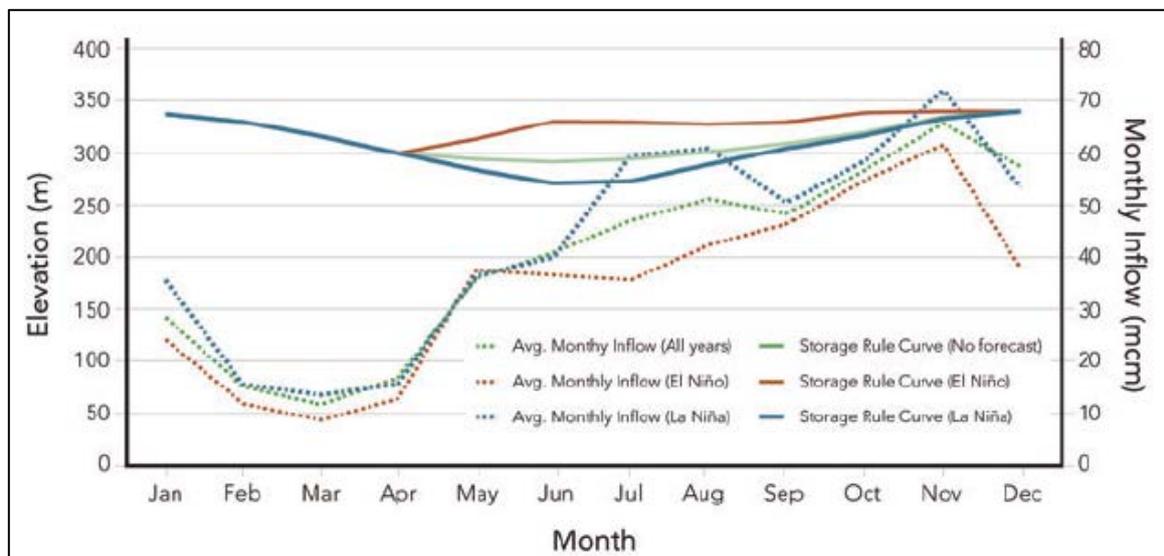


Figure 65: Storage rule curves and average monthly inflows to Lake Madden, Panama

Siting, design and operational decisions should also consider the overall electricity system in the relevant market. Hydropower stations are typically dispatched by some central dispatch center (that may be within the utility, outside the utility in some government or independent agency, or within the customer). They will be dispatched according to merit order (i.e. lowest cost station are dispatched first, in order to reduce overall system costs). This means that run-of-river stations are always dispatched, as long as they have water. Reservoir stations should only be dispatched if the value of using one m<sup>3</sup> of water now is higher than keeping that m<sup>3</sup> in storage for future generation. In addition to generation, reservoir stations can provide, and are operated for, ancillary services such as voltage stabilization and black start capability. The water value in a reservoir is a function of future generation options, and these depend on the overall system.

Climate change influences all currently operating projects, as well as the operations of potential future hydropower projects. Operating projects are constrained in their choices by the infrastructure and the rules that have already been established. New projects have a greater degree of freedom in their choices. Whether existing or new, operational considerations include:

- How much water should be stored for dry periods and periods of high demand?
- How much water should be released in anticipation of the wet season or a flood?
- When should non-generation outlets be used? When should sediment be flushed?
- How should fluctuations of the reservoir level and of downstream flows be managed to minimize environmental and social impacts?

Currently, these questions, as well as the siting and design considerations listed above, are usually resolved without taking longer-term climate change into account.

This session introduced the choices planners have. The two following sessions will discuss how possible changes in water quantity and water quality might modify the choice between different sites, designs, and operational regimes. The final session of this Module 3 will then review the tools which can be used to bring climate change into siting, design and operational decisions.

## 3.2 Session 3.2 Water Quantity

Purpose and Learning Objectives	<p>This session explores what changing (or 'non-stationary') water quantities will mean for the economics and the safety of hydropower stations.</p> <p>Trainees will learn to understand the different impacts of the multiple, time-dependent dimensions of water quantity.</p>
Key Reading	<p>Item 3.2.1 - Milly et al (2008) Stationarity is dead.</p> <p>Item 3.2.2 - Hamadudu and Killingtveit (2012) Assessing Climate Change Impacts on Global Hydropower.</p>
Content	<p>What effects are expected from reduced or increased total inflows?</p> <p>What effects are expected from extreme events?</p> <p>What effects are expected from changed timing of inflows?</p> <p>What effects are expected from increased variability of inflows?</p>
Key Aspects	<p>Optimal capacities of turbines, storage capacities, spillways and other project features are changing in a non-stationary climate.</p> <p>Some regions will benefit, while others will not.</p> <p>Optimal capacities are becoming less certain, and robust designs and adaptive management will play a larger role in the future.</p>
Discussion Topics and Exercises	<p>Role play on integrating climate forecasts into water allocation processes at <a href="http://crk.iri.columbia.edu/water/course/view.php?id=55">http://crk.iri.columbia.edu/water/course/view.php?id=55</a></p> <p>Item 3.2.5 - Materials for role play</p>
Additional Resources	<p>Item 3.2.3 - Vattenfall Power Consultant AB (2007) Addressing Climate Change-Driven Increased Hydrological Variability in Environmental Assessments for Hydropower Projects – a Scoping Study.</p> <p>Item 3.2.4 - Brown et al (2010) Managing Climate Risk in Water Supply Systems: Materials and tools designed to empower technical professionals to better understand key issues.</p> <p>This manual is accompanied by a series of technical exercises at <a href="http://crk.iri.columbia.edu/water/course/category.php?id=7">http://crk.iri.columbia.edu/water/course/category.php?id=7</a>, covering issues such as: a) flow duration analysis and reservoir storage allocation, b) inflow forecast development, c) hydroclimatic risk assessment, d) integrating seasonal forecasts into reservoir reliability analysis and management, e) integrating forecasts into institutional decision-making processes (this is the role play exercise, item 3.2.5).</p>

In the hydropower world, problems involving water can generally be divided into five categories:

- having too much water
- having too little water
- having water at the wrong time
- not knowing how much water there will be
- having water of inadequate quality (next session)

These problems are compounded by climate change.

The effects of climate change on water quantities can be visualized through FDCs in the same way as other effects previously discussed (i.e., land use or environmental flow demands). For example, total inflow may be higher or lower, shown by an increased or decreased area under the FDC. This either increases or reduces the viability of hydropower investments, and changes the optimal plant capacity (Figure 67).

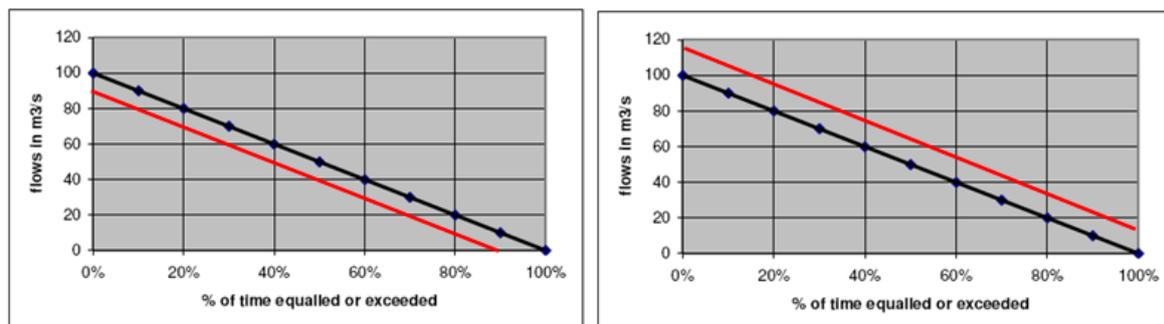


Figure 66: Total inflows lower (left) and higher (right)

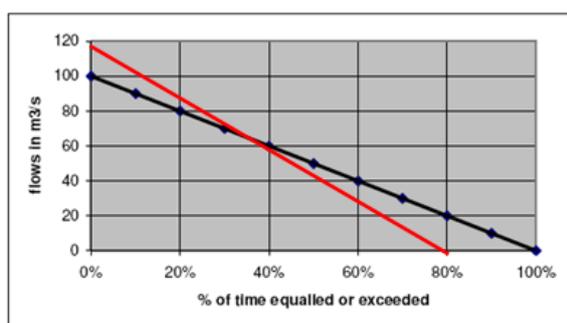


Figure 67: Steepening FDC due to more extreme flows

Seasonal variations may also be amplified, further increasing high and reducing low flows (thus an increase of flood and drought events), steepening the natural FDC (Figure 68). At a given powerhouse capacity, this reduces the load factor. By adding storage capacity, the load factor may be restored. However, this comes with a cost and reduces the viability of hydropower.

Finally, not only can the FDC, as a representation of average, expected flows, shift, it can also become less certain. The range of conditions around the average may increase and the confidence intervals may broaden.

Potential flow changes have been modelled for many river systems, and one projection is shown in Table 16.<sup>62</sup> The numbers are indicative only as there are large methodological uncertainties (e.g., regarding water use changes); however, they indicate that some important Asian rivers may see an increase in discharge. Interestingly, in this analysis, the only exception would be the Mekong which is projected to have unchanged total flows. This outcome has been contradicted by other studies with different methodologies; there are currently no conclusive predictions for future Mekong runoff.<sup>63</sup>

<sup>62</sup> Palmer et al (2008) Climate change and the world's river basins: anticipating management options. *Front Ecol Environ* 2008; 6, doi:10.1890/060148.

<sup>63</sup> Beilfuss & Triet (n.d.) Climate change and hydropower in the Mekong River Basin: a synthesis of research. A scoping study prepared for the MRC and GIZ. Draft.

River	Discharge at mouth, average 1960s - 1990s (km <sup>3</sup> / year)	Discharge at mouth, 2050s (km <sup>3</sup> / year)	Change
Amazon-Orinoco	6,802	5,537	-19%
Congo	1,349	1,268	-6%
Ganges-Brahmaputra	1,187	1,389	+17%
Yangtze	955	1,122	+17%
Irrawaddi	564	713	+26%
Mekong	422	418	-1%
Amur	331	413	+25%
Zhu Yiang (Pearl River)	271	330	+22%
Indus	121	175	+44%
Salween	99	135	+37%
Hong Ha (Red River)	68	78	+15%

Table 16: Predicted changes of annual discharge

Regional changes in annual runoff due to climate change have also been modelled. One of the models shows that the south and west of Europe will experience much less runoff and the north and east of Europe will experience a significant increase. Figure 69 overlays areas with increased or reduced discharge with the existing hydropower stations in Europe.<sup>64</sup>

<sup>64</sup> Lehner et al. at [http://www.rit.edu/~w-cenr/documents/data/Europe\\_Hydropower.pdf](http://www.rit.edu/~w-cenr/documents/data/Europe_Hydropower.pdf)

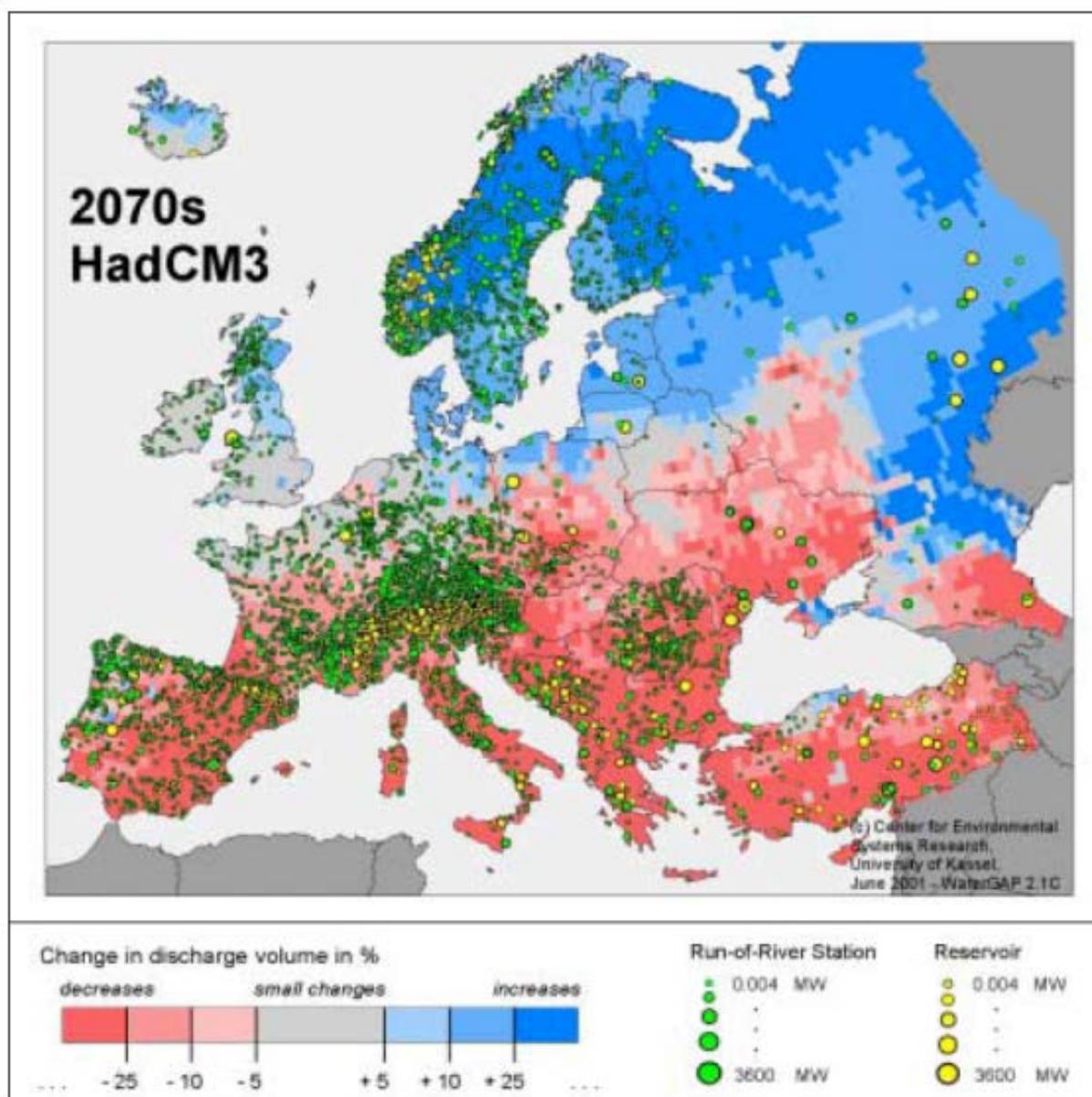


Figure 68: Modelled change in discharge volume and future European hydropower potential

At a global level, Hamududu and Killingtveit (2012) have published the first overview of the effect of runoff changes on hydropower generation for countries and for Canada, US, Brazil and China, also for states/provinces (Figure 70). Based on 12 global circulation models, some notable changes in runoff are expected (for example, large increases in Québec and large decreases in Turkey and Venezuela). Changes in much of Asia are expected to be positive. Effects of runoff are expected to be proportional to effects in generation. Limitations of these projections include that only current hydropower systems were analyzed; no future hydropower development was included. The impacts of changes in timing of flow, storage management, or changes in sediment transport were also not included. In addition, the climate change effects were disaggregated to the level of jurisdictions, but not in hydrological units (basins).

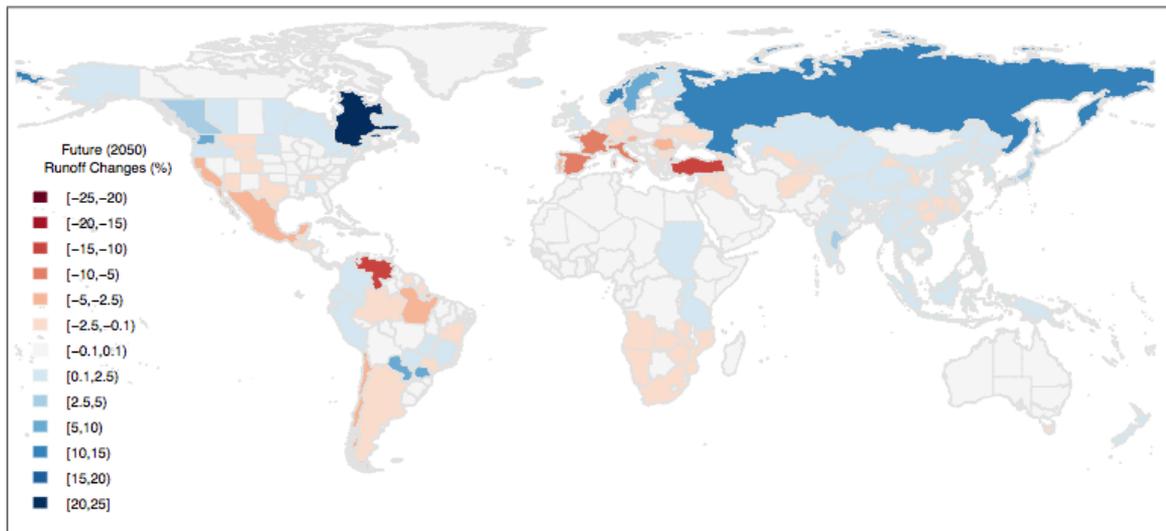


Figure 69: Percentage changes in global runoff

Apart from total runoff, the frequencies, intensities and durations of extreme events such as droughts and floods are also likely to change as a result of climate change, and produce subsequent effects. The mid-continental regions may become especially prone to increased summer drought (Figure 71).<sup>65</sup> This occurs as a result of a combination of reduced summer rainfall in many continental interiors such as southern Russia, central Europe and the American mid-West, and increased potential evaporation globally.

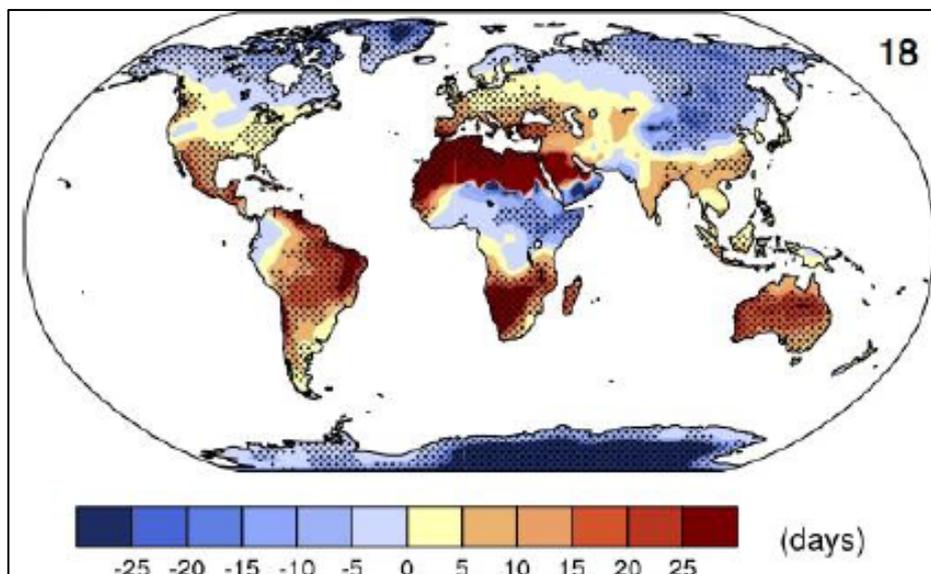


Figure 70: Projected annual maximum consecutive dry days from 2081-2100 under RCP 8.5 scenario

Drought conditions are not unusual in hydropower operations, and precedents already exist for dealing with them. For example, the Nam Theun Power Company (NTPC), under the concession agreement with the government of Lao PDR, has the responsibility for water management in the reservoir. Under its power purchase agreement with EGAT, NTPC bears the hydrological risk. NTPC has to pay penalties to EGAT if, among other things, it fails to

<sup>65</sup> Krishna (2013) Regional climate change: Findings of IPCC AR5 WGI

maintain guaranteed 'primary energy'. To reduce the risk, NTPC is entitled to declare two years as 'drought years' during which it is exempted from these penalties. Hydrology is more variable than generation (primary plus secondary energy), which in turn is more variable than EGAT payments; therefore, the hydrological risk for NTPC is reduced. Figure 72 shows an economic simulation over the 52-year hydrological period of record under this scenario. In the driest years, revenues would have fallen to 86%.<sup>66</sup>

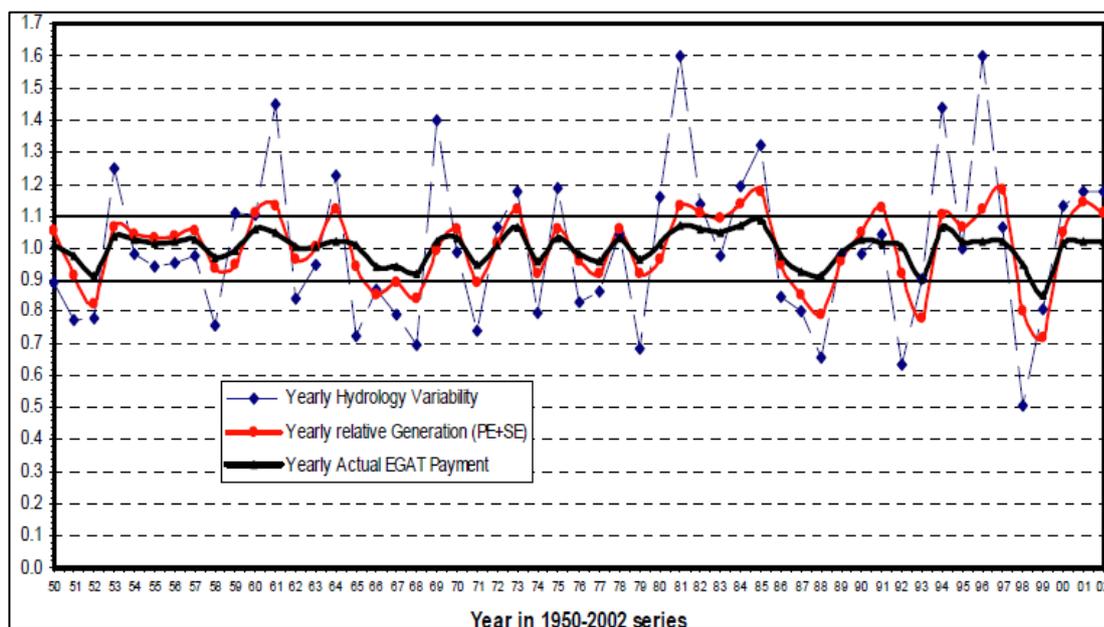


Figure 71: Relative variations of flows, power generation, and actual EGAT payment

The question is whether such arrangements, negotiated on the basis of historical hydrology, will be adequate in the future. Since most power purchase agreements are not made public, very little information exists on how more flexible and adaptive arrangements could be negotiated.

Just as much of a problem as 'too little water' (drought), is 'too much water' (floods). Floods are categorized as large, rare or extreme according to their annual exceedance probability (1 in every defined number of years; Figure 73).<sup>67</sup> The 1-percent annual exceedance probability (AEP) flood, or the "100-year flood" has a 1 in 100 chance of being equaled or exceeded in any 1 year, and it has an average recurrence interval of 100 years. The accuracy of the 1-percent AEP flood estimate varies depending on the amount of data available, the accuracy of those data, future land-use changes in the river drainage area, climate cycles and trends, and how well the data fits the statistical probability distribution.

<sup>66</sup> NTPC (2005) PPA Summary for Public Disclosure

<sup>67</sup> Presentation at <http://www.ferc.gov/industries/hydropower/safety/initiatives/risk-informed-decision-making/extreme-hydro.pdf>

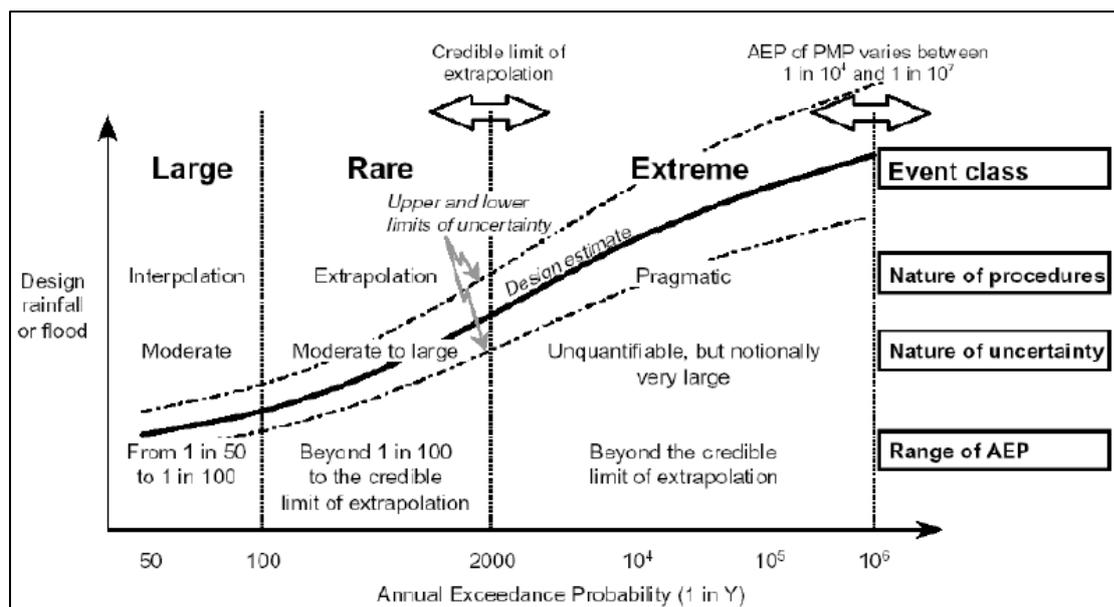


Figure 72: Estimating and interpreting 1-in-x-years floods

The probable maximum flood (PMF) is the theoretical largest flood resulting from a combination of the most severe meteorological and hydrologic conditions that could conceivably occur in a given area. The spillway of many dams (two-thirds of a sample of 90 large dams built since the mid-1960s) is designed to pass the PMF.<sup>68</sup>

PMF is closely related to probable maximum precipitation (PMP), the greatest depth of precipitation for a given duration that is meteorologically possible for a given size storm area at a particular location and time of year.<sup>69</sup> Modeling studies of extreme rainfall show that the volume of storm precipitation is strongly related to atmospheric water vapor. Increased air temperatures due to climate change will mean an increase in atmospheric water vapor content, and thus an increase in amount of available precipitable water. Increases in the amount of available moisture should result in heavy rainfall beginning earlier, lasting longer, and being more continuous over time.

Processes by which extreme floods are generated (e.g., overland flows) are difficult to model, and hydrological data are often insufficiently detailed (i.e., local data and short duration rainfall). However, global and regional climate models generally agree in predicting higher probability and shorter return periods for heavy precipitation. In the long run (2081-2100) and in the most severe emissions scenario, South-East Asia would be one of the regions with the highest increases in maximum precipitation, beyond 25% (Figure 74).<sup>70</sup>

<sup>68</sup> Fahlbusch, F.E. (1999) Spillway design floods and dam safety. International Journal on Hydropower & Dams.

<sup>69</sup> WMO (1986)

<sup>70</sup> Krishna (2013) Regional climate change: Findings of IPCC AR5 WGI

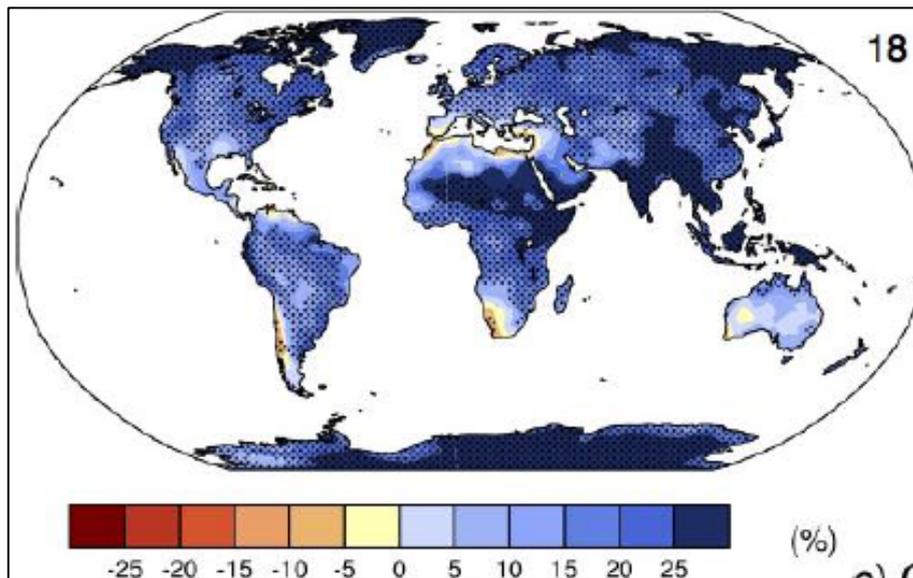


Figure 73: Maximum 5-day precipitation predicted for 2081-2100 under RCP 8.5 scenario

Such projections always come with some uncertainty, and it is useful to be able to quantify that uncertainty. As a demonstration of the uncertainty in the estimates of flood probability, the flood probability relation for the Big Piney River near Big Piney, MO, is plotted in Figure 75.<sup>71</sup> Above and below the flood probability, the solid black line, are two dashed lines that represent the 90-percent confidence intervals of this relation. The 1-percent AEP flood for the Big Piney River at this location has an estimated magnitude of 44,300 cfs, with 90-percent confidence that the true value of the 1-percent AEP flood is between 36,600 cfs and 56,400 cfs.

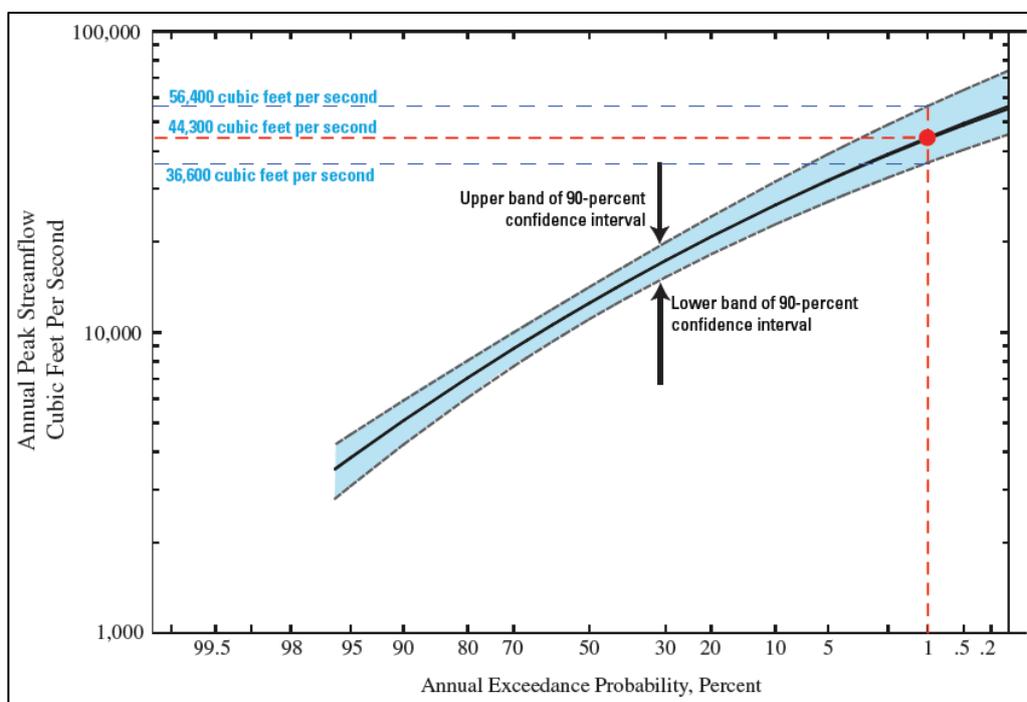


Figure 74: Flood probability relation for the Big Piney River near Big Piney, MO

<sup>71</sup> <http://pubs.usgs.gov/gip/106/pdf/100-year-flood-handout-042610.pdf>

Floods in the LMB region are caused by two major phenomena: the southwest monsoons and tropical weather systems.<sup>72</sup> The southwest monsoons arrive in May and generally last until October. The wet season winds bring moisture from the Bay of Bengal to the LMB, causing widespread, heavy, and extended rainfalls. The tropical weather systems are westward-tracking tropical depressions, storms, and cyclones (collectively called TWS), generated in the western Pacific Ocean, the South China Sea and occasionally in the Andaman Sea. Typically, four to six TWS make landfall on the Vietnamese coast each year, most commonly during the period August to November, migrating southwards from the Northern to the Central coast as the cyclone season develops. After making landfall, TWS continue westward to enter the LMB, where they can deliver regional high intensity rains to all parts of the LMB, but especially the Northern Highlands and the catchments of the Sekong, Sesan and Sre Pok rivers. TWS initially cause flooding in Mekong tributaries. On entering the Mekong, these tributary floods travel downstream as separate flood crests, adding onto the underlying southwest monsoonal flood wave, where they amplify the peak water level, discharge, and volume of the mainstream flood wave and sustain flood duration.

How will climate change affect these flood-producing phenomena? There is significant uncertainty over the timing and extent of seasonal phenomena like the monsoon and cyclones. What appears to be certain is that climate change may induce seasonal shifts in many parts of the world – for example, by postponing the onset of monsoons, or by bringing on an early spring snowmelt in temperate regions. (This effect does not necessarily show up in an FDC, which shows data without their chronological order). It may bring the seasonality of flows either more or less in line with seasonal peak electricity demand (which is also expected to shift to summer months). As an example for seasonal shifts, Figure 76 shows expected inflows into three of Hydro Tasmania's reservoirs (relative to historic inflows, represented by the factor 1.0).<sup>73</sup> Values above 1.0 show seasons that are wetter than historical averages, and values below 1.0 show seasons that are drier than historical averages. In this case, strong reductions in inflows are expected for some months.

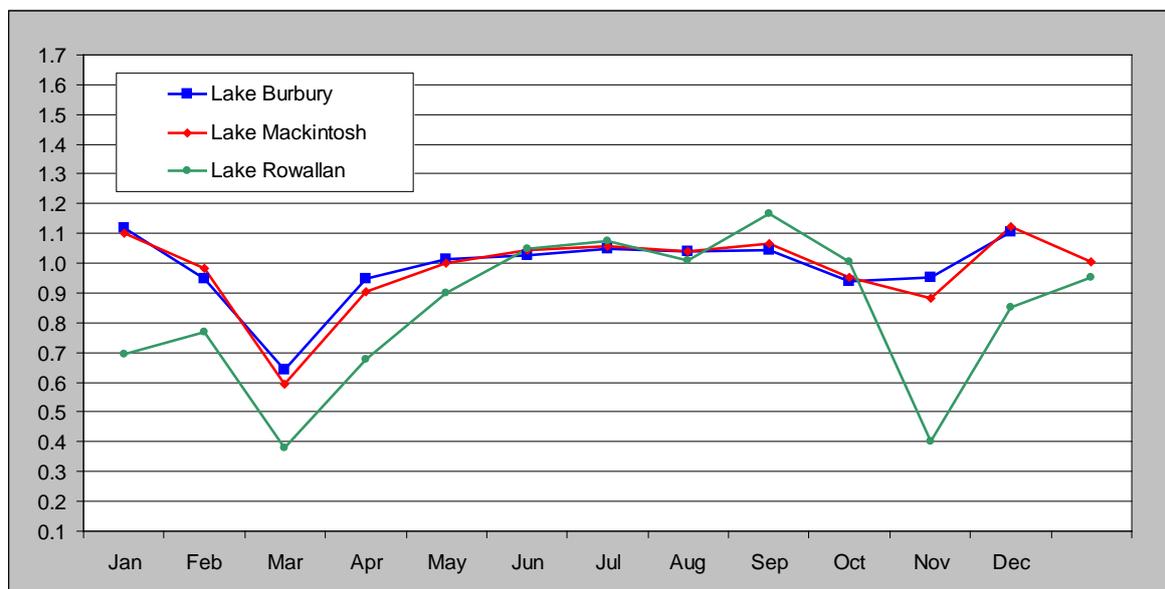


Figure 75: Monthly expected inflows into three Hydro Tasmania reservoirs

<sup>72</sup> <http://www.mrcmekong.org/assets/Publications/basin-reports/FMMP-working-paper-110820.pdf>

<sup>73</sup> <http://siteresources.worldbank.org/EXTWAT/Resources/4602122-1213366294492/5106220-1213649450319/4.5.1 Drought and CC.pdf>

Variable and changing flow regimes translate into either positive or negative outcomes for hydropower developers. Hydro Québec, the second largest global hydropower utility, states that runoff conditions are their most significant risk factor, which could increase or decrease their annual net income by hundreds of millions of CAD.<sup>74</sup> All hydropower companies have to prepare for these uncertainties.

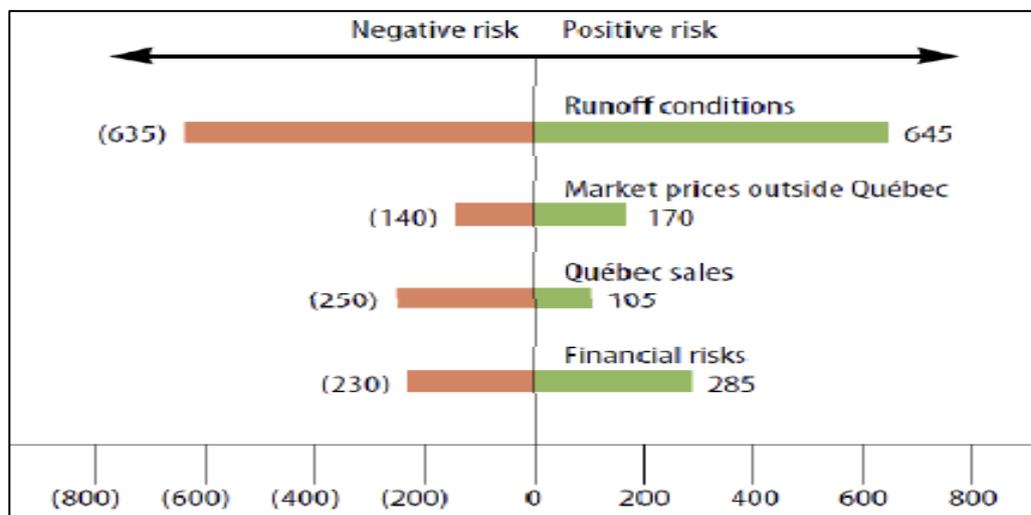


Figure 76: Variability in net income for 2008 (CAD million)

If precipitation falls as snow instead of rain, it only delays runoff seasonally until the next melting season. However, ice formation can delay runoff over many years. While the Mekong flows are only marginally influenced by glaciers, glaciers as a source of flows are important for many other river systems. Climate change impacts in glacier dependent systems are therefore unique. They include temporary increases in runoff due to the melting of ice. FDCs temporarily shift outward as a result of the increasing annual flows. For example, due to significant glacial loss, Swiss hydropower production in the year 2003 (the hottest and driest of the last 500 years) was only 0.8% below the 10-year average. Ice fields in Iceland (Figure 78)<sup>75</sup> store 15-20 years of precipitation, and are expected to melt within the next 200 years. Seasonal flows will shift to late summer. The ability to use the meltwater productively, however, depends on the capacity to store the high summer flows. The present hydropower infrastructure in Iceland will be able to use only 38% of the additional flows by 2050.

<sup>74</sup> Hydro-Québec Strategic Plan 2006-2010 at [http://www.hydroquebec.com/publications/en/strategic\\_plan/pdf/plan-strategique-2006-2010.pdf](http://www.hydroquebec.com/publications/en/strategic_plan/pdf/plan-strategique-2006-2010.pdf)

<sup>75</sup> [http://www.raunvis.hi.is/~sg/CE\\_report.pdf](http://www.raunvis.hi.is/~sg/CE_report.pdf)

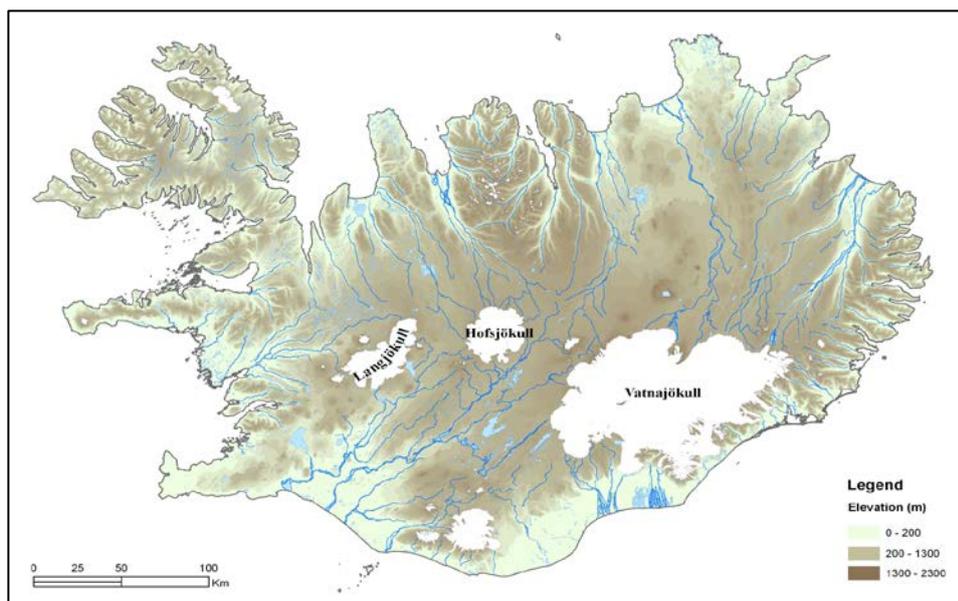


Figure 77: Storage in Iceland ice fields

### What are the responses available to possible changes in water quantity?

Firstly, it would be highly desirable to predict future runoff with more certainty. Efforts are ongoing to provide improved downscaled hydro-meteorological information, but there are some limits to predicting the climate. One reason is that a number of underlying parameters, such as the rate of future increase of greenhouse gases, are simply unknown. Planners may have to settle for less reliable hydrological information, specific for their sites, than they were used to in the past.

Planners should therefore accept a higher level of uncertainty and attempt to make projects more resilient and flexible to cope with such uncertainty. This can mean changes to both 'hard' and 'soft' components, infrastructure as well as operational rules. Examples for making infrastructure more resilient includes increasing the spillway capacity of dams, which is important for safety reasons. Increasing the generation and storage capacity will increase power output from flows that are more irregular than in the past.

At a regional level, where increased runoff is predicted as in the North and some other regions, this will provide incentives for increased hydropower investment. In other regions, the hydropower potential will be reduced.

Adaptation to changed quantities will be costly and might reduce the attractiveness of hydropower investments. This is particularly the case for private investors. Storage capacity is often seen as a primarily public, multi-purpose asset, and the incentives for private investors to pay for it are limited. Many private companies prefer to invest in run-of-river schemes. If and where these are subject to greater uncertainty in flows, investment may be reduced. For the public sector, general water security concerns will often play a greater role in decision-making than hydropower optimization concerns. Session 4.3 will provide more discussion on how hydropower can help with adaptation in the broader water resources sector. Where a reservoir is used for multiple purposes and inflows are variable, hydropower may be relegated to a secondary priority.

A role play exercise can give more insight into the dynamics of decision-making about water quantity allocations, given uncertain information (Brown et al 2010).

### 3.3 Session 3.3 Water Quality

Purpose and Learning Objectives	<p>The session provides an overview of the physical, chemical and biological quality of reservoir water. The determinants of quality and its evolution over time are reviewed. Both catchment erosion and reservoir sedimentation, and stratification, temperature and biogeochemistry are expected to change with climate. Management options to respond to such changes will be reviewed.</p> <p>Trainees will learn to appreciate that reservoirs may present some difficult quality management issues in the future.</p>
Key Reading	<p>Item 3.3.1 – Dortch (n.d.) Water Quality Considerations in Reservoir Management.</p> <p>Item 3.3.2 – Moss et al (2011) Allied attack: climate change and eutrophication.</p>
Content	<p>What are the key chemical, physical and biological characteristics of water?</p> <p>How does reservoir water quality develop over time?</p> <p>Which quality impacts are expected from climate change?</p> <p>How can reservoir water quality be managed?</p>
Key Aspects	<p>Water quality is generally not affected by run-of-river projects, but reservoirs can have a large impact on quality.</p> <p>Processes in catchments and reservoirs that determine water quality will be compounded by climate change.</p> <p>Quality can be managed through siting, design and operational choices.</p>
Discussion Topics and Exercises	<p>Group discussion:</p> <p>Is it possible for reservoirs to compensate for climate and land-use change, and provide close-to-historic water temperature and sediment loads? Can reservoirs make a river more 'natural' again?</p>
Additional Resources	<p>Item 3.3.3 - UNESCO-WHO-UNEP (1996) Reservoir Water Quality Assessments.</p>

Water quality is described by physical, chemical, and biological characteristics:

- Physical characteristics include temperature, turbidity, solids, color, taste, and odor.
- Chemical characteristics include inorganic minerals and indicators (i.e., pH, hardness, total dissolved solids, conductivity, adsorption ratio), organic materials and indicators (i.e. biological and chemical oxygen demand), and dissolved gases.
  - Biological characteristics include the larger flora and fauna as well as plankton (organisms that live in the water column and are incapable of swimming against currents). Plankton consists of: phytoplankton (algae; through photosynthesis they are producers), zooplankton (animals such as crustaceans, eggs and larvae of fish and worms; they are consumers), and bacterioplankton (recyclers).

Reservoir water quality is a function of the characteristics of the quality and quantity of inflows to the reservoir, and processes operating in the reservoir itself. There have been very few studies assessing the potential effects of climate change on river water quality, but those that have been undertaken suggest that changes in streamflow volume will have the biggest influence. Climate change is likely to alter the volume and timing of these streamflows into a reservoir system. Changes of water quality in the reservoir itself, given inflows from upstream, are then largely determined by the residence time and temperature profile of the water.

Water bodies in different latitudes and ecosystems vary greatly in water quality, due to the availability of light, temperature differences, and the type and quantity of nutrients – all factors that influence primary production. Water quality may also vary within different zones of a reservoir (Figure 79).<sup>76</sup>

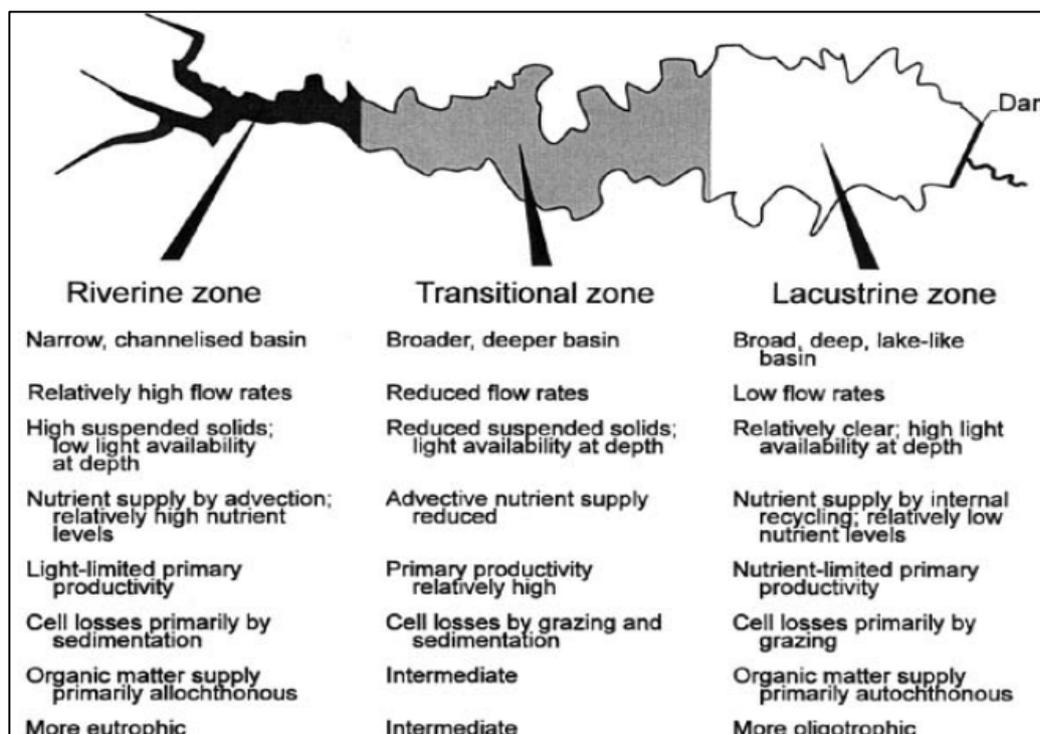


Figure 78: Longitudinal zonation of water quality conditions in reservoirs

Water quality in lakes is well studied; however, the data is of limited application to hydropower reservoirs. Reservoirs typically receive water from larger catchments, as compared to lakes, and are therefore more exposed to changes in hydrology, land use and river quality. Most lakes are located in northern latitudes (Figure 80), and the features in these systems are not always transferable to tropical reservoirs (Table 17).<sup>77</sup>

<sup>76</sup> UNESCO-WHO-UNEP (1996) Reservoir Water Quality Assessments

<sup>77</sup> Lewis (2000) Basis for the protection and management of tropical lakes.

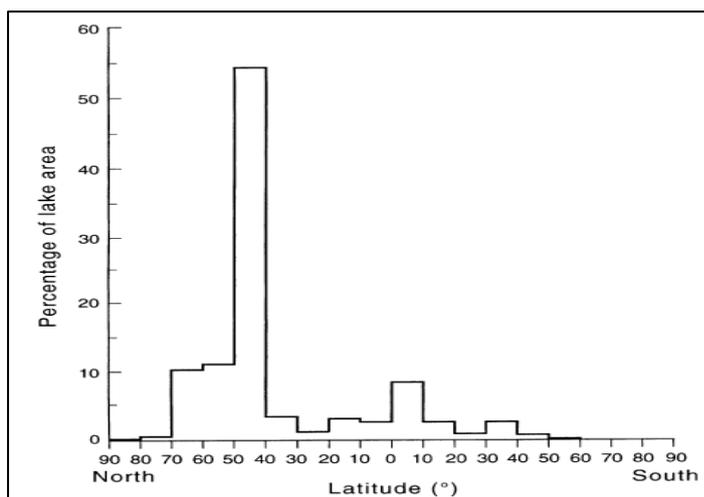


Figure 79: Lake distribution by latitude

Features of tropical lakes	Consequences	Implications
Natural lakes not abundant	Reservoirs of high relative importance	Management of reservoirs is of high priority
Glacier lakes scarce among natural lakes	River lakes are the predominant natural type	Status of rivers dictates welfare of most lakes
Predominantly warm monomictic	Predictable annual mixing season except in shallow lakes	Seasonal anoxia likely in deep water; seasonal cycle in water quality
High hypolimnetic temperature, long stratification season	High probability of hypolimnetic oxygen depletion	High vulnerability to eutrophication or organic loading
Recurrent changes in thickness of mixed layer	Recurrent nutrient enrichment of mixed layer	High efficiency of nutrient use; strong response to anthropogenic nutrient loading
Nitrogen limitation of autotrophs predominate over phosphorus limitation	Nitrogen pollution especially problematic	Denitrification of waste critical; phosphorus removal also important
Invertebrate predators favoured by anoxia	Herbivores consumed mostly by invertebrate predators	Low fish production per unit primary production; eutrophication may lower fish production
Planktonic and benthic biodiversity similar to those of temperate lakes	Analogies with temperate lakes closer than for terrestrial environments	Biodiversity protection challenging but less so than in terrestrial tropics

Table 17: Characteristics of tropical lakes and reservoirs

An important determinant of water quality is mixing. Mixing in reservoirs is largely controlled by stratification, i.e. the vertical positioning of water layers in order of their density with lighter (warmer, less dense) water forming above heavier (colder, denser) water. The layers resulting from stratification are termed epilimnion, metalimnion, and hypolimnion. The top layer is the epilimnion, a mixed zone with typically the highest oxygen content. Below the top layer is the metalimnion, a zone in which temperature changes at least 1°C per vertical meter (also called a thermocline). The bottom layer is the hypolimnion. It is fairly stagnant and can become anoxic due to bacterial decomposition of organic matter, which uses oxygen (Figure 81).<sup>78</sup> The more organic matter (such as in eutrophic lakes), the more likely is an oxygen deficit in the bottom layer.

<sup>78</sup> Lake.Access Project at <http://www.lakeaccess.org/ecology/lakeecologyprim4.html>

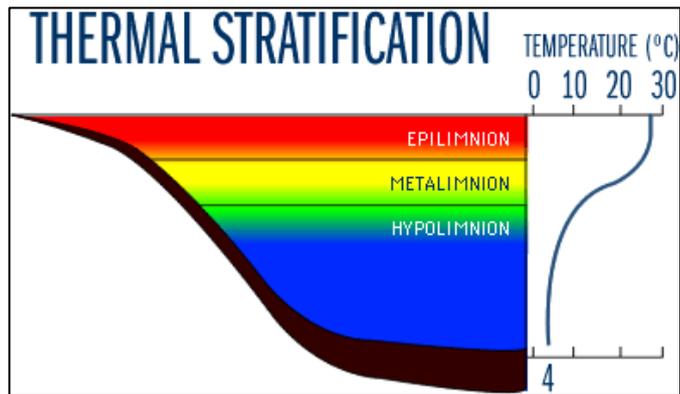


Figure 80: Thermal stratification in a reservoir

The development of stratification depends on flow, residence time, and topography as well as external energy dynamics (i.e., wind and solar radiation). One of the most useful ways of classifying lakes and reservoirs is by their mixing dynamics, i.e., how often mixing occurs between the surface and the deep waters (Figure 82).<sup>79</sup> In monomictic waters the mixing occurs once per year (either in the cold or in the warm season). In dimictic lakes the mixing occurs twice a year (typically spring and autumn). In polymictic lakes – which are usually shallow - the mixing occurs continuously or discontinuously, multiple times a year. (Amictic waters are under ice and never mix.)

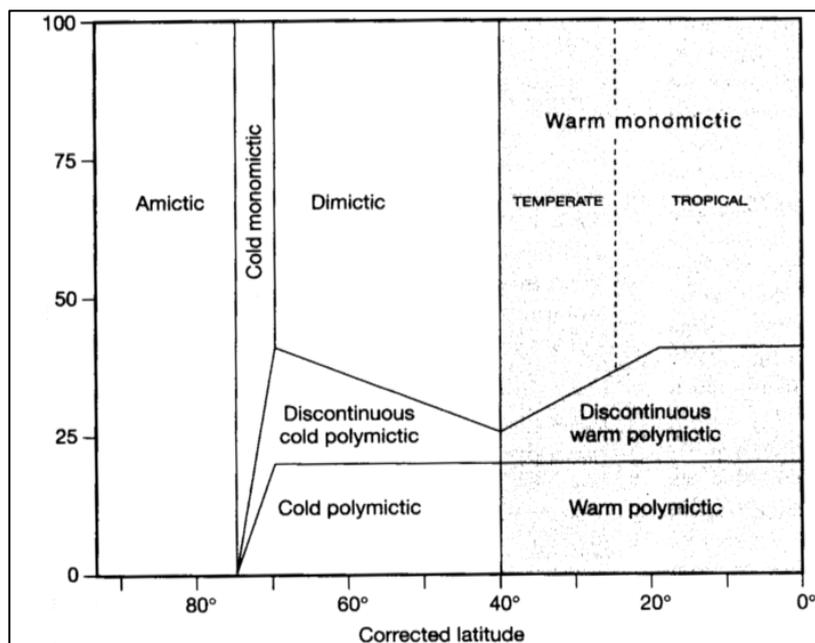


Figure 81: Typical mixing regimes of lakes as a function of latitude and depth

The example below in Figure 83 illustrates the monomictic condition typical of many warm water reservoirs.<sup>80</sup> In 1969 (left panel), mixing occurred in April-July as seen by the uniform temperature throughout the water column and oxygen reaching the bottom of the reservoir.

<sup>79</sup> Lewis, W.M., JR. (1983). A revised classification of lakes based on mixing. Can. J. Fish. Aquat. Sci. 40: 1779-1787

<sup>80</sup> Thornton (1982)

The right panel (1977 values) shows the same reservoir undergoing multiple annual mixings, a rare event in this reservoir.

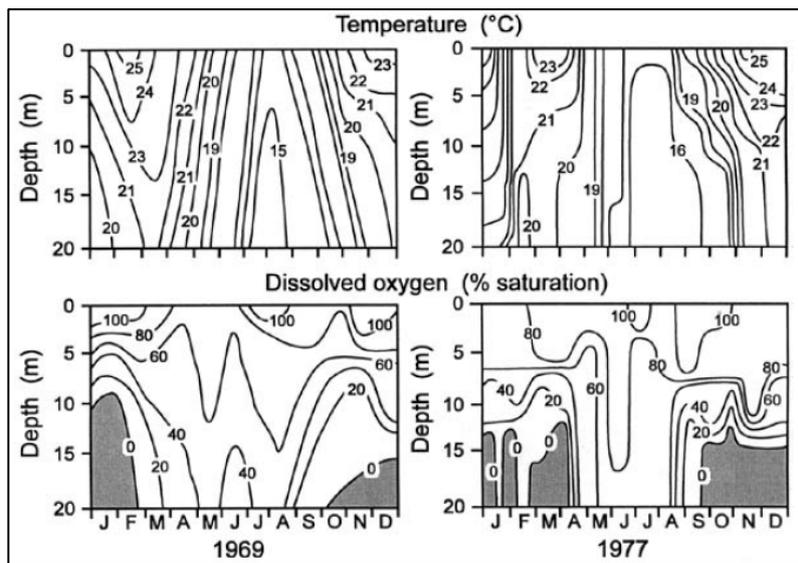


Figure 82: Monthly temperature and dissolved oxygen % saturation in Lake Chivero, Zimbabwe

So far we have described factors that influence reservoir water quality, and can now turn to how these factors are modified under climate change.

Climate change will affect the biological, chemical, and physical characteristics of water quality. For example, increases in the risk of algal growth and cyanobacterial blooms will result from higher temperatures, increased frequency and duration of heatwaves, and increased nutrient loading from extreme runoff events and reductions in mixing. Figure 84 shows the relationship between water temperature and cyanobacteria in Japanese reservoirs.<sup>81</sup> Also, increases in pathogen loads will result from increased temperatures and greater variability in inflow events. Increases in turbidity will be the outcome of greater droughts and flash floods. The frequency of hypoxia (“blackwater”) may increase as a consequence of changes in temperature, inflows, and land use. Changes in dissolved organic carbon load will result from the increases in temperature and runoff. Increases in temperatures will increase evaporation rates, which would lead to an increase in salinity. Other factors to consider include inhabitation by invasive species, land-use changes, and a different pattern of wildfires.<sup>82</sup> The complex interactions of the physical,

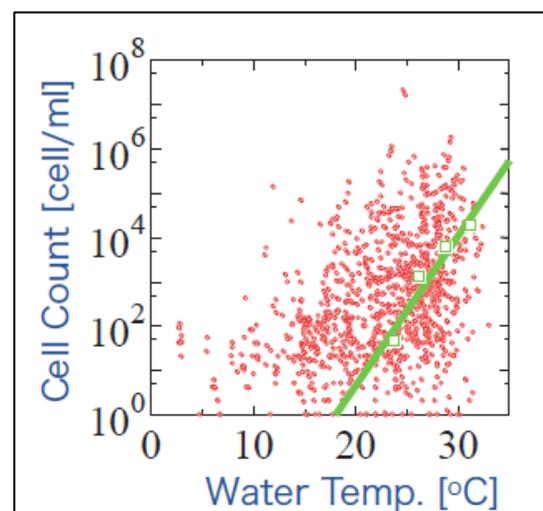


Figure 83: Blooming cyanobacteria (*Microcystis aeruginosa*) in Japanese reservoirs

<sup>81</sup> Umeda and Tomioka (2007) Water Quality in Reservoirs under a Climate Change

<sup>82</sup> Burch et al: WATER RF PROJECT 4468: Comprehensive assessment of the impacts of climate change on reservoir water quality in a range of climatic regions

biological, and chemical characteristics in both the stream inflow and reservoir waters make specific predictions difficult.

Algal blooms are a result of eutrophication, the aquatic ecosystem response to the addition of substances, such as nitrates and phosphates. Chlorophyll a, which is found in the cells of algae and other phytoplankton, is used to measure trophic levels. Oligotrophic systems contain very low levels of nutrients, which makes it difficult to sustain life. Mesotrophic systems contain moderate amounts of nutrients and are able to support some productivity. Eutrophic systems are rich in nutrients to support abundant productivity.

How will eutrophication be affected by climate change? As stated above, increased nutrients and higher water temperatures will cause an increase in cyanobacteria, which cause noxious blooms in water bodies. Warmer water will support higher densities of fish species that eat zooplankton, which normally feeds on and control algae populations. Zooplankton is also highly sensitive to warming water; its ability to control algae is diminished because zooplankton has a more difficult time feeding on and digesting cyanobacteria in warm waters. This reinforces the potential for harmful blooms (Figure 86; Moss et al., 2011).

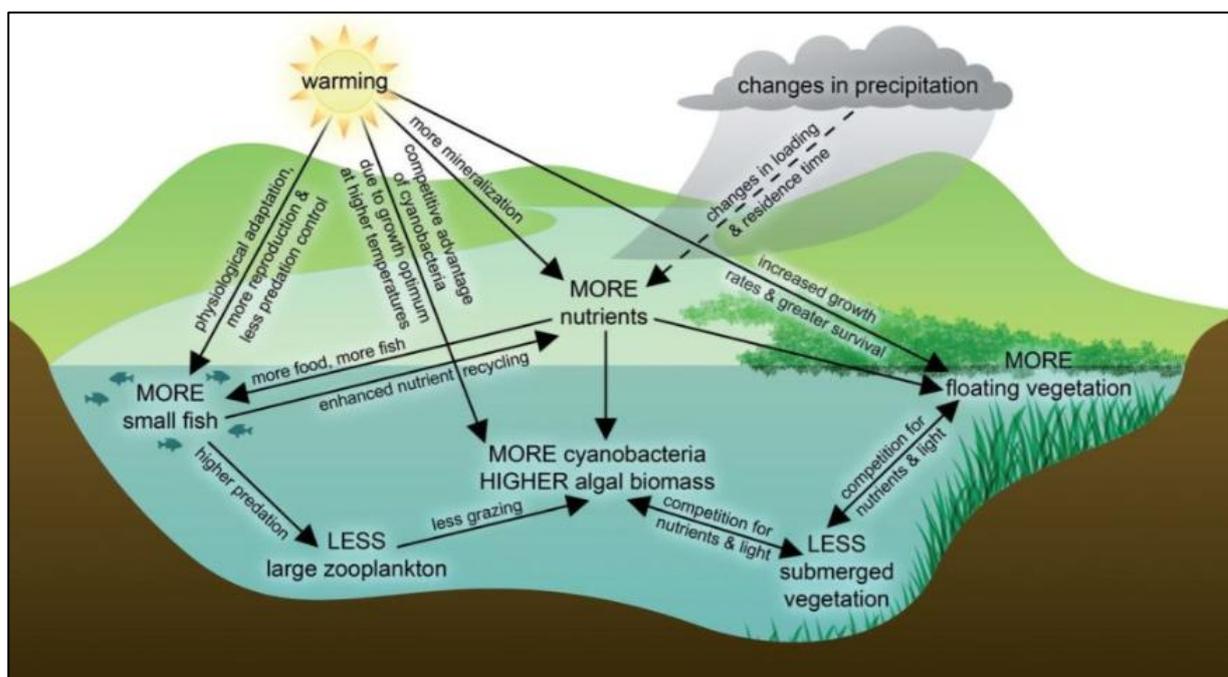


Figure 84: Eutrophication in a warming climate

The following graph shows the results of one predictive model for a reservoir, which predicts a rise in Chlorophyll a levels resulting from increased temperatures and reduced inflow rates:<sup>83</sup>

<sup>83</sup> Umeda and Tomioka (2007)

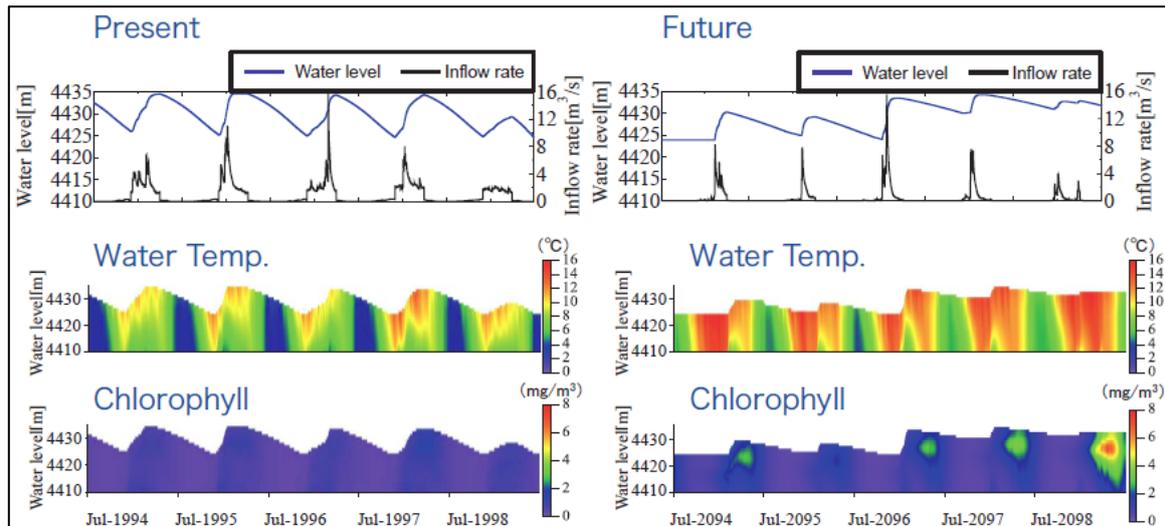


Figure 85: Modeled temperature and Chlorophyll a levels in Tuni Reservoir, Bolivia

The same effect is predicted in a study examining the future eutrophication of a sample of reservoirs in Japan:<sup>84</sup>

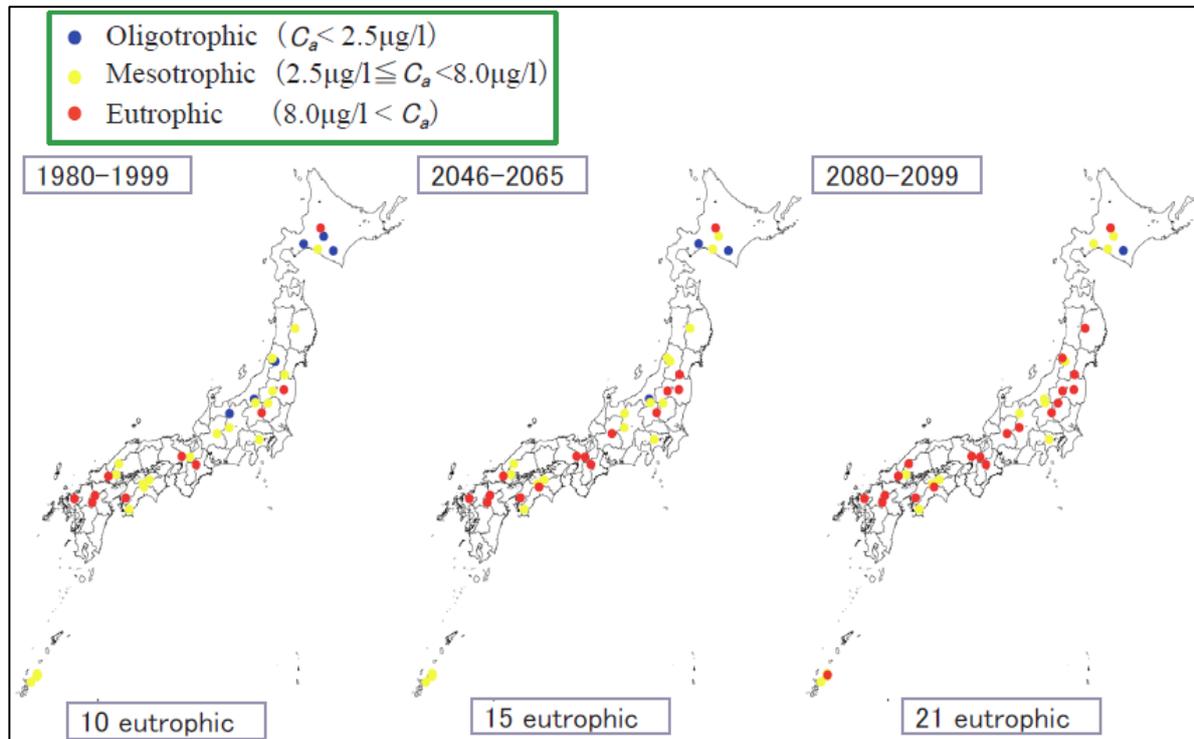


Figure 86: Future eutrophication of reservoirs in Japan.

Erosion and sediment load will also be impacted by climate change, as in the example from Thailand (Figure 88).<sup>85</sup> Soil loss is a function of precipitation, wind speed, storm frequency, soil characteristics, vegetative cover, and topography. Given similar vegetation and ecosystems, areas with high-intensity precipitation, more frequent rainfall, more wind, or

<sup>84</sup> ibid

<sup>85</sup> Plangoen et al (2013) Simulating the Impact of Land Use and Climate Change on Erosion in the Mae Nam Nan

more storms are expected to have more erosion. Of these weather factors, rainfall intensity is the primary determinant of erosivity.

The composition, moisture, and compaction of soil are all major factors in determining the erosivity of rainfall. Wet, saturated soils will not be able to absorb as much water, leading to higher levels of surface runoff. More compacted soils will have a larger amount of surface runoff than less compacted soils.

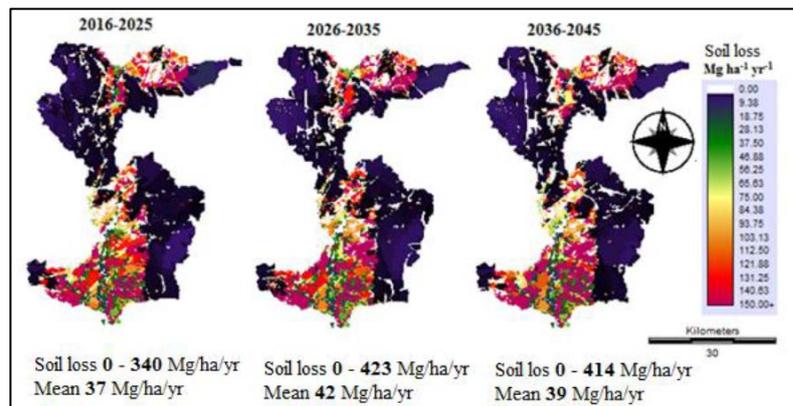


Figure 87: Predicted soil loss from 2016-2045

Vegetation increases the permeability of the soil to precipitation, thus decreasing runoff. It shelters the soil from winds, which results in decreased wind erosion, as well as advantageous changes in microclimate. The roots of plants bind the soil together, and interweave with other roots, forming a more solid mass that is less susceptible to both water and wind erosion. The removal of vegetation increases the rate of surface erosion.

The topography of the land determines the velocity at which surface runoff will flow, which in turn determines the erosivity of the runoff. Longer, steeper slopes (especially those without adequate vegetative cover) are more susceptible to high rates of erosion than shorter, less steep slopes. Steeper terrain is also more prone to mudslides, landslides, and other forms of gravitational erosion processes.

Yang et al. (2003) analyzed global soil loss potential using the Revised Universal Soil Loss Equation model coupled with a GIS model, based on land use, vegetation cover and climate change (doubling of CO<sub>2</sub> levels by 2090s) data. From the 1900s to the 1980s, the rates of soil loss have increased by about 1.5 t per hectare per year (i.e., by ~17%). The present global rate of soil loss is about 10.2 t per hectare per year. Yang et al. project that by the 2090s, soil erosion rates would increase by a further 14%. About 65% of this increase is the result of climate change and increased erosivity, and about 35% the result of population growth and changes in land use. Reductions in soil loss are predicted for North America and Europe as a result of land use changes, and additionally in North America due to climate change).<sup>86</sup> Figure 89 shows which world regions are most susceptible to erosion; the northern part of the Mekong basin does belong to these regions.

<sup>86</sup> Yang, D., Kanae, S., Oki, T., Koike, T. and Musiake, K. 2003. Global potential soil erosion with reference to land use and climate change. *Hydrological Processes*, Vol. 17. Chichester, UK, Wiley, pp. 2913–28.

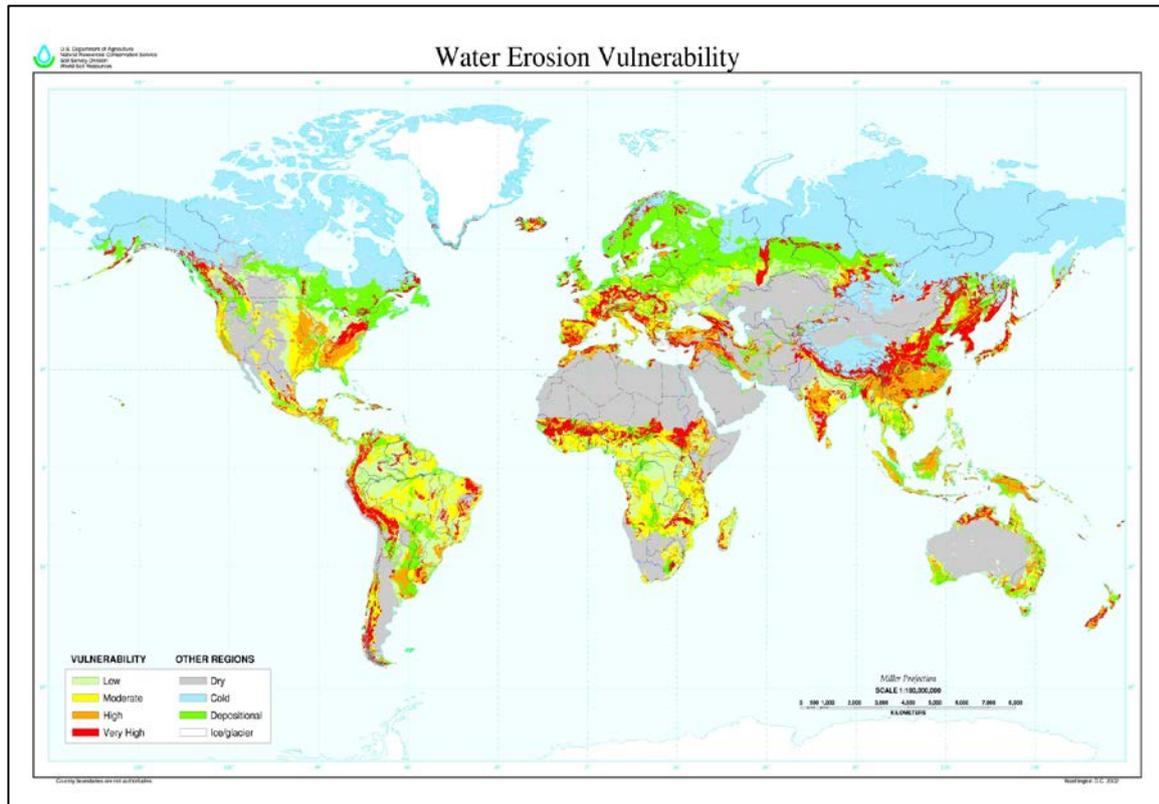


Figure 88: Water erosion vulnerability<sup>87</sup>

Several water resource management options are available to mitigate the effects of climate change on reservoir water quality. First, the improvement of inflow quality by managing point and non-point sources of nutrients will minimize eutrophication due to algal blooms. Managers can influence stratification by altering the depth of reservoirs and of intakes and thus influence density currents. Biological processes may be controlled to limit invasive species. Sedimentation may be managed through operational maintenance (dredging and flushing), influencing density currents, and protecting the watershed from erosion. Turbines and other outflows may also be manipulated to manage chemical processes such as oxygenation and degassing.

<sup>87</sup> [http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/maps/?cid=nrcs142p2\\_054006](http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/maps/?cid=nrcs142p2_054006)

### 3.4 Session 3.4 Planning Resilient Hydropower under Uncertainty

Purpose and Learning Objectives	<p>The session provides an overview of planning tools under climate change. The focus is on recommended changes to project feasibility studies (in particular, hydrological and financial studies) and to assessments of environmental and social impact and sustainability. Emerging planning approaches to deal with non-stationary hydrology will be introduced.</p> <p>Trainees will become familiar with the need for modifications to traditional planning instruments, but also the limits and uncertainties of long-term planning.</p>
Key Reading	<p>Item 3.4.1 – Major (1998) Climate change and water resources: The role of risk management methods.</p> <p>Item 3.4.2 – Byer &amp; Yeomans (2007) Methods for Climate Uncertainties in EIAs.</p> <p>Item 3.4.3 – Hallegatte (2009) Strategies to adapt to an uncertain climate change.</p>
Content	<p>What are the main tools for hydropower planning?</p> <p>How should planning tools be adapted?</p> <p>How do different adaptation and decision-making approaches apply to hydropower?</p>
Key Aspects	<p>All tools traditionally used for hydropower planning can and should be adapted to include climate change considerations.</p> <p>Terms of references for hydrological and financial feasibility studies should evaluate the sensitivity to climate change, and EIAs should include an analysis of ongoing changes (climate, population, land use etc.) in the project area.</p> <p>Planning approaches that accept the inevitable uncertainties and still deliver actionable advice are required.</p>
Discussion Topics and Exercises	<p>Group discussion:</p> <p>How could an EIA practically deal with the issue of 'climate refugia' for fish (suitable habitat for fish, which may move higher up in the same watershed, or into different watersheds at higher latitudes)? Are there other planning tools which would be required?</p>
Additional Resources	<p>To follow up on the ecological dimension of planning:</p> <p>Item 3.4.4 – Pittock et al (2008) Running dry: Freshwater biodiversity, protected areas and climate change.</p>

We have seen how climate change can cause significant changes to water quantity and quality, and also that hydropower engineers have many siting, design and operational options to deal with such changes. However, most hydropower planning today ignores climate change.

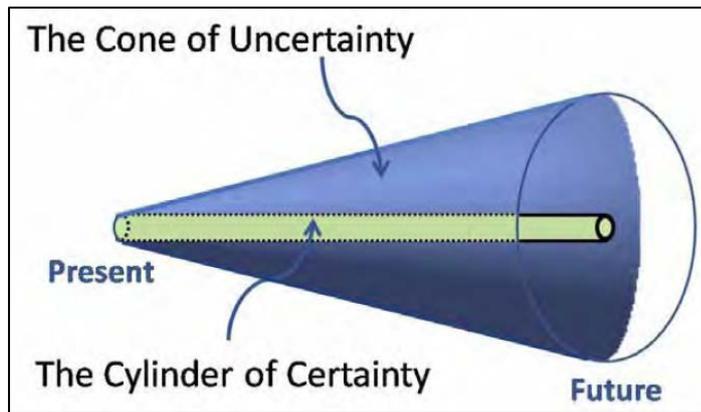


Figure 89: Planning for an uncertain future

Planning by its very nature deals with uncertainty. The future is always uncertain, in particular over long periods of time like the lifetime of a hydropower plant. Often however, planners assume that they can operate within a 'cylinder of certainty' where the range of uncertainty stays the same over time. In reality, uncertainty increases steadily with the time horizon of prediction, creating a 'cone of uncertainty'.<sup>88</sup>

There is a range of views among planners regarding the relevance of climate change. At one extreme, some would deny that climate change is happening or that it will affect their region at all. Others may agree that it is happening, but would say that it is too far into the future to worry about now. Many hydropower projects only have a 30 year concession, for example, and hope that they can understand the climatic conditions at least for that period. Indeed, climate change effects will take time to become more obvious. As the European Environment Agency has expressed it, "most water ... planning horizons end before the 2050s, the point at which climate-driven changes ... are expected to emerge from natural variability."<sup>89</sup>

Other planners would say that they have always dealt with variability, and that they do not need to change their planning approaches fundamentally: "Water management is all about managing climate variability. Climate change and increased climate variability will only transform boundary conditions for water managers. Many water managers consider that such changing boundary conditions will not dramatically influence their basic approach."<sup>90</sup> Finally, there is an increasing number of planners who are arguing for a clean break with the past, and who are looking for new approaches: "In view of the magnitude and ubiquity of the hydroclimatic change apparently now underway, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning."<sup>91</sup>

To ignore climate change appears unsatisfactory because (a) climate-driven variability may arrive sooner and take other forms than expected, and (b) the lifetime of projects will often be longer than the planning horizon. Current planners have a responsibility beyond the next 30 years, as water infrastructure will continue to be in service beyond that. But it is often not clear by how much the 'boundary conditions' should be changed or what should replace the assumption of 'stationary' hydrology.

<sup>88</sup> Waage, M. (2010) Nonstationarity Water Planning Methods. In: Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management. Boulder, CO at <http://www.cwi.colostate.edu/publications/is/109.pdf>

<sup>89</sup> European Environment Agency (2007) Climate change and water adaptation issues.

<sup>90</sup> van Beek (2009) Managing Water under Current Climate Variability, author of chapter in 'Climate Change Adaptation in the Water Sector', edited by F. Ludwig, P. Kabat, H. van Schaik and M. van der Valk, Earthscan, UK.

<sup>91</sup> Milly et al (2008) Stationarity is dead.

This session deals with emerging ideas how climate change should be taken into account, in planning documents and approaches.

Large infrastructure projects, such as hydropower stations, require the development of a number of documents as steps in the planning process; many of these may also be legal requirements:

- Masterplan
- Electricity generation expansion plan
- Strategic environmental assessment
- River basin development plan
- Project identification / pre-feasibility study
- Feasibility study (sometimes with multiple sub-studies, such as hydrological studies)
- Detailed design
- Environmental and social impact assessment
- Environmental and social management plan
- Sustainability assessment
- Construction plan
- Operations plan

A systematic approach should be implemented to accomplish these plans, studies, and analyses in a climate-aware manner. We will focus here on hydrological studies, EIAs and sustainability assessments.

Hydrology must be addressed as part of design, safety, and sensitivity analyses. These include at a minimum, even for small projects: the average flow duration curve that is the basis for the calculation of average annual generation and determination of the design discharge; the flow duration curve of the driest year on record for the sensitivity analysis (to check whether debt can be serviced even during droughts); correction factors considering quality of data base (to assess the sensitivity against variations of water availability and the influence of missing or vague data); environmental flow requirements; and estimated flood events and water levels (to design the hydraulic structures safely).

For larger projects that have more resources available for planning, <sup>92</sup> first, baseline assessments are performed based on reliable, available information. Then, standard trend analyses are conducted for existing hydrological records. (This is empirical evidence, and does not depend on modeling.) Next, scenario projections for the particular region in question should be obtained from global climate models (or regional models, if such are available). All available outputs that could serve as input to next tier models (e.g., hydrological simulation models) are important.

If sufficient data are available, runoff scenarios can be built with deterministic hydrological models (option 1). The focus should be on quantity (annual volumes), seasonal distribution, and variability as the main outputs. Potential changes in environmental flow requirements should be assessed.

If there are insufficient outputs from the climate models as input for deterministic hydrological models (option 2), and also as an alternative approach for control purposes, planners can revert to the use of statistical models.

The outputs from options 1 and 2 can be used in simulation models, and probabilistic techniques can be applied for assessing the impacts of the various flow scenarios on water

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<sup>92</sup> This approach is derived from Vattenfall Power Consultants AB (2007) Addressing Climate Change-Driven Increased Hydrological Variability in Environmental Assessments for Hydropower Projects – a Scoping Study for World Bank.

resources. Other, and often competing, water uses should be included in these simulations. This will then allow an assessment of the impacts on hydropower plant and reservoir operating rules and, hence, on the potential for hydropower generation. This allows normal economic and risk analyses. Lastly, but perhaps most importantly, because of the uncertainty, an adaptive-management approach is required that includes regular monitoring, evaluations and reviews, with possible redesign of the management program, as found necessary. This needs to be based on a reliable set of indicators.

Feasibility studies increasingly include testing for sensitivity to climate change, as for the Trung Son project in Vietnam (Figure 91).<sup>93</sup> The simplest way to do this is to test the impacts of increases or decreases in generation. In this case, generation would have to drop by an unrealistically large amount (to 36% of projected generation) before the economic rate of return drops below 10% (the 'hurdle rate') and the project becomes economically unfeasible.

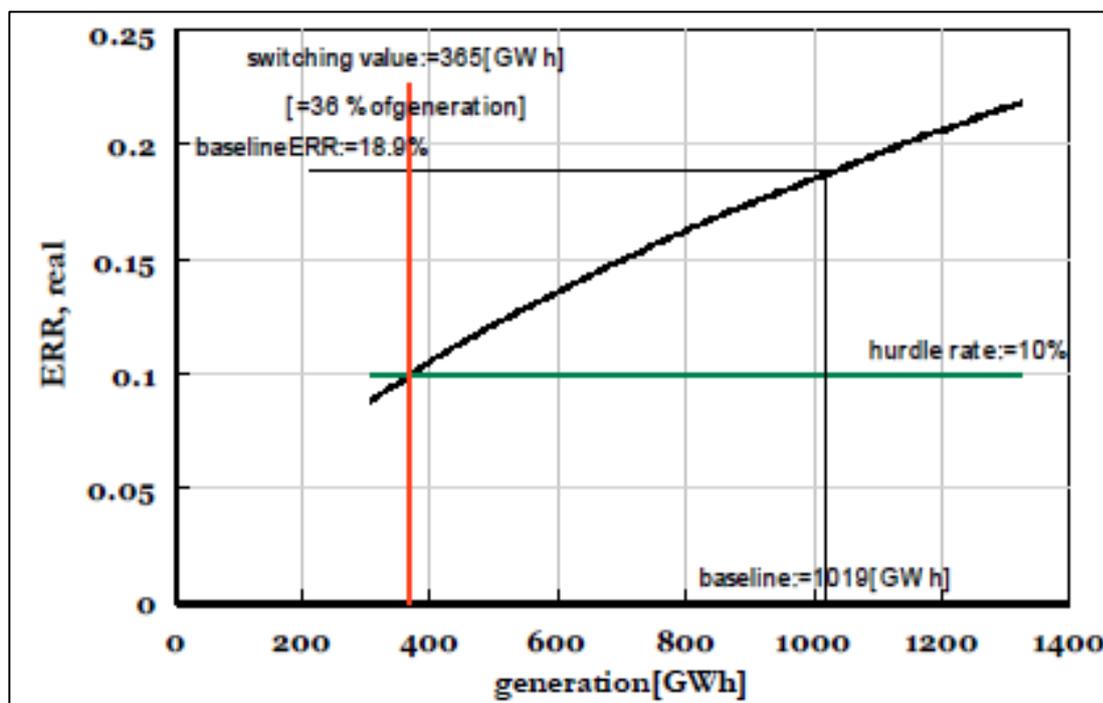


Figure 90: Sensitivity of economic returns to generation

Climate change that is likely to affect the environment and social conditions in the project area must be evaluated in Environmental Impact Assessments (EIAs). Project impacts that are acceptable in today's environment may not be acceptable in a future environment, or vice versa. In addition, impacts traditionally assessed as part of a project evaluation may be cumulative when considered with impacts of climate change. Thus climate change effects should be incorporated into EIAs. Possible ways that this could be accomplished include:<sup>94</sup>

- Scenario analysis – choose a representative sample of possible future scenarios and investigate impacts on the project and its environment

<sup>93</sup>

[http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2011/04/07/000356161\\_20110407010926/Rendered/PDF/579100PAD0P0841OFFICIALOUSEONLY191.pdf](http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2011/04/07/000356161_20110407010926/Rendered/PDF/579100PAD0P0841OFFICIALOUSEONLY191.pdf)

<sup>94</sup> Byer & Yeomans (2007)

- Sensitivity analysis – choose a set of changes in parameters and investigate their impacts on the project and its environment; in particular, whether any thresholds may be crossed and whether the project or its environment are vulnerable
- Probabilistic analysis: identify uncertain risk factors; appraise the likely range and probability distributions of these risk factors; simulate system performance with parameters sampled from the probability distributions developed for the various risk factors; and summarize results of the analysis in a risk profile for system performance.

For sustainability assessments the current tool of choice is the Hydropower Sustainability Assessment Protocol (IHA 2010). Because climate change has many different dimensions, it is referenced in various topics in the Protocol. Demonstrated Need & Strategic Fit (P-3) addresses water and energy needs that may have strong climate change drivers - for example, the need to have low carbon energy options and the need to mitigate climate-induced changes to water supply. Siting & Design (P-4) includes consideration of a range of issues including the potential for greenhouse gas emissions. Financial Viability (P-9) depends on runoff and includes carbon finance as an option for finance. Hydrological Resource (P-7, O-4) includes understanding hydrological trends and long-term water availability that may be influenced by climate change. It also includes the ability of the project to anticipate and adapt to any hydrological changes. Reservoir Planning (P-22) includes reference to vegetation clearance, which may or may not be undertaken for the purpose of addressing greenhouse gas emissions. (There is no specific requirement to assess greenhouse gas emissions from reservoirs in the 2010 version of the Protocol because there is no established methodology as yet to do this; it is anticipated that it could be built into the Protocol in the future when a methodology is determined.)

“Best practices” as defined by the Protocol includes a broad understanding of issues, attention to emerging risk and opportunities, monitoring, and adaptive management. Specifically, in the topic Management of the Hydrological Resource (P-7), best practice requires that

- “an assessment of hydrological resource availability has been undertaken utilizing available data, field measurements, appropriate statistical indicators, and a hydrological model; issues that may impact on water availability or reliability have been comprehensively identified; and **uncertainties and risks, including climate change, have been extensively evaluated over the short- and long-term**”; and
- “a plan and processes for generation operations have been developed to ensure efficiency of water use, based on analysis of the hydrological resource availability, a range of technical considerations, an understanding of power system opportunities and constraints, and social, environmental and economic considerations including downstream flow regimes. **Generation operations planning has a long-term perspective**; takes into consideration multiple uses and integrated water resource management; fully optimizes and maximizes efficiency of water use; and **has the flexibility to adapt to anticipate and adapt to future changes.**”

Waage (2010) has described four standard water resource planning methods which can incorporate climate change (Figure 92):

Traditional scenario planning seeks to identify near-term actions that prepare a utility for several different, plausible future scenarios. The goal of this approach is to develop a range

of future scenarios that go beyond extrapolation of current trends and represent plausible conditions. Typically, scenarios are treated as equally likely to occur. Implications and future needs for each scenario are identified and adaptation strategies are developed. Signposts can be established to monitor the development of the scenarios and determine when adaptation measures are no longer common to all or most scenarios. A benefit of traditional scenario planning is that those involved in the planning process do not need to agree on a single future when developing the plan.

Classic decision analysis supports utility planners by systematically cataloging information and mathematically evaluating and ranking decision alternatives against multiple, decision objectives. The process is illustrated through decision trees or influence diagrams. Uncertainty is handled through the use of probabilities. Classic decision analysis is used to find a preferred plan with the best value.

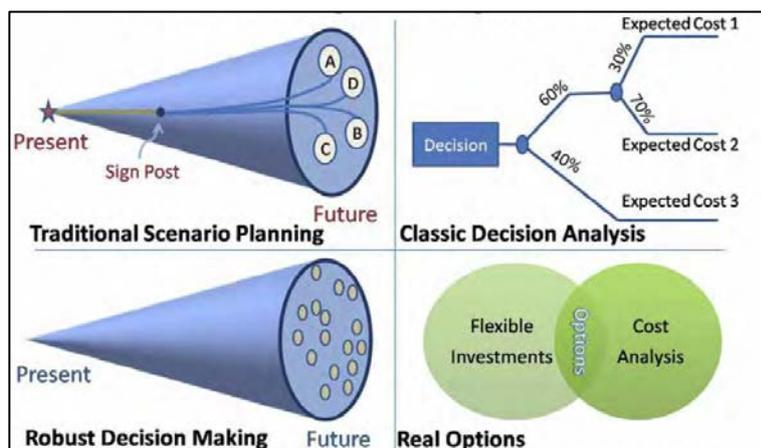


Figure 91: Planning methods

Classic decision analysis techniques have been used in some water planning applications for many years. When considering climate change uncertainty, though, assigning probabilities to future conditions can be difficult and hard to defend.

Robust decision making uses complex modeling processes and combines features of both decision analysis and scenario planning to develop adaptation hedging strategies for a large number of future conditions. The approach provides a systematic way of developing a water management strategy to best adapt to a wide range of plausible future conditions. Robust decision making is particularly useful when agencies want to examine uncertainties that cannot easily be assigned probabilities. Also, it does not require agreement by decision makers, experts, or stakeholders on the likelihood of different future conditions occurring. The method is most useful when there are many decision alternatives and a detailed analysis of every possible alternative is not possible.

Real options is a method to help water managers identify strategies that adjust over time and balance risks. Flexible investment strategies are sought that can be risk-adjusted with time and deferred into the future. Uncertainties in real options are handled through the use of probabilities. Results are flexible in that they may incorporate delaying and phasing of projects.

Others are distinguishing between prediction and resilience oriented approaches. Prediction oriented approaches to adaptation focus on characterizing, reducing, managing and communicating uncertainty, resulting in increasing sophisticated modelling tools and

techniques to describe future climates and impacts. Once the future climate is made predictable, a piece of infrastructure can be designed for it. Some observers are criticizing the prediction oriented approaches for creating a false sense of certainty. Relying on climate models and projections, too many planners are just replacing historic flow data with model-generated future flow data. However, these may not be valid for planning because

- more than one climate may exist over the lifetime of a project,
- the scale of GCMs is not decision-relevant (i.e. the cells in a GCM are different from a catchment area), and downscaling is imperfect,
- the differences between the projections of different GCMs remain large,
- the main driver of the GCMs – the GHG emissions - remain difficult to predict,
- and the usual scientific mechanism to improve models (to check predictions against observed data) does not work well, because these models are so long-term that climate observations will only be available decades from now, too late to confirm or reject models that are required for decisions today.

Resilience oriented approaches to adaptation are accepting that some uncertainties cannot be reduced, and emphasize learning from experience. A planner would hesitate to commit to a certain design, and would value the option to change the design at a later stage. This may require some technical preparation, but the cost of this may be seen as the price of flexibility.

As an example, water resource engineers can apply these concepts in the design of a dike. A prediction-oriented approach would calculate an engineering safety margin to manage uncertainties in physical processes that will influence the level of a waterbody:

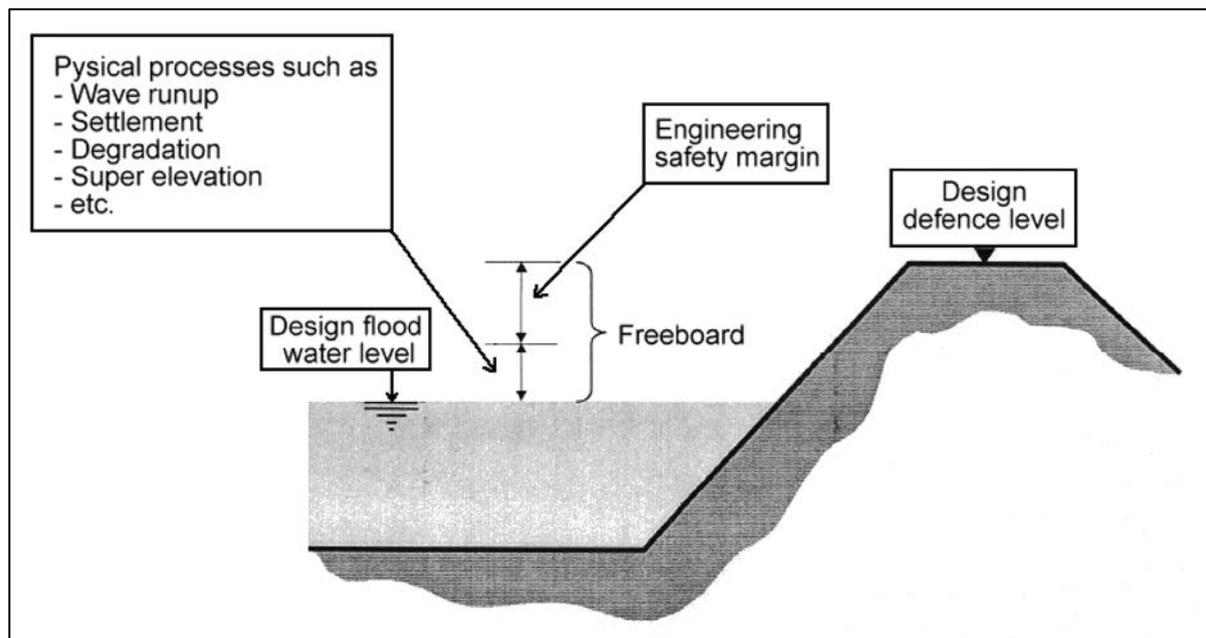


Figure 92: Prediction oriented approach to adaptation<sup>95</sup>

A resilience-oriented approach might factor in an additional margin on top of the engineering margin in order to account for any long term scenarios that may be hypothesized (for example, in the case of coastal dikes, a higher-than-expected sea level rise). Because it is unknown at this stage whether the additional margin is necessary, a stronger foundation is

<sup>95</sup> Dessai and van der Sluijs (2007) at [http://www.aguaycambioclimatico.info/biblioteca/CC\\_2045.pdf](http://www.aguaycambioclimatico.info/biblioteca/CC_2045.pdf)

built so that the dike can be raised in the future, and the inside of the dike is protected from intrusions. (One of the problems that made New Orleans so vulnerable to the storm surge from Hurricane Katrina, was that the dikes could not be raised as people had built their houses too close to the dike.)

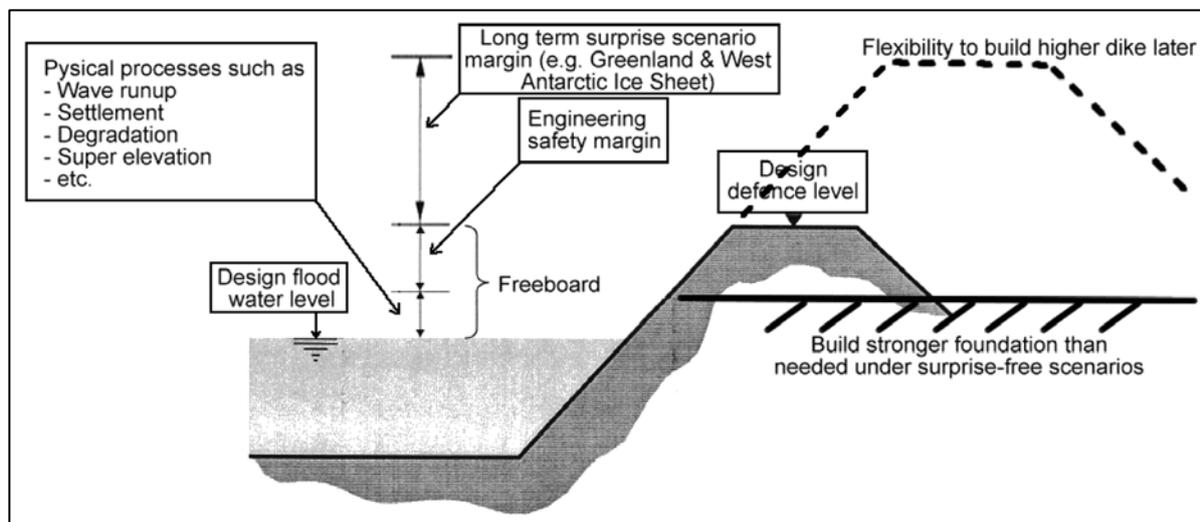


Figure 93: Resilience-oriented approach to adaptation<sup>96</sup>

There is broad agreement that planners should look for robust designs that can deal with a broader range of climate conditions. In general, more robust design are those that are no-regret (yield good results under all circumstances), reversible (at low cost), include safety margins, rely on soft rather than hard instruments (for example, a new operational strategy instead of a physical retrofit), or reduce the decision-making time horizons. Some of these principles may be applicable to some degree on hydropower.

An early summary of water resource planning recommendations under climate change still appears to include the most relevant recommendations:<sup>97</sup>

- Interconnection of systems to provide additional backup for changing regional conditions.
- Incremental construction where possible and economically feasible (e.g., a number of small systems rather than one large one) to allow for adaptation to changing circumstances.
- Choice of robust designs in which the chosen design will be fairly good under a wide range of outcomes rather than optimal under one outcome.
- Postponement of irreversible (or very costly to reverse) decisions.
- Use of a range of formal decision techniques, including scenario analysis, sensitivity analysis, Monte Carlo methods, and others.
- Designing for extreme conditions. Using historical or synthesized flows, the water resource planner can suggest approaches that deal with extreme events (floods and droughts) rather than simply maximizing the expected value of net benefits.
- Reallocation of storage. After projects are constructed, and circumstances change, storage can be reallocated to improve project performance under changed climatic conditions.

<sup>96</sup> ibid

<sup>97</sup> Major (1998)

- Reallocation of supply through the development of water markets.
- Development of non-structural measures such as warning systems. Flood and storm warning systems (inland and coastal) can be used to adjust to the risks and uncertainties of flooding.
- Demand management measures. These measures, such as implementing pricing schemes, requiring low-demand appliances, or formulating drought contingency plans, can be used to control demand and thus provide a measure of safety in available supplies.
- Preservation of ecosystems. As an adjustment to uncertainty, areas can be reserved to protect against the uncertain effects of climate change on ecosystems.

Many of these recommendations fall under the 'robust' approaches described above. However, there is as yet very little documented experience in the application of these principles to hydropower planning.

## 4 MODULE 4. HYDROPOWER AND ADAPTATION

### 4.1 Session 4.1 Adaptation to Changes in Water and Electricity Demand

Purpose and Learning Objectives	<p>This session provides an overview of 3 key climate-driven changes which can be expected in the water and electricity sector, and the need of the hydropower sector to adapt to such changes: rising demand for cooling; rising evaporation from reservoirs; and rising water demand from other sectors such as irrigation.</p> <p>Trainees will be able to understand the multiple pathways through which climate change affects hydropower, beyond the more obvious hydrological determinants.</p>
Key Reading	<p>Item 4.1.1 – Cox (2013) Cooling a warming planet.</p> <p>Item 4.1.2 - Parkpoom et al (n.d.) Climate Change Impacts on Electricity Demand in Thailand.</p> <p>Item 4.1.3 – Mekonnen and Hoekstra (2012) The blue water footprint of electricity from hydropower.</p> <p>Item 4.1.4 – Doell (2002) Impact of Climate Change and Variability on Irrigation Requirements.</p>
Content	<p>Besides changes in hydrology, what other changes will hydropower be exposed to?</p> <p>How sensitive is electricity demand for cooling to climate change?</p> <p>How sensitive is evaporation from reservoirs to climate change?</p> <p>How sensitive is water demand for other sectors to climate change?</p>
Key Aspects	<p>The demand for all forms of electricity, including hydropower, for cooling purposes will increase.</p> <p>Hydropower has to adapt not only to changing runoff, but also to other changes in the watersheds that are likely to reduce water availability.</p>
Discussion Topics and Exercises	<p>Watch <i>Deutsche Welle</i> video on Toshka Lakes project (6:23 min). Discuss Egypt's water management choices under climate change.</p>
Additional Resources	<p>Item 4.1.5 - Mideksa and Kallbecken (2010) The impact of climate change on the electricity market.</p>

This session looks at climate change affecting the hydropower sector via multiple pathways. In earlier sessions, the hydrological and environmental effects were discussed, which are traditionally the focus of attention. Commercial changes (through mitigation policies) will be covered in session 4.2. In this session, three other impacts which are potentially relevant in South East Asia will be analyzed:

- changes in electricity demand (through increased cooling requirements),
- changes in evaporation from reservoirs, which may make reservoirs less attractive, and

- changes in water demand (especially irrigation) which may reduce water availability for hydropower.

The degree to which electricity demand in a given country is sensitive to changes in climate depends on its climate type, its energy mix, and the level of its economic development. The impact on electricity demand also depends on the mix of resources used for heating and cooling. Cooling systems such as air conditioning require more energy than a similar amount of heating. Other heating options exist, such as wood and gas, whereas cooling can only be powered by electricity.

Electricity demand displays a significant elasticity to temperature changes. Temperature changes will have a different impact on electricity demand depending on location and local climate. A warming climate at high latitudes will tend to reduce heating demand (heating effect) whereas a warming climate at lower latitudes will increase cooling loads (cooling effect). This means that climate change will increase electricity demand, but overall energy use could instead decrease. It has been estimated that by the year 2100 the benefits of climate change in the energy sector (reduced heating) will amount to 0.75% of GDP globally, whereas the damages (increased cooling) would be approximately 0.45%.<sup>98</sup>

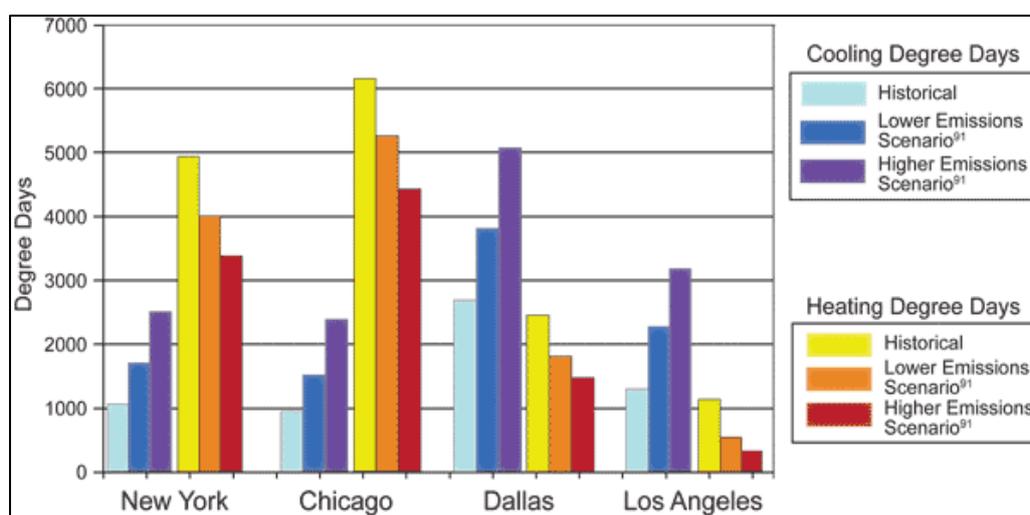


Figure 94: Energy demand sensitivity to climate change

As an example for these effects, Figure 93 shows how climate change will affect the need for heating or cooling in four cities with different climates in the United States.<sup>99</sup> A degree-day refers to the sum of the number of degrees that the day's average temperature is hotter or colder than the base temperature (~18-22° C, i.e., where no heating or cooling is required). For example, historically, New York has almost 5000 heating degree-days/year, where heating sources were required because the temperature was below base temperature. Under the more severe climate change scenario, the number of heating degree-day will decline to ~3200. Historically, New York experienced ~1000 cooling degree-days, where cooling sources were required because the temperature was above base temperature. Under the more severe climate change scenario, the number of cooling degree-days will more than double to ~2500.

<sup>98</sup> Mideksa & Kallbecken (2010)

<sup>99</sup> United States Global Change Research Program. <http://www.epa.gov/climatechange/impacts-adaptation/energy.html>

As temperatures change, consumers will adjust their behavior regarding electricity demand. Table 18 shows the impact of a 1% increase in temperature on electricity demand, under different conditions.<sup>100</sup>

	Warm Countries	Cold Countries
Summer	1.17	- 0.21
Winter	0.10	- 0.07

Table 18: Elasticity of electricity demand to temperature

Figure 94 graphically displays an example of this relationship between electricity demand (GWh) and a temperature index (°C), on weekdays in 1998 in Spain.<sup>101</sup> The slopes of the curves to the left and to the right of the base temperature (~19°C) indicate elasticity.

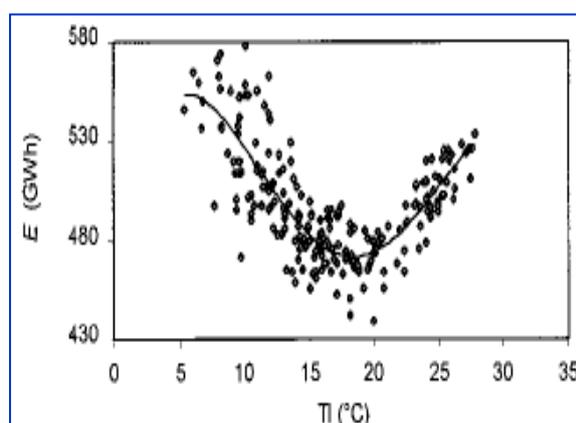


Figure 95: Elasticity of electricity demand to temperature

In the short term people will work with their existing capital stock and will want to maintain the temperatures they are used to. In the long term people can adapt their temperature sensitivity and can purchase new heating or cooling equipment. Therefore, the long term elasticity is expected to be lower.

These principles can be applied to short- and long-term changes in electricity demand in LMB countries, for example in Thailand. Through quantitative modeling and analysis, it was shown that a 4°C temperature rise increases demand by 1400 MW (a quantity equivalent to 2.6%/°C at system peak demand). This was derived from a strong correlation between demand and temperature (Figure 95). Further, studies found that in developing nations there is a good correlation between growth in GDP and electricity demand. For example, Figure 96 shows Thai GDP and demand growth over the period from 1994 and as forecast until the end of 2004, which have been found to have a correlation coefficient of 0.77.<sup>102</sup> Thus, forecasts of future electricity demand growth need to take account of both future economic growth and climate change.

<sup>100</sup> Mideksa & Kallbecken (2010) Impact of climate change on the electricity market.

<sup>101</sup> Valor et al (2001) Daily Air Temperature and Electricity Load in Spain.

<sup>102</sup> Parkpoom et al (n.d.) Climate change impacts on electricity demand.

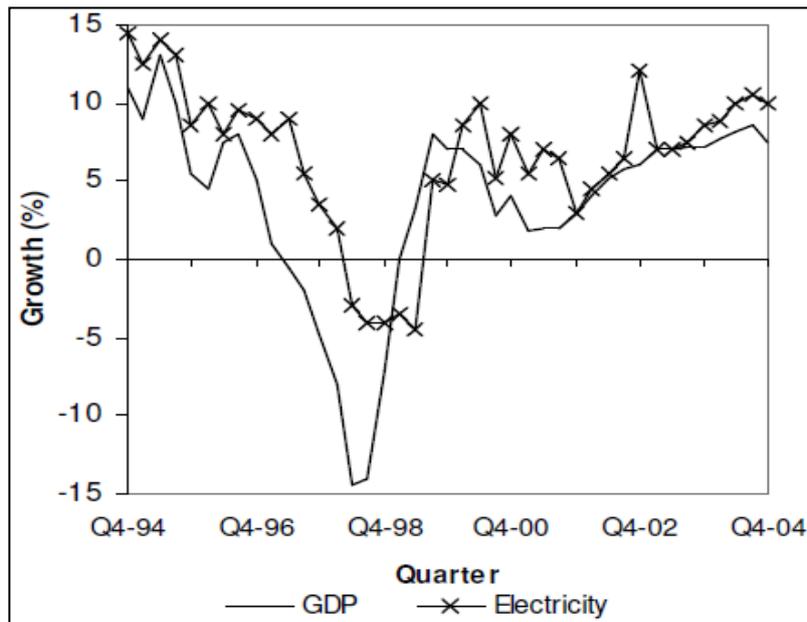


Figure 96: Thai peak demand versus temperature (short term)

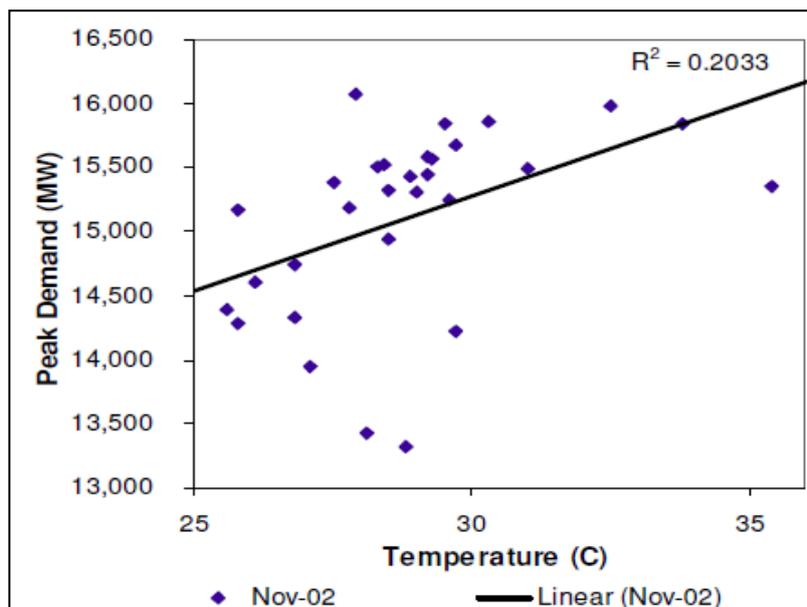


Figure 97: Thai GDP and electricity demand growth (medium term)

Increasing evapotranspiration (ET) is another effect of climate change that will impact hydropower development, especially in South East Asia. It is composed of ‘evaporation’ (a physical process, free water becoming vapor) and ‘transpiration’ (a biological process, water stored in plants becoming vapor). Potential evapotranspiration (PET) is the expected ET if water is not limiting. Actual evapotranspiration (AET) is the amount of water that is actually lost. The ratio of ET to PET is low in arid areas due to water limitations and ET is approximately equivalent to PET in humid areas (Table 19).<sup>103</sup>

<sup>103</sup> Arnell and Hulme (2000) Implications of climate change for large dams and their management. Working paper prepared for the World Dam Secretariat.

Annual amount (mm/a)	Tropical humid (Singapore)	Arid (Iraq)	Temperate humid (Netherlands)
Precipitation	2500	150	750
Open water evaporation	1500	2250	650
Potential ET	1400	1800	525
Actual ET	1200	100	450

Table 19: Precipitation, evaporation, and evapotranspiration rates for various climates

Evaporation affects the entire catchment above a hydropower station, but here we will focus on evaporation from the reservoir.

Reservoir evaporation is a function of the climatic controls on the rate of evaporation (i.e., net radiation, humidity, wind-speed, and temperature) and also of the amount of heat stored in the reservoir. Also important in some reservoirs is the stability of the air column, and hence upward transport of water vapor, which is affected by the difference in temperature between the air and the water surface.

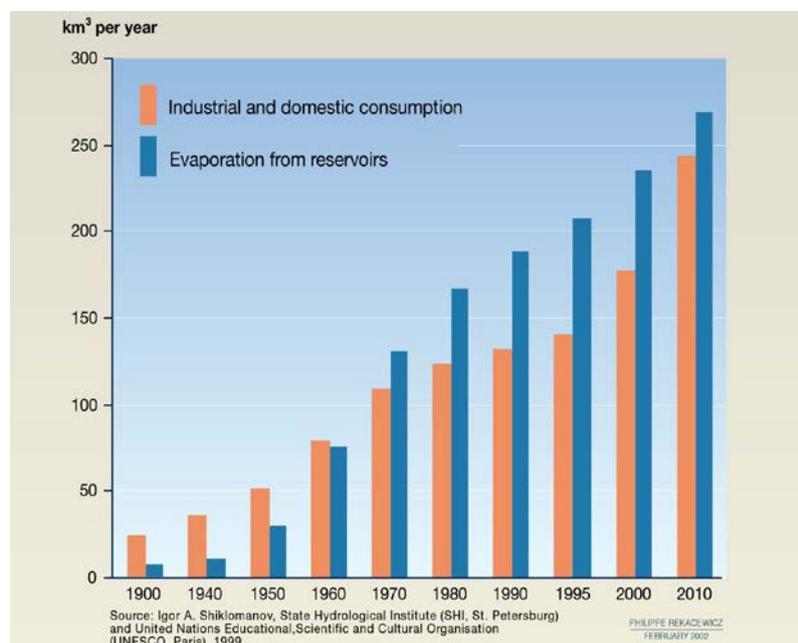


Figure 98: Global reservoir evaporation compared to industrial and domestic consumption of water

Very few studies have considered the implications of climate change for evaporation from lakes and reservoirs. Croley assessed the implications of a change in climate for the Great Lakes.<sup>104</sup> He showed substantial increases in lake evaporation, attributed to large increases in the amount of heat stored in the lakes throughout the year. The paucity of other studies

<sup>104</sup> For example, at [ftp://ftp.glerl.noaa.gov/publications/tech\\_reports/glerl-126/tm-126.pdf](ftp://ftp.glerl.noaa.gov/publications/tech_reports/glerl-126/tm-126.pdf)

regarding the sensitivity of reservoir evaporation to climate change means that effects are generally only estimated very roughly at present. For example, the Zambezi River Authority established that evaporation from hydropower reservoirs is by far the largest water use in the basin (16.46% of runoff), but in projections for 2025, only included additional reservoir surface areas, but not higher evaporation rates. There was also no consideration for changes in runoff (Table 20).<sup>105</sup>

	Mm <sup>3</sup>	%
Available run off	103,224	100
Rural domestic consumption	24	0.02
Urban domestic consumption	175	0.17
Industrial consumption	25	0.02
Mining	120	0.12
Environmental/ flood releases	1,202	1.16
Irrigated agriculture	1,478	1.43
Livestock	113	0.11
Hydropower (evaporation)	16,989	16.46
<b>Total consumptive water use</b>	<b>20,126</b>	<b>19.49</b>

	Mm <sup>3</sup>	%
Available run off	103,224	100
<b>Water demand</b>		
Rural domestic consumption	43	0.04
Urban domestic consumption	676	0.65
Industrial consumption	85	0.08
Mining	408	0.40
Environmental/ flood releases	6,445	6.24
Irrigated agriculture (2005)	1,477	1.43
Additional under Partial Scenario (50%)	2,217	2.15
Additional under Full Scenario (100%)	4,635	4.49
Livestock	167	0.16
Hydropower	16,989	16.46
Additional under Moderate Scenario	175	0.17
Additional under Medium Scenario	1,365	1.32
Additional under Mega Scenario	7,609	7.37
<b>Total (high development scenario)</b>	<b>38,534</b>	<b>37.32</b>

Table 20: Current (left) and future (2025; right) water use in Zambezi River Basin

The following hypotheses may be considered as potential effects of climate change on reservoir evaporation:<sup>106</sup>

- in both cool regions and the tropics, evaporation rates will be most influenced by changes in wind-speed and lake heat storage, which is a function of the change in temperature throughout the year;
- climate change may affect the stability of air above large reservoirs by changing the differential between air and water temperatures. This would affect evaporation rates, depending on the relative change in temperatures;
- evaporation from small reservoirs will be sensitive to changes in vapor pressure. Vapor pressure deficit is not a constraint on evaporation from large reservoirs because air passing over a reservoir will become saturated by evaporation from the water surface; and
- in high latitudes, changes in lake ice cover may alter evaporation rates.

More recently, the concept of 'water footprint' has been used in an effort to understand the water impacts of different industrial and agricultural processes. Assessments of the volumes of water consumed and polluted may become part of planning efforts for hydropower projects.

The most significant water footprint impact of hydropower is during the storage phase due to evaporation. Methodological discussions on calculating that evaporation are ongoing. Often, total or gross evaporation effects are included in water footprint assessments. An alternative approach would be to include the net evaporation, which is the evaporation as it differs from a natural reference condition - in other words, what the evaporation from the land would have been if the dam had not been constructed. With net evaporation, the capturing of rainfall, which

<sup>105</sup> SADC-WD/ Zambezi River Authority; SIDA/ DANIDA, Norwegian Embassy Lusaka (2008) Integrated Water Resources Management Strategy and Implementation Plan for the Zambezi River Basin

<sup>106</sup> Uhlenbrook. <http://ocw.tudelft.nl/courses/watermanagement/>

would not otherwise have been captured, should also be taken into account. Also, where a reservoir serves multiple functions, evaporation losses from it should not only be attributed to hydroelectricity generation.

The results of a water footprint assessment for hydropower depend profoundly on which approaches are used. Mekonnen and Hoekstra's study (2012) calculates the blue water footprint of hydroelectricity through a study of 35 dams (Figure 98). Their method used gross evaporation as opposed to net evaporation, and attributed all evaporative losses to hydropower generation. The main findings include:

- The size of the reservoir has a larger impact on evaporation than climate
- The size of the reservoir surface area in relation to the installed capacity is the largest determining factor of the size of the water footprint.

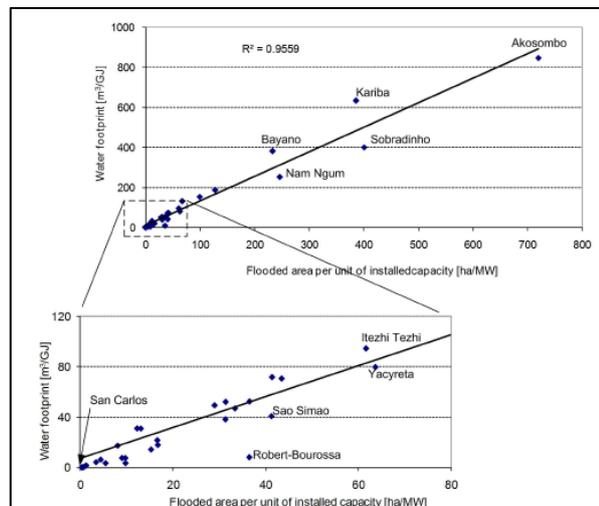


Figure 99: Water footprint in relation to flooded area

In 2011, Manitoba Hydro completed a water footprint assessment that used a net instead of a gross evaporation calculation.<sup>107</sup> In this study, due to the cold climate and high rainfall, the reservoir actually resulted in a net water gain because it captured more rainfall than was evaporated from the reservoir. A case study in New Zealand also took a net instead of a gross approach, and showed that comparing evaporation to the evapotranspiration that would have occurred if the dam had not been built, has profound consequences on the size of the water footprint.<sup>108</sup> Pegram et al. (2011) assert that in order to reflect the impact of water use on local water resources, net evaporative loss is the appropriate measure. Caution must be taken in comparing results of water footprint assessments as the differing approaches may produce misleading outcomes.<sup>109</sup>

The effects of climate change on agriculture – the biggest water user in most countries - will be considered as the third category of impact on hydropower important to South East Asia. The degree of this effect is strongly dependent on the quantity and timing of the precipitation that supplies rain-fed agriculture and water supplies used in irrigated agriculture. Too much precipitation will cause direct damage to crops and soil erosion, while too little precipitation will also directly damage crops. Early snowmelt may cause water shortages during the summer growing season. In addition, strong spatial and social differences exist. Those least able to cope (i.e., small farmers in marginal areas) will be affected more significantly. Climate change may have additional effects, such as fertilization of plants through increased CO<sub>2</sub> concentrations, and longer growing seasons.

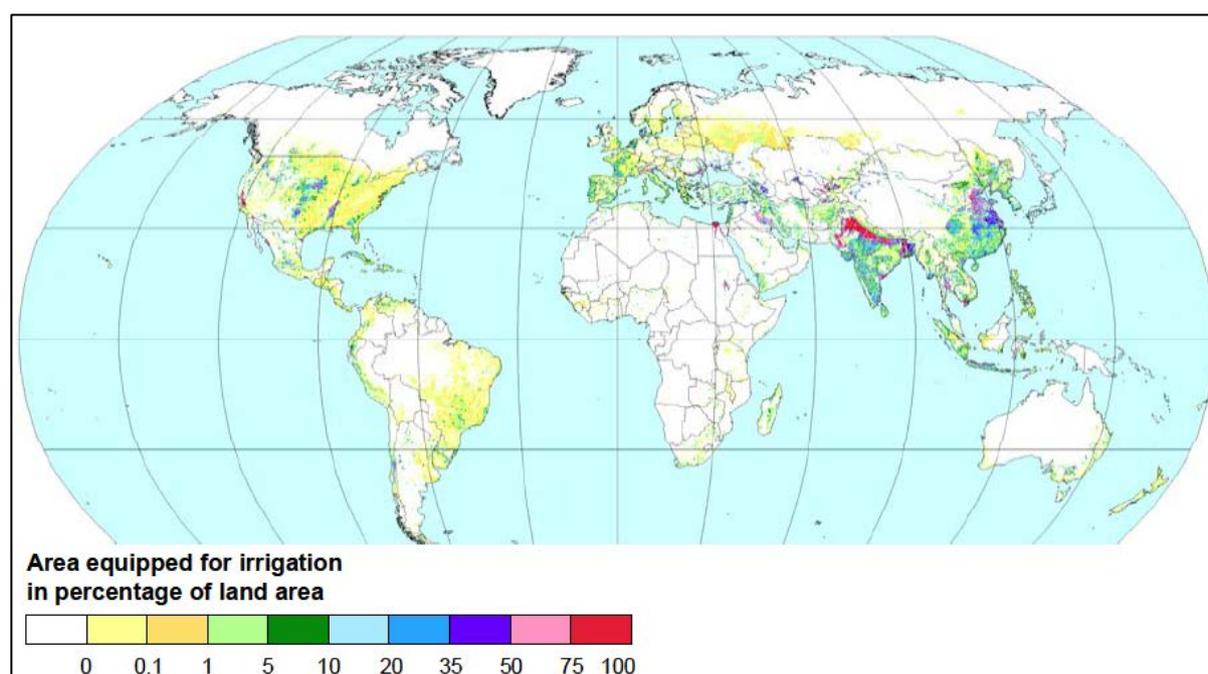
South and East Asia have some of the highest irrigation demands in the world (Figure 99 and Table 21). Figure 100 shows existing and planned irrigation projects in the LMB,<sup>110</sup> and Figure 101 the rapid increase of irrigated area in Laos.

<sup>107</sup> Adams (2011)

<sup>108</sup> Herath et al (2011)

<sup>109</sup> Hastings and Pegram (2012)

<sup>110</sup> [https://cityofwater.files.wordpress.com/2012/06/irrigation\\_hw-uc2.png](https://cityofwater.files.wordpress.com/2012/06/irrigation_hw-uc2.png)

Figure 100: Global irrigation demand<sup>111</sup>

	Irrigated area 1995, 1000 km <sup>2</sup>	Cropping intensity	Long-term average $IR_{net}$ , km <sup>3</sup> /yr				
			Baseline	2020s		2070s	
				ECHAM4	HadCM3	ECHAM4	HadCM3
Canada	7.1	1.0	2.4	2.9	2.7	3.3	2.9
U.S.A.	235.6	1.0	112.0	120.6	117.9	123.0	117.9
Central America	80.2	1.0	17.5	17.0	17.6	18.1	19.7
South America	98.3	1.0	26.6	27.1	27.5	28.2	29.1
Northern Africa	59.4	1.5	66.4	62.7	65.3	56.0	57.7
Western Africa	8.3	1.0	2.5	2.2	2.4	2.4	2.6
Eastern Africa	35.8	1.0	12.3	13.1	12.2	14.5	14.3
Southern Africa	18.6	1.0	7.1	7.0	7.4	6.4	7.2
OECD Europe	118.0	1.0	52.4	55.8	55.2	56.5	57.8
Eastern Europe	49.4	1.0	16.7	18.4	19.0	19.7	22.1
Former U.S.S.R.	218.7	0.8	104.6	106.6	112.1	104.4	108.7
Middle East	185.3	1.0	144.7	138.7	142.4	126.5	137.8
South Asia	734.6	1.3	366.4	389.8	400.4	410.7	422.0
East Asia	492.5	1.5	123.8	126.0	126.6	131.3	127.1
<b>Southeast Asia</b>	<b>154.4</b>	<b>1.2</b>	<b>17.1</b>	<b>20.3</b>	<b>18.8</b>	<b>30.4</b>	<b>28.6</b>
Oceania	26.1	1.5	17.7	17.8	17.6	18.2	19.7
Japan	27.0	1.5	1.3	1.3	1.8	1.4	1.5
<b>World</b>	<b>2549.1</b>		<b>1091.5</b>	<b>1127.5</b>	<b>1147.0</b>	<b>1151.0</b>	<b>1176.8</b>

Table 21: Impact of climate change on computed global net irrigation requirements<sup>112</sup><sup>111</sup> Siebert et al (2013) Update of the Digital Global Map of Irrigation Areas to Version 5.<sup>112</sup> Doell (2002)

Indicative projections of agricultural productivity suggest a 3.6% increase in productivity of the LMB under the most likely projected climate for 2030. Irrigation requirements for the projected median climate condition would be 1.6 to 3.4% higher than the current requirements. If additional irrigation requirements will be met by increasing diversion of water from the river, the increase in diversion for the whole LMB in 2030 under the median climate condition would be 283 MCM.

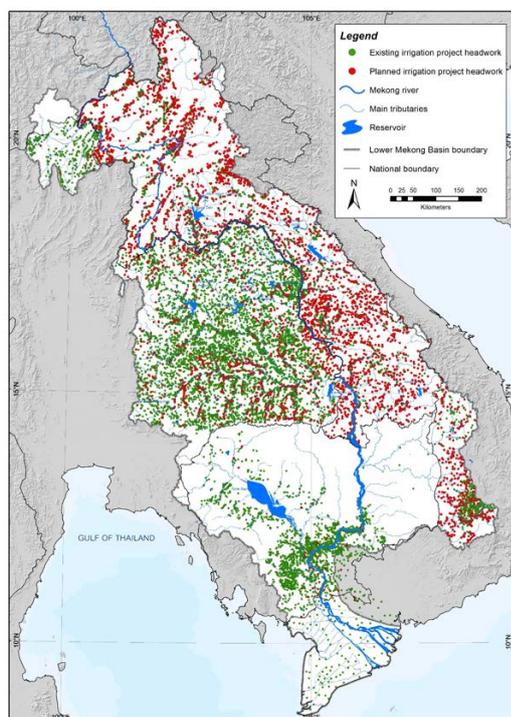


Figure 101: Existing and planned irrigation in the LMB

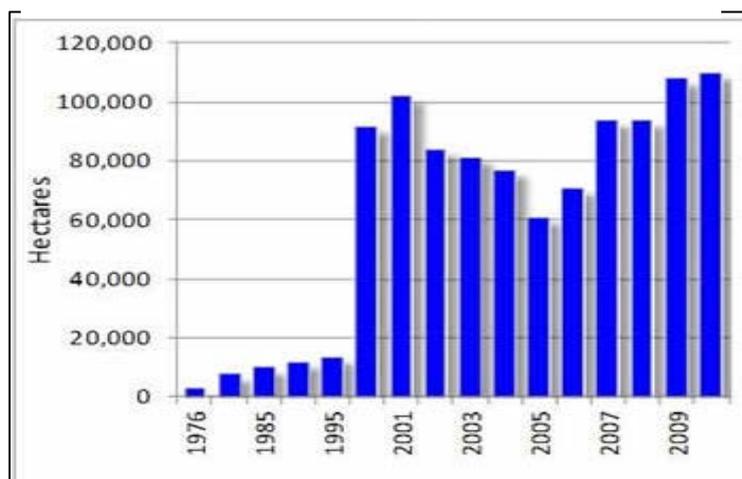


Figure 102: Laos historical irrigated rice area<sup>113</sup>

Diversion of more irrigation water due to increased requirements may have several impacts:

- Existing irrigation system capacity – including storage capacity - may not be enough to deliver the increased requirements; this may require additional investments.
- Increased diversion for irrigation will reduce the dry season flow in the river, which may significantly affect the river ecology and overall environment. There could be an impact on salt-water intrusion in the Mekong delta of Vietnam.

Besides irrigation, it is also possible that other water abstractions upstream will increase due to climate change.

<sup>113</sup> [http://www.pecad.fas.usda.gov/highlights/2011/12/Laos\\_13Dec2011/](http://www.pecad.fas.usda.gov/highlights/2011/12/Laos_13Dec2011/)

## 4.2 Session 4.2 Adaptation to Changes in Commercial Context

Purpose and Learning Objectives	<p>The session provides an overview of changing electricity markets under climate change (variability of electricity prices and regulatory changes such as taxes and subsidies, carbon markets, feed-in tariffs, water fees) which may make hydropower less or more competitive and commercially attractive.</p> <p>Trainees will gain a sense of how the financial and economic viability of hydropower will evolve and drive investment, design and operational decisions.</p>
Key Reading	Item 4.2.1. REN21 (2013) Global Status Report. Chapter: 4 Policy Landscape.
Content	<p>How will climate change influence other electricity sources – physically and through mitigation policy?</p> <p>How will hydropower be affected by policies to promote renewable energies?</p> <p>How will a changing energy mix influence the attractiveness of hydropower?</p>
Key Aspects	<p>The commercial context of hydropower will change because different sources of electricity are affected differently by mitigation policies.</p> <p>An evolving energy mix with a larger share of new renewables will present a new environment, with some positive and some negative influences on the attractiveness of hydropower.</p>
Discussion Topics and Exercises	<p>Group discussion (divided by country origin):</p> <p>What are the current renewable policies and initiatives in your country, and how are they influencing hydropower investment?</p>

Climate change will influence other aspects of the electricity sector besides hydropower generation, both through environmental changes and through mitigation policy. Investments in hydropower will be affected by commercial changes such as reduced or increased efficiency, and costs of competing sources of electricity. Table 22 shows the results of a literature review on changes that may be expected.

	Demand	Thermal supply	Renewable supply	Transmission
Change in temperature	Change in heating and cooling degree days (comparatively well studied for some regions)	Increased water and air temperature decreases the efficiency of thermal cooling (some research for some regions)	Decreased icing increases efficiency of wind power (little research)	Increased transmission losses due to higher temperatures (little or no research)  Negative impact of thawing permafrost (little research) Underground cable de-rating due to higher temperatures and drier soils (little or no research) (no research in this review)
Changes in precipitation	Fuel choice (very little research)	Change in river flow affects cooling in thermal power plants (little or no research)	Hydropower potential affected by changes in river flow and evaporation (some research for some regions)	
Extreme weather events	(no research in this review)	(no research in this review)	Dam safety affected by frequency of erratic river flow (little research)	Potentially costly interruption of supply (little research)
Changes in wind speed	(no research in this review)	(no research in this review)	Potentially large change to wind power potential (comparatively well studied for some regions, though not for extreme wind speeds)	(no research in this review)
Sea level rise, subsidence and other effects	(no research in this review)	Damages due to inundation and subsidence (little or no research)	Damages due to inundation and subsidence (little or no research)	(no research in this review)

Table 22: Climate impacts on electricity sector by type of climatic change<sup>114</sup>

Although not much research exists on the potential impact pathways, it has been stated that “the impact of climate change on the energy sector is likely nowhere near as large as the potential impacts of climate change policy.”<sup>115</sup>

Financial schemes such as carbon taxes, carbon cap-and-trade schemes, domestic or international tax benefits and subsidies (e.g., through below market-rate financing), and feed-in tariffs may alter the attractiveness of investment in hydropower. Renewables portfolio targets or tradable renewable energy credits will incentivize low carbon energy technologies, such as hydropower.

Feed-in tariffs are in place, for example, for hydropower projects in Germany; they receive a guaranteed tariff (from 12.7 cents to 3.4 cents / kWh, depending on size) for 20 years if they are new or substantially technically improved, and if they can demonstrate ecological compliance. Carbon taxes indirectly increased Hydro Tasmania’s profit by AUD 70 million in 2012-2013 because the AUD 23/ton CO<sub>2</sub> tax increased electricity prices in Australia. Renewables portfolio targets are established in 29 US states, with various rules on the eligibility of hydropower.

The Brazilian development bank BNDES has financed about 50 GW of hydropower projects over the last 10 years, including its biggest loan ever, USD 10.8 billion for the Belo Monte project. BNDES finances hydropower generation projects over 20 years, up to 70% of project costs, at relatively low rates.

Many of these renewable energy support policies are being implemented at the national, state, or provincial level in the LMB. Thailand has incorporated renewable energy targets, feed-in tariffs, premium payment, tax reductions, loans, grants, and technology obligations.

<sup>114</sup> Mideksa and Kallbecken (2010)

<sup>115</sup> *ibid*

Vietnam has implemented renewable energy targets, tradable renewable energy credits, capital subsidies, grants, rebates, and investment or production tax credits.<sup>116</sup>

Another strategy being applied is the Clean Development Mechanism (CDM). Created through Article 12 of the Kyoto Protocol, the CDM allows a country with an emissions commitment to implement an emission-reduction project in developing countries. Such projects can earn marketable certified emission reduction (CER) credits, each equivalent to one ton of CO<sub>2</sub>, which can be counted towards meeting Kyoto targets. The CDM does not actually reduce emissions, but rather it reduces the cost of emissions reductions. Its implementation mechanism is detailed in Figure 105.

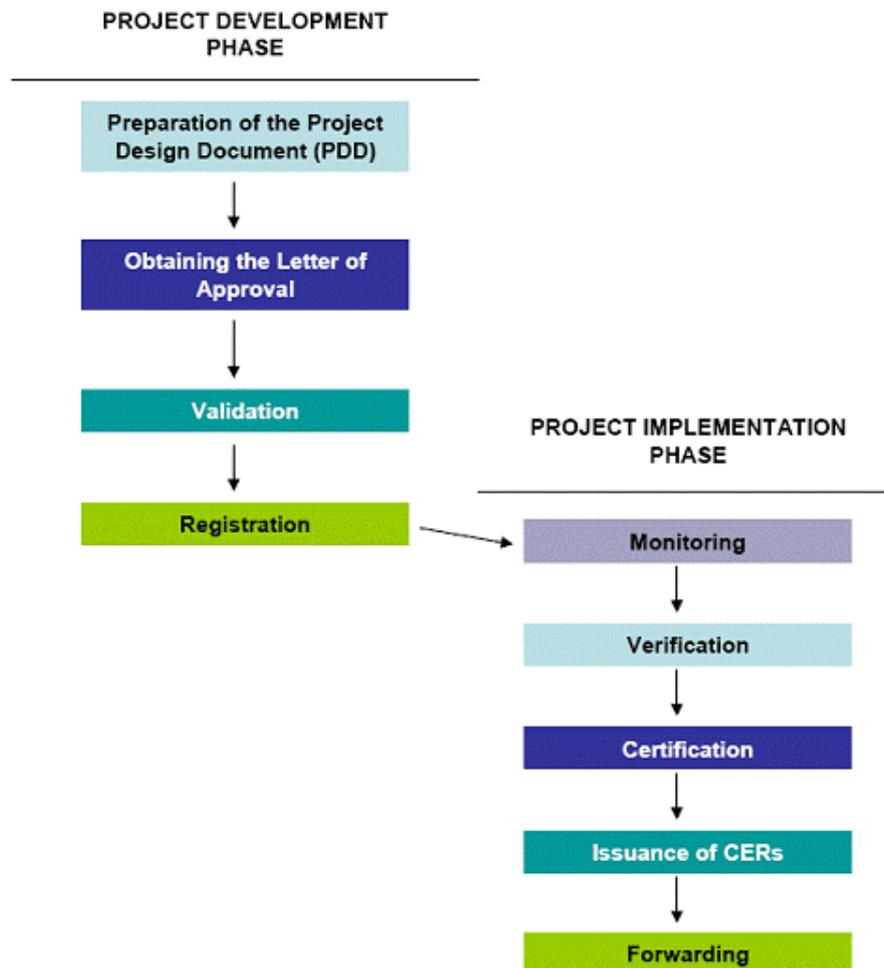


Figure 103: Implementation of clean development mechanism<sup>117</sup>

A CDM project must provide emission reductions in the host country that are additional to what would otherwise have occurred. The projects may come from any sector, but must qualify through a public registration and issuance process. Over 7000 projects are registered, many in the in the energy generation sectors (Figure 106). In the hydropower sector, China is the global leader in CDM projects (Figure 107).

<sup>116</sup> REN21 <http://www.ren21.net/RenewablePolicy/GSRPolicyTable.aspx> .

<sup>117</sup> <http://www.cdmrulebook.org/305>

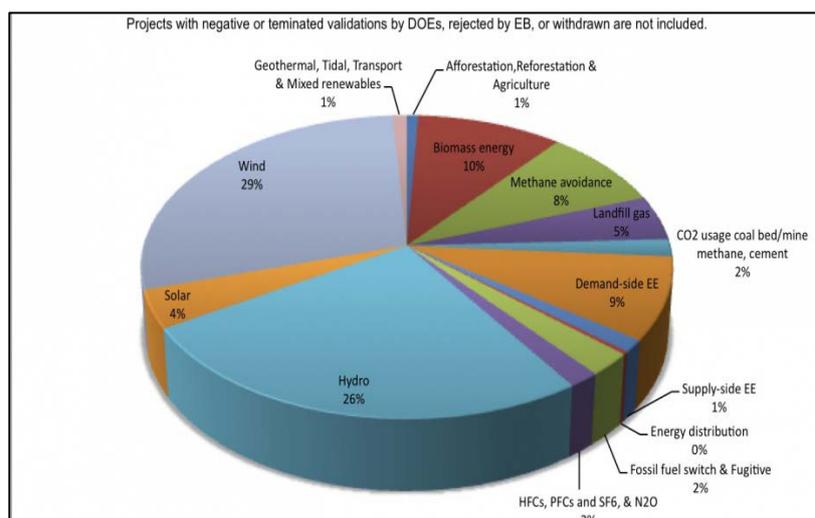


Figure 104: Projects in the CDM pipeline, by type<sup>118</sup>

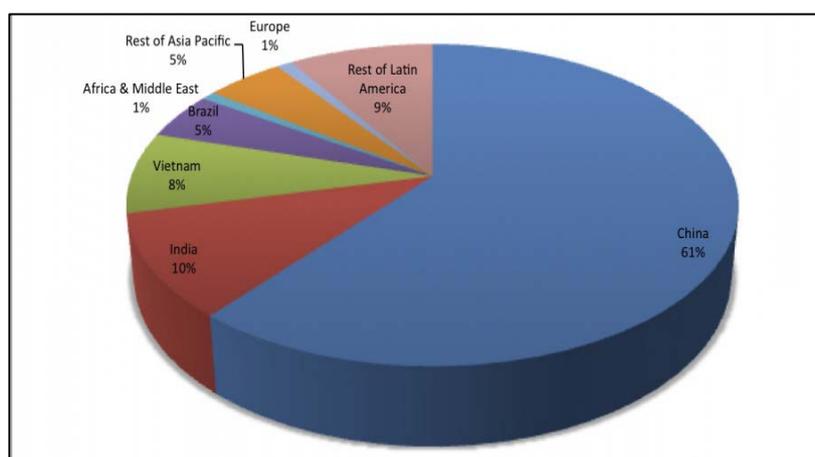


Figure 105: Percentage of all hydro projects in the CDM pipeline by country/region<sup>119</sup>

An important commercial change for hydropower comes from the increasing amount of new, intermittent renewables. Not all power markets actually reward the delivery of ancillary services (such as reserve capacity), but it is expected that more and more markets will do so.

In many places this will place a premium on dispatchable power, which storage hydropower (but not run-of-river) can deliver. This will encourage the development of storage hydropower, potentially even of pumped storage. There may also be cases, however, where the timing of intermittent renewables is such that value of peak power from hydro schemes is reduced.

Figure 108 shows an example from Germany. Wholesale prices move during the day, in response to changing supply of wind and solar PV power. While prices rise towards mid-day, at 2pm more than 45 GW of wind and solar are generated. Hydropower will be dispatched when prices rise; in this case prices are high in the morning hours and also more than triple in the evening.

<sup>118</sup> <http://www.internationalrivers.org/blogs/246/crunching-the-hydro-numbers-2012-cdm-update>

<sup>119</sup> *ibid*

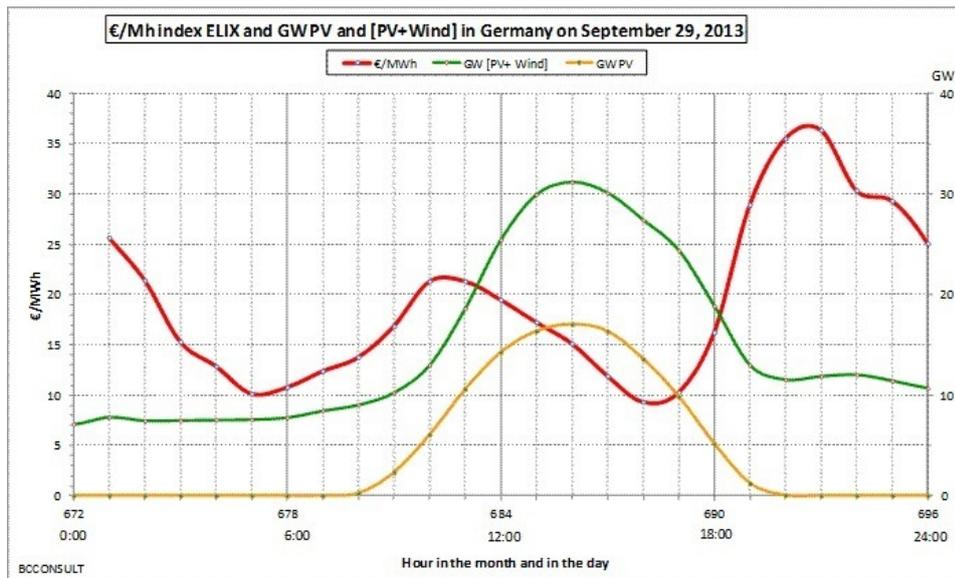


Figure 106: Spot-market electricity prices dependence on intermittent renewables

Some systems may already or may soon have such a high share of renewable sources that, depending largely on the weather, on some days, generation from renewables is higher than demand (Figure 109). Since the marginal cost of another KWh from renewables is very low, they are always dispatched first. Prices may actually become negative if too much renewable generation is in the market – producers are paid to turn their machines off (Figure 110). On days when there is a gap between renewable generation and demand, other power stations have to fill the gap, and power prices go up.

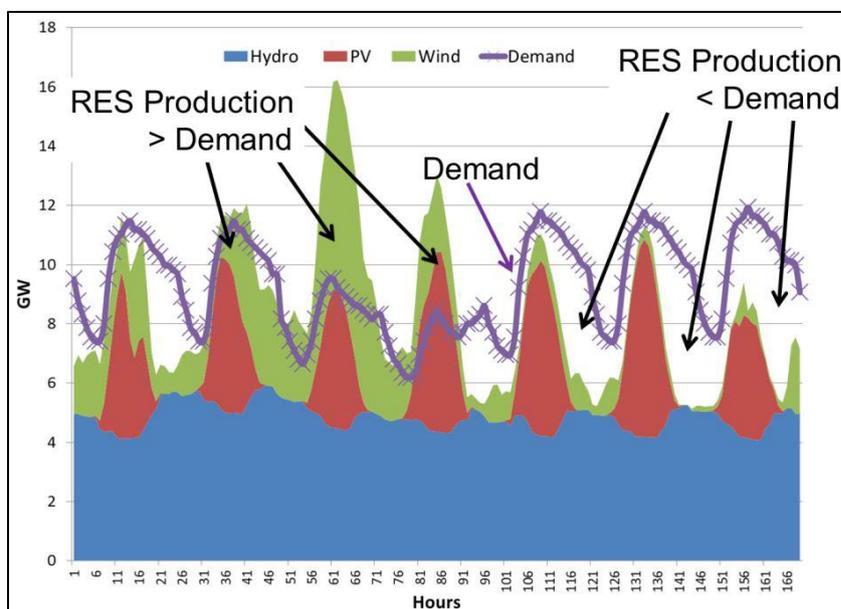


Figure 107: Renewable energy generation over time<sup>120</sup>

<sup>120</sup> [http://cec.tuwien.ac.at/news\\_events/news\\_details/article/7556/12165/](http://cec.tuwien.ac.at/news_events/news_details/article/7556/12165/)

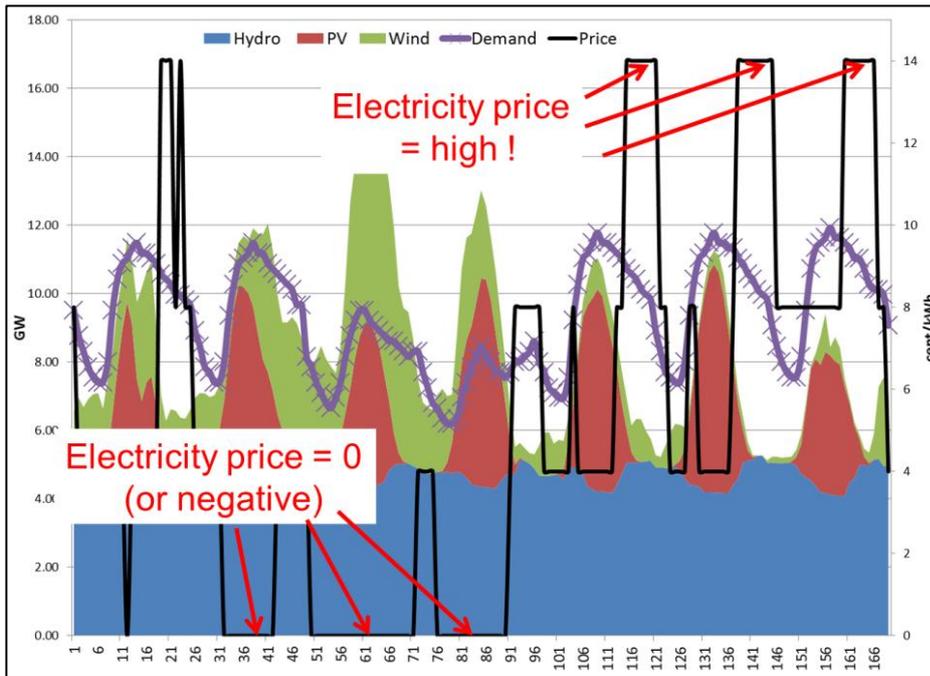


Figure 108: Price effects of renewable generation over time<sup>121</sup>

Another example from Germany demonstrates that solar PV (which peaks at mid-day) can actually take the peak off consumption and make prices less volatile (Figure 111). The price differential for dispatchable power sources is reduced. This is increasingly used as an argument against pumped storage in the Alps. But it is equally possible to find periods where intermittent renewables increase volatility. This creates a new source of uncertainty over the value of dispatchable sources.

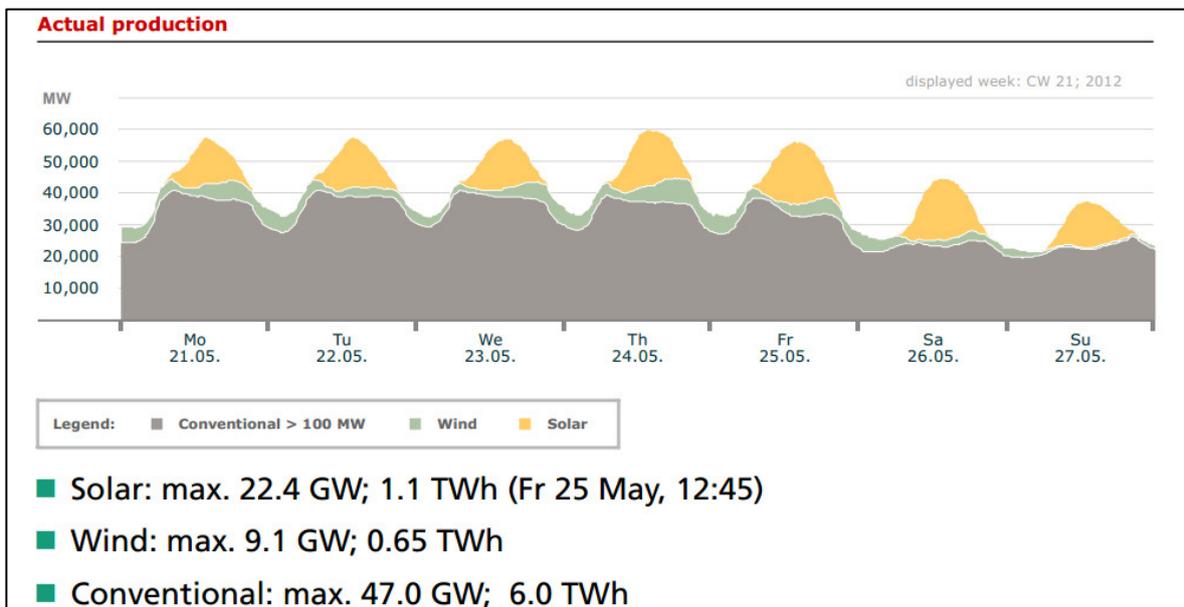


Figure 109: Energy production over a week<sup>122</sup>

<sup>121</sup> ibid

<sup>122</sup> Burger, Fraunhofer ISE. Data: EEX, <http://www.transparency.eex.com/de>

A final consideration with commercial implications is that the opportunity costs of land or water may increase. Water fees for hydropower are typically low and do not reflect the full opportunity cost of water. Hydropower facilities may have to pay higher fees in the future that reflect their growing consumption of water and the increased value of that water to other sectors. The cost of land that is required for projects might also increase as the value of agricultural production increases. Some land used for hydropower projects is high-quality, valley-bottom land with irrigation potential, and farmers may require higher compensation payments.

It is difficult to say what the commercial environment of a hydropower station will be over its lifetime. What is increasingly clear is that climate change will influence that environment, through multiple pathways, in parallel to the more obvious effect of changed hydrology.

### 4.3 Session 4.3 Hydropower as an Instrument for Adaptation

Purpose and Learning Objectives	<p>Hydropower is just one among many industries that needs to adapt to climate change. But it may be able, through the water storage it provides, to support adaptation in other sectors. This session looks at practical water-resource management issues such as storage requirements and flood risk management strategies from an adaptation perspective.</p> <p>Trainees should become confident in discussing the potential contributions, but also the limitations of hydropower in an adaptation context.</p>
Key Reading	<p>Item 4.3.1 – The Economist (2010) How to live with climate change.</p> <p>Item 4.3.2 - Hallegatte (2009) Strategies to adapt to an uncertain climate change.</p> <p>Item 4.3.3 – DFID (2010) Water storage and hydropower: supporting growth, resilience and low carbon development. A DFID evidence-into-action paper.</p>
Content	<p>How do different adaptation and decision-making approaches apply to hydropower reservoirs?</p> <p>What role can hydropower play for broader water resources adaptation needs?</p>
Key Aspects	<p>Hydropower projects do not generally fit well into typical ‘robust’ adaptation approaches.</p> <p>Under some circumstances, hydropower projects can support adaptation in the water resources sector.</p>
Discussion Topics and Exercises	<p>Group discussion (divided by country origin):</p> <p>Can you point out specific examples from your country in how hydropower projects are supporting (or hindering) adaptation?</p>
Additional Resources	<p>Item 4.3.4 – McCartney &amp; Smakhtin (2010) Water Storage in an Era of Climate Change. IWMI.</p> <p>Cap-Net course on IWRM as a Tool for Adaptation to Climate Change at <a href="http://www.gwp.org/Global/GWP-CACENA_Files/en/pdf/capnet-adapt-to-climate-manual_en.pdf">http://www.gwp.org/Global/GWP-CACENA_Files/en/pdf/capnet-adapt-to-climate-manual_en.pdf</a> and <a href="http://www.thewaterchannel.tv/tutorial/en/index.html">http://www.thewaterchannel.tv/tutorial/en/index.html</a></p>

This session deepens the discussion from Session 1.3 on hydropower and adaptation, and also uses insights from Session 3.4 on decision making under uncertainty.

It is sometimes argued that hydropower can help societies adapt to climate change. What is generally meant by this is that hydropower reservoirs can be used for other purposes. Some of these may be compatible and others may be conflicting with hydropower. Multi-purpose reservoir management is addressed in a number of places in this manual. Most hydropower projects in the LMB region are either run-of-river projects or they have been built as single-purpose hydropower reservoirs. Even if there is no explicit intent to manage for other purposes, these may have secondary benefits, for example for flood control, and in an adaptive management context the complementarities and trade-offs between different purposes should be re-evaluated from time to time.

Various types of adaptation should be considered, and may be classified by their intent, their temporal scale, their spatial scale, or by their implementers. Autonomous adaptation is spontaneous, triggered by physical or market changes. Planned adaptation, at the other end of the spectrum, is the result of a deliberate policy decision. Adaptation may come from the private or the public sector. It may be anticipatory, happening before climate changes occur, or reactive, happening in response to climate changes.

There is widespread agreement that under some circumstances, increasing the amount of storage can be a smart planned or anticipatory adaptation option:

#### **The Benefits of Water Storage<sup>123</sup>**

“Improved water storage is a driver for economic growth. In poor countries with highly seasonal and often unpredictable rainfall, a lack of adequate water storage already causes large and avoidable economic losses from floods and droughts, and constrains long-term growth...

Multipurpose water storage, justified economically on returns from hydropower, may be used to provide additional benefits such as irrigation to support local livelihoods and improve food security.

Improved water storage will increase resilience to climate change and support better water and food security in poor and vulnerable countries. This will require actions to improve both natural water storage in rivers, lakes, aquifers, wetlands and soils, as well as built storage. In many countries, built water storage of a range of sizes will offer the most effective means of hedging risks from more variable rainfall. Demand management to ensure efficient use of water is a crucial complement to improved storage.”

It is also acknowledged that hydropower is often the only major source of financial revenues from the use of water resources, so that the initiative to build a reservoir may have to come from the hydropower sector. Irrigation schemes often do not cover their costs; municipal water supply needs are generally small; and other water uses that might benefit from storage are either public goods or have low potential for revenues.

If this is accepted, the next step is to consider the options for specific cases of potential reservoirs. Colombo & Byer (2012) have put together the following categorization of adaptation options, i.e. options for planning approaches under climate change. It distinguishes between five generic options:

- Do nothing: build a reservoir without influence of climate change on design, i.e. based on historic flows

<sup>123</sup> DFID (2010)

- Bolster existing designs: stronger/larger structures
- Variability management: prepare projects for larger variability
- Reconceptualization: consider new design elements, approach problems differently
- Adaptive management: wait-and-see.

'Wait-and-see' is not a passive strategy, but based on active observation of how initial decisions perform. Adaptive management has been defined as "a strategy that can be modified to achieve better performance as one learns more about the issues at hand and how the future is unfolding. A key feature of adaptive management is that decision makers seek strategies that can be modified once new insights are gained from experience and research. Learning, experimenting and evaluation are key in this approach and are actively planned for in decision-making."<sup>124</sup> This is also called 'informational flexibility'.

Supported by 'informational flexibility', the design and the operations of a future reservoir should also be able to deal flexibly and adaptively with climate change. In terms of design, a project may be able to be constructed in various stages, and technical options can be provided that allow a faster or cheaper expansion in the future. In terms of operations, the physical processes (such as release schedules) can be made flexible, but there is also an option to use financial instruments (such as insurance, swaps and financial options).

These options are not mutually exclusive, but can work in conjunction. For example, the flood control function of a reservoir can be strengthened by larger designs and operational flexibility (timely emptying of the reservoir before a flood wave) based on real time weather monitoring and forecasting. But even then, the ability to control floods will always be limited, at least in the case of the largest possible floods, and can be complemented by flood insurance for downstream communities.

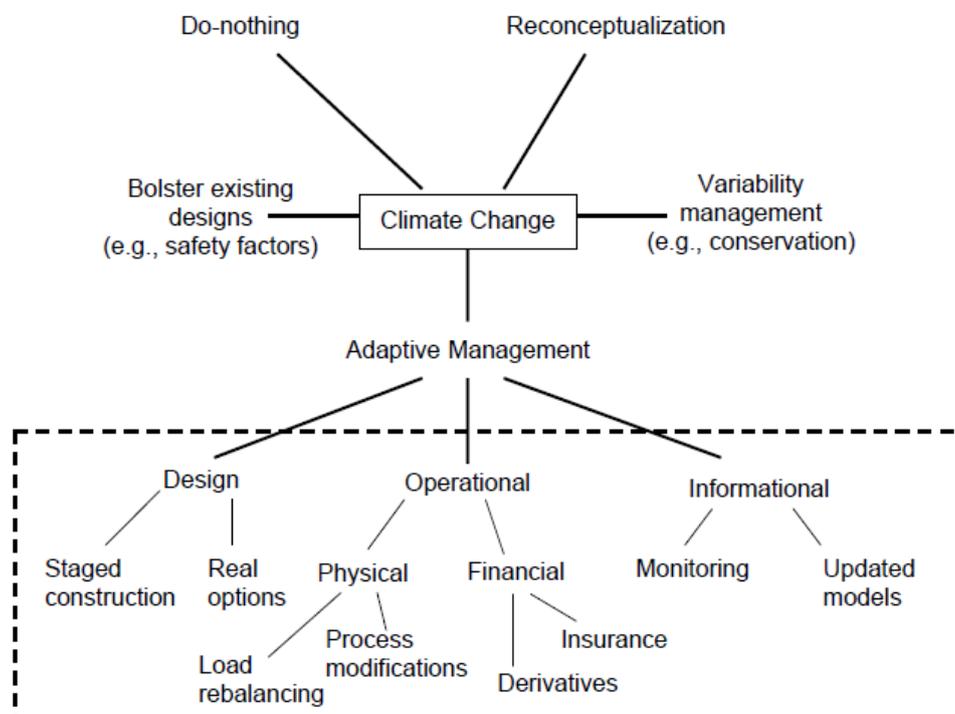


Figure 110: Classification of broad approaches for adapting to climate change at the project level

<sup>124</sup> Quoted in Colombo & Byer (2012).

To achieve such multi-pronged and relatively sophisticated adaptation however will present many challenges. Currently, there is a lack of relevant baseline information and insufficient monitoring, observation systems, and data sharing, which makes identifying, analyzing, and modeling effects much more difficult. Political, technological and institutional frameworks are not designed to deal with continuous change and adaptation. Social equity often does not exist in the decision-making process, and the poor and most vulnerable may be neglected in the adaptation process and will have to fend for themselves.

If water resources adaptation is to a large extent about management of increased flood and drought risks, during the decision-making process, participants must understand the nature and consequences of the risks involved. By critically examining the risk, public attention is focused onto societal consequences of events (which can be controlled) instead of on uncontrollable natural processes. Regions are identified that may warrant additional hazard assessments, new adaptation strategies, preparedness plans, public education, or land-use changes. Knowledge gained through this process serves as baseline information for response efforts.

Hydropower may be able to support adaptation through providing storage, but this does not mean that built storage is the only solution. Even if it has been identified that more storage is needed, because flows will become more irregular and less predictable, new reservoirs may not be the best response. While they offer a high degree of storage reliability, their management is the most complex of all storage options and has the most environmental and social costs. Maybe other storage options, such as the protection or re-planting of a forest in the watershed can be considered. The pressure to adapt may cause planners to re-conceptualize the problem, to break out of traditional patterns and consider a broader range of options that can be supported.

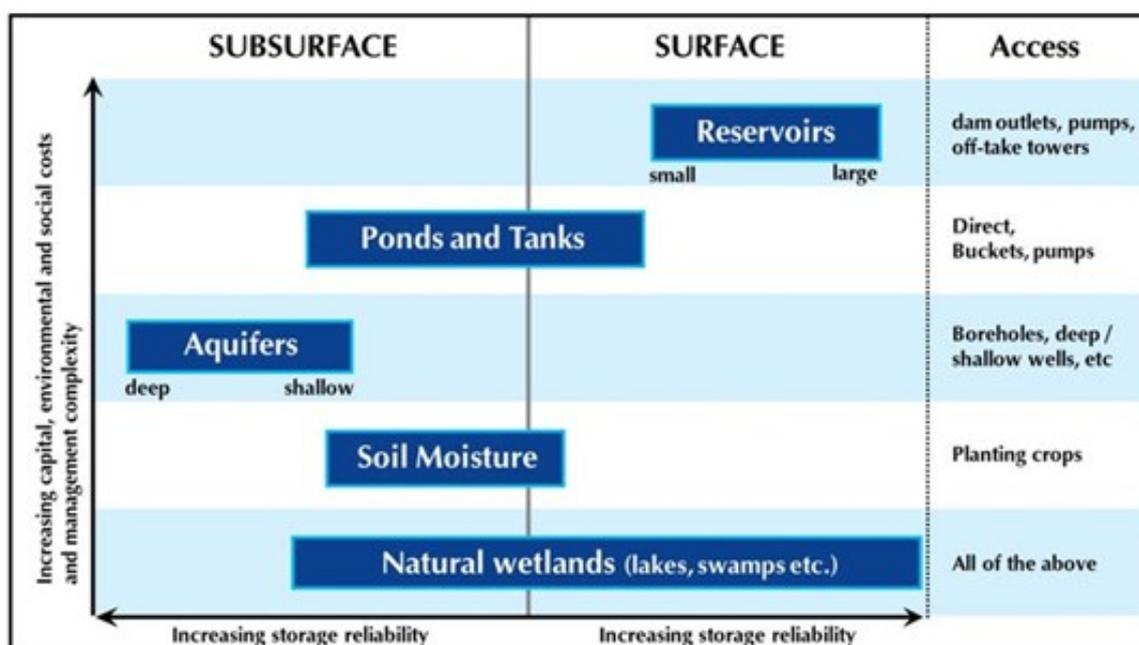


Figure 111: Storage options<sup>125</sup>

<sup>125</sup> International Water Management Institute at [http://www.iwmi.cgiar.org/Publications/Water\\_Policy\\_Briefs/PDF/WPB31.pdf](http://www.iwmi.cgiar.org/Publications/Water_Policy_Briefs/PDF/WPB31.pdf)

These different storage options all have their advantages and disadvantages, both under 'normal' operating conditions and under climate change. Table 23 below provides a generic comparison of these storage options. Decision-makers must be aware that while climate change may be a reason to seek more storage capacity, that storage itself is going to be affected by climate change.

	Inherent benefits (pros)	Inherent risks (cons)	Possible risks from climate change	Possible social and economic implications
<b>Natural wetlands</b>	<ul style="list-style-type: none"> <li>Water storage is provided as an ecosystem service without the need for costly infrastructure</li> </ul>	<ul style="list-style-type: none"> <li>Excessive utilization of water in, or upstream of, natural wetlands may undermine other ecosystem services.</li> </ul>	<ul style="list-style-type: none"> <li>Reduced rainfall and runoff inputs resulting in desiccation</li> <li>Higher flood peaks resulting in wetland expansion and flooding of fields/homes</li> <li>Improved habitat for disease vectors</li> </ul>	<ul style="list-style-type: none"> <li>Increased failure to provide community/household needs</li> <li>Loss of water-dependent ecosystem services</li> <li>Increased risk of waterborne diseases</li> </ul>
<b>Soil moisture</b>	<ul style="list-style-type: none"> <li>Generally, low-cost options that can be implemented by individual farmers and communities</li> </ul>	<ul style="list-style-type: none"> <li>Where landholdings are extremely small, farmers may be unwilling to use precious land for these interventions.</li> <li>Limited storage - will not provide water for more than a few days without rain</li> </ul>	<ul style="list-style-type: none"> <li>Reduced infiltration or waterlogging/erosion resulting from modified rainfall intensities and durations</li> <li>Depleted soil moisture arising from higher evaporative demand</li> <li>Reduced soil quality (including water holding capacity) resulting from modified rainfall and temperature</li> </ul>	<ul style="list-style-type: none"> <li>Decreased productivity – more frequent crop failures and reduction in yields</li> </ul>
<b>Groundwater</b>	<ul style="list-style-type: none"> <li>Evaporation losses are low or non-existent</li> <li>Multi-year storage that is largely decoupled from seasonal variability</li> </ul>	<ul style="list-style-type: none"> <li>Detailed geological information is required to locate wells and estimate yields</li> <li>Depending on geology, may contain high concentrations of toxic chemicals (e.g., arsenic)</li> </ul>	<ul style="list-style-type: none"> <li>Reduced recharge resulting from modified rainfall intensities</li> <li>Reduced recharge resulting from land-cover modification and increased soil moisture deficits</li> <li>Saline intrusion in near-coast aquifers</li> </ul>	<ul style="list-style-type: none"> <li>Falling water levels make it increasingly costly to access groundwater</li> <li>Poor water quality makes groundwater unsuitable for use</li> </ul>
<b>Ponds and tanks</b>	<ul style="list-style-type: none"> <li>Generally, relatively low-cost options, implementable by communities and non-governmental organizations (NGOs).</li> </ul>	<ul style="list-style-type: none"> <li>High evaporation losses</li> <li>Water contamination (e.g., from water flowing in and livestock entering the water)</li> <li>Risk of siltation</li> <li>May provide breeding habitat for disease vectors</li> </ul>	<ul style="list-style-type: none"> <li>Reduced inflow, resulting in longer periods between filling</li> <li>Higher evaporation, increasing rates of pond/tank depletion</li> <li>Infrastructure damage caused by larger floods</li> <li>Improved habitat for disease vectors</li> <li>Increased risk of eutrophication, salinization and siltation</li> </ul>	<ul style="list-style-type: none"> <li>Increased failure to provide community/household needs</li> <li>Increased labor requirements and costs to repair structures</li> <li>Increased risk of waterborne diseases</li> </ul>
<b>Reservoirs</b>	<ul style="list-style-type: none"> <li>Large volumes of water stored, which can be used for multiple purposes</li> <li>The only option that enables production of electricity and can offer protection from floods</li> </ul>	<ul style="list-style-type: none"> <li>Significant capital investment</li> <li>Often displacement of large numbers of people</li> <li>Significant environmental and social impacts arising from changes to river flows</li> <li>May provide breeding habitat for disease vectors</li> </ul>	<ul style="list-style-type: none"> <li>Reduced inflow, resulting in longer periods between filling</li> <li>Higher evaporation, increasing the rate of reservoir depletion</li> <li>Infrastructure damage caused by larger floods</li> <li>Improved habitat for disease vectors</li> <li>Increased risk of eutrophication, salinization and siltation</li> </ul>	<ul style="list-style-type: none"> <li>Increased failure to meet design specifications (irrigation and hydropower, etc.)</li> <li>Increased costs due to the need to redesign infrastructure (e.g., spillways)</li> <li>Increased risk of waterborne diseases</li> </ul>

Table 23: Comparison of storage options<sup>126</sup>

Perhaps the most obvious and critical risk management area in planning hydropower projects is the possibility of floods. Again, storage (of any kind) is just one among many possible flood risk management approaches. Re-conceptualizing the problem as 'how best to reduce people's vulnerability' from floods, rather than how to stop floods, allows a broader view at the many options available - to reduce the actual hazard, the exposure, or the vulnerability to floods:<sup>127</sup>

<sup>126</sup> McCartney and Smakhtin (2010)

<sup>127</sup> USGS Factsheet (2011) Understanding Risk and Resilience to Natural Hazards

Reduce Hazard	Reduce Exposure	Reduce Vulnerability
<ul style="list-style-type: none"> <li>• Retaining water where it falls (increasing infiltration, rooftop storing)</li> <li>• Retention basins (natural wet lands or depressions, human constructed tanks etc)</li> <li>• Dams and reservoirs</li> <li>• Diversion channels</li> <li>• Land use management (e.g., house building codes in urban areas, infrastructure building practices, appropriate landscape planning)</li> </ul>	<ul style="list-style-type: none"> <li>• Structural measures on the river (dykes, river training work such as channelization, flood walls, raised infrastructure such as roads and railways)</li> <li>• Structural and non-structural measures/actions by individuals (flood proofing)</li> <li>• Land regulation</li> <li>• Flood emergency measures (flood warning and evacuation)</li> </ul>	<ul style="list-style-type: none"> <li>• Physical: by improving the infrastructure, well-being, occupational opportunities, and living environment</li> <li>• Constitutional: by facilitating equal participation opportunities, education and awareness, providing adequate skills and social support systems</li> <li>• Motivational: by building awareness and facilitating self-organization</li> <li>• Economic: Flood insurance</li> </ul>

*Table 24: Options for flood risk management*

To summarize, under some circumstances, hydropower projects can support adaptation in the water resources sector. If properly designed and managed, their reservoirs can provide additional storage to protect downstream populations from floods and droughts. However, there are often alternative options to provide the same service. Also, hydropower projects do not generally fit well into the ‘robust’ adaptation approaches described in Session 3.4 (no-regret strategies, reversible strategies, safety margin strategies, soft strategies, strategies that reduce decision-making time horizons): They are certainly not a soft or reversible option. They cannot easily be built in stages. It is uncertain whether there could be regrets, given the many things that could occur over the lifetime of a project. And safety margins can be very expensive.

Given these complexities, while many adaptation decisions will be taken spontaneously and individually, there is definitely a role for government to ensure the best possible planned adaptation for and through strategic, long-lived infrastructure.

### **Case Study for a Complex Adaptation Problem**

Adaptation strategies usually include balancing competing objectives. These trade-offs may be explored in an example of complex adaptation: managing Egypt’s water. This example shows the trade-offs and synergies that already exist, and how they may evolve under climate change, in a transboundary context.

Practically all of Egypt’s water comes from the Nile and is stored in Lake Nasser, a reservoir built and first filled in the 1960s (it took one decade to fill due to its size).

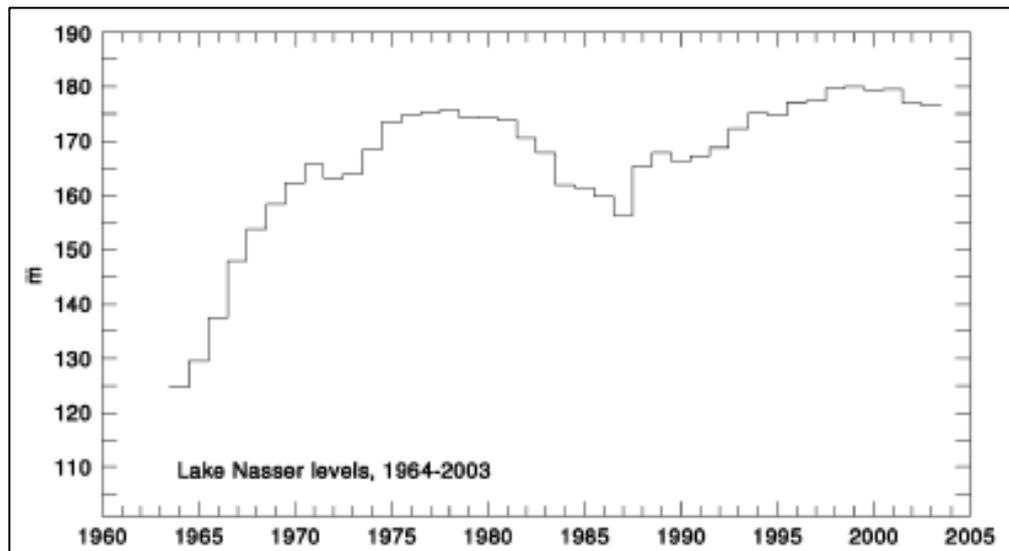


Figure 112: Lake Nasser, Egypt levels 1964-2003<sup>128</sup>

Lake Nasser serves several purposes; some water uses are compatible with each other and others are not. It was able to help Egypt through a decade of drought in the 1980s (see dip in lake levels in Figure 102 during this time). Water stored in the lake is released into the Nile for use in hydropower generation and for downstream irrigation. However, stored water can also be diverted from Lake Nasser directly into irrigation schemes, thus preventing its downstream use.

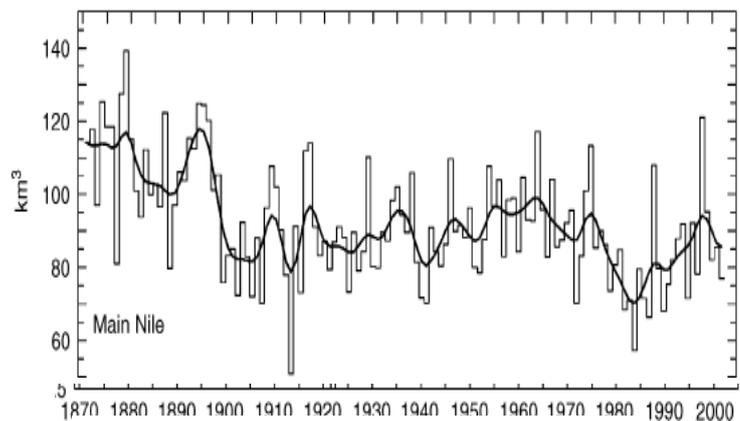


Figure 113: Historical flows on the Nile River

A portion of the lake water supply is being considered for use in irrigating the Toshka depression, a region west of Lake Nasser in the Sahara desert.<sup>129</sup> The requirement of the first phase (210,000 ha) of the Toshka Irrigation Scheme is 5 km<sup>3</sup> / year of water. These water demands need to be integrated into existing uses of Lake Nasser. The 1959 Nile Waters Agreement between the Sudan and Egypt allocated water rights of the Nile based on an average flow at Egypt's border of 84 km<sup>3</sup>/year. The average flow for the 1960s-1990s was actually only 76 km<sup>3</sup>/year, and predictions for the 2050s show further reduction to 65 km<sup>3</sup>/year. Evaporation from Lake Nasser is 10-14 km<sup>3</sup>/year.

There are several opportunity costs associated with the irrigation project. The Nile delta comprises 80% of agricultural land and reduced flows have already led to loss of nutrients, saline intrusion, coastal erosion, and reduced fish yields. Sea level rise is now adding to the pressure on the delta. These combined adverse effects cause the delta population to be vulnerable to displacement and loss of livelihood. The Nile delta is considered (together with

<sup>128</sup> Conway (2005) From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile basin. Figure 103 is from the same source.

<sup>129</sup> <http://na.unep.net/atlas/onePlanetManyPeople/downloads/conferencePosters/Toshka.pdf>

the Mekong and the Ganges/Brahmaputra deltas) to be among the most vulnerable deltas worldwide (Figure 104). There are also 2800 MW of installed hydropower capacity (10% of Egypt's total) downstream of Toshka, and all water diverted to Toshka is reducing the generation potential.



Figure 114: Relative vulnerability of delta populations as indicated by population potentially displaced by current sea-level trends to 2050<sup>130</sup>

Policy makers must balance the increased demands for food and electricity of a growing population with environmental services that protect these same populations, and all of this under conditions which are constantly shifting. The dilemmas are illustrated in a recent article:

*“Egypt’s electricity ministry on Tuesday apologized for a recent spate of nationwide power cuts, which it attributed to ongoing fuel shortages. Egypt’s state-run National Energy Control Centre, the statement explained, has been forced to reduce pressure on the national electricity grid, and therefore calls on the citizenry to ration their use of electricity, especially the use of air conditioners and heaters.”<sup>131</sup>*

<sup>130</sup> <http://www.epa.gov/climatechange/impacts-adaptation/international.html>

<sup>131</sup> Ahram Online (21 May 2013) “After power cuts, Egypt government calls on citizens to ration electricity.”

## 5 MODULE 5. HYDROPOWER AND MITIGATION

### 5.1 Session 5.1 Emissions Avoided by Hydropower

Purpose and Learning Objectives	<p>This session provides an overview of the benefits of hydropower deployment for greenhouse gas emissions. It covers both the direct avoidance of emissions, by replacement of thermal generation, and the indirect avoidance of emissions, by enabling the integration of intermittent renewables, globally and in the Mekong region.</p> <p>Trainees will learn to understand and estimate GHG emissions benefits.</p>
Key Reading	<p>Item 5.1.1 – Project Design Document for Xekaman 3 project (2011). Annex 3 (calculation of avoided emissions).</p> <p>Item 5.1.2 – Manitoba Hydro (2012) Climate Change Report. Chapter 4: Contribute to GHG Emission Reductions.</p> <p>Item 5.1.3 – CEATI (2011) The Hydroelectric Industry’s Role in Integrating Wind Energy.</p>
Content	<p>How many units of carbon emissions does hydropower generation displace?</p> <p>What benefits does this provide?</p> <p>How does this apply to the Mekong region?</p>
Key Aspects	<p>Avoided emissions from hydropower depend on the specific characteristics of the served electricity system, usually described by the operating and build margin, as in the Clean Development Mechanism.</p> <p>Benefits of avoided emissions can be estimated through economic analysis, and may provide financial revenue.</p> <p>Benefits also include support for the expansion of new renewables, which require back-up and energy storage.</p>
Discussion Topics and Exercises	<p>Group discussion:</p> <p>How significant are the potential avoided emissions (direct and indirect) from hydropower in the different LMB countries?</p>
Additional Resources	<p>Manitoba Hydro’s Climate Change Report (2012) provides a good overview of a range of climate change issues for a hydropower utility, including issues beyond avoided emissions.</p>

Hydropower is a clean energy technology and one of the options to reduce the amount of greenhouse gas emissions. This is achieved directly through the replacement of thermal generation. In order to calculate the effect of feeding into the grid, the electricity source that is displaced (both today and in the future) must be known.

GHG PROJECT	PROJECT ACTIVITY	PRIMARY EFFECT
Install and operate grid-connected wind turbine facility	Generate zero-emission electricity from wind energy	Reduce combustion GHG emissions from grid-connected power plants
Install and operate grid-connected natural gas combined-cycle power plant	Generate low-emission electricity from high-efficiency natural gas plant	Reduce combustion GHG emissions from (higher emitting) grid-connected power plants
Install and operate combined heat-and-power generation equipment at an electric grid-connected building	1. Generate electricity for onsite consumption, avoiding the need for grid electricity	Reduce combustion GHG emissions from grid-connected power plants
	2. Generate heat for onsite consumption, avoiding the need for a separate boiler	Reduce combustion GHG emissions from generating (onsite) energy
Retrofit an existing grid-connected coal-fired power plant to improve its generation efficiency and capacity	1. Generate current levels of electricity output more fuel-efficiently	Reduce combustion GHG emissions from "off-grid" electricity generation*
	2. Generate more grid electricity, due to greater capacity and utilization	Reduce combustion GHG emissions from grid-connected power plants
Install compact fluorescent light bulbs in an existing building	Reduce consumption of grid electricity	Reduce combustion GHG emissions from grid-connected power plants
Retrofit an off-grid diesel generator to improve its generation efficiency	Generate electricity more efficiently	Reduce combustion GHG emissions from off-grid electricity generation

Table 25: Examples for GHG reducing power sector investments<sup>132</sup>

Most of the methodological discussion on how to calculate emissions reductions is taking place in the context of carbon markets. The UNFCCC CDM Tool 07<sup>133</sup> determines the CO<sub>2</sub> emission factor for the displacement of electricity generated by power plants in an electricity system. The outcomes depend upon several factors:

- Context: excess capacity, suppressed demand, fixed investments
- Project characteristics: peak vs. baseload, load-following vs. resource-driven (firm vs. non-firm)
- Market behavior: plans, intuition, and time-scale of interest (short-term vs. long-term)
- Project size: Cumulative effects of small projects, delay vs. displace new capacity additions

CDM Tool 07 calculates the combined margin emission factor (CM) of the electricity system, the weighted average of two emission factors: operating margin (OM) and build margin (BM). The OM is the emission factor that refers to the group of existing power plants whose current operation would be affected by the new project. The BM is the emission factor that refers to

<sup>132</sup> WRI & WBCSD (2005) Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects

<sup>133</sup> <http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-07-v4.0.pdf>

the group of prospective power plants whose construction and future operation would be affected by the new project (choice and/or timing of new power plants, or life extension of existing ones). In mature systems, where electricity demand is stable, the OM will dominate. In rapidly growing systems the BM will dominate.

The CM is also known as baseline emissions rate in some contexts:

$$(1) \quad ER_{baseline} = wBM + (1-w)OM$$

Where:

- $ER_{baseline}$  is the baseline emission rate with respect to generation (e.g., tons CO<sub>2</sub>-equivalent / MWh);
- $BM$  is the build margin emission factor (t CO<sub>2</sub>-e / MWh);<sup>4</sup>
- $OM$  is the operating margin emission factor (t CO<sub>2</sub>-e / MWh);
- $w$  is the weight (between 0 and 1) assigned to the build margin.

To determine the weights of BM and OM, several methodological options may be applied. First, a model capable of reflecting all effects (i.e., full simulation or optimization models and not just short-term dispatch model) could be used. Alternatively, models or algorithms could estimate each effect separately and then combine them. Finally, one could decide which effect predominates and ignore the others.

In a rapidly expanding system, the main effect of a small renewable project may be to delay the entry of new fossil capacity. But the effect of this should not be underestimated: the later GHG emissions occur, the better.

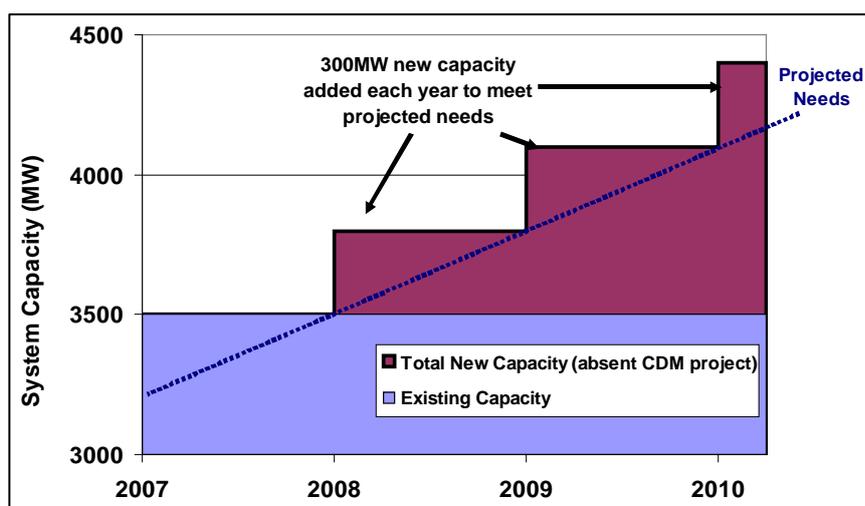


Figure 115: System expansion, prior to CDM project<sup>134</sup>

<sup>134</sup> Lazarus (2004) The Combined Margin Approach: Issues and Options. World Bank workshop, Buenos Aires

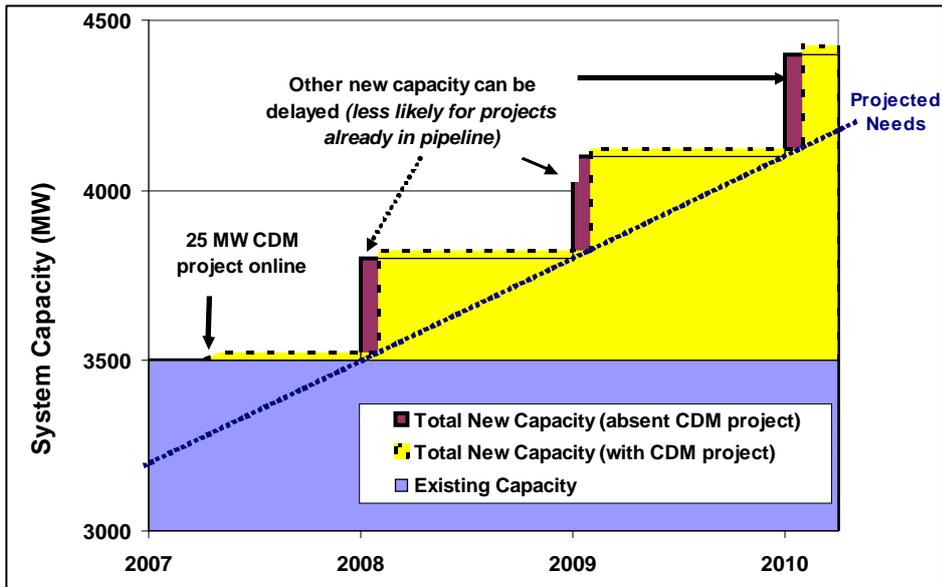


Figure 116: Potential delaying impact of a small hydro project<sup>135</sup>

The practical difficulties of determining an operating margin can be illustrated with a typical load duration curve. The marginal plant that is replaced by hydropower may change several times during a day, and many times over a week. Where hydropower actually lies in a merit order depends on many factors, including which kind of hydropower plants are available. Run-of-river is always at the bottom of the merit order, but the water value in a storage project can be quite high (consider pumped storage) and the project will be higher up in the order.

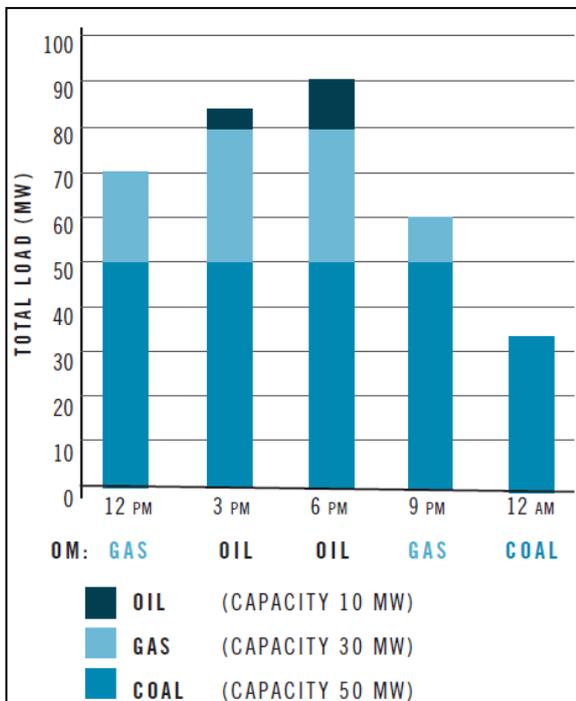


Figure 117: Changes in the operating margin over a day<sup>136</sup>

<sup>135</sup> ibid

<sup>136</sup> WRI & WBCSD (2005) Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects.

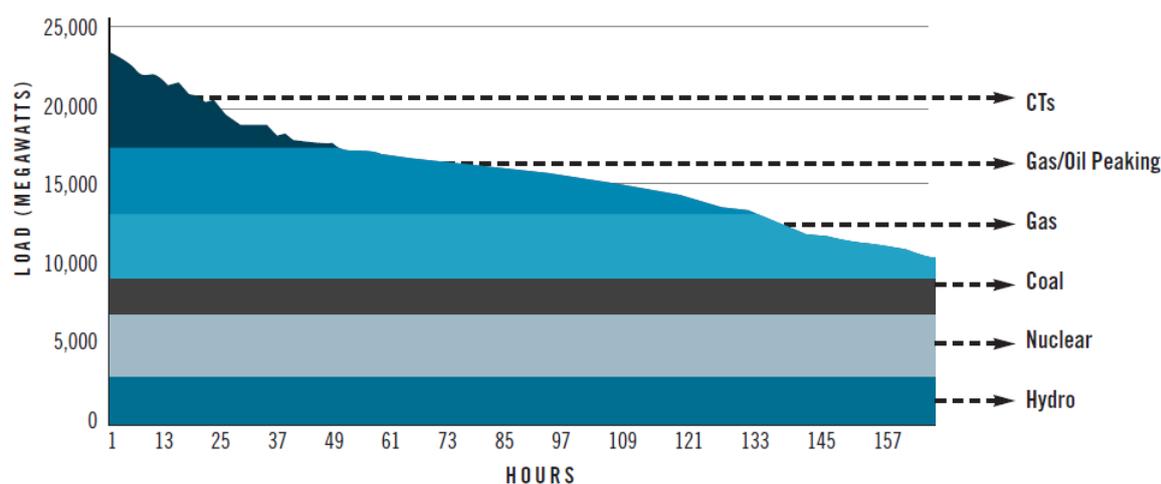


Figure 118: Changes in the operating margin over a week<sup>137</sup>

In practice, simplifying assumptions are made in order to calculate emissions displacement. The first example below is from three CDM projects serving the Vietnamese market, where the weights of OM and BM have been arbitrarily determined as 50% each.

Project	Country	OM (tCO <sub>2</sub> e/MWh)	BM (tCO <sub>2</sub> e/MWh)	CM (tCO <sub>2</sub> e/MWh)	Power Density <sup>2</sup> (W/m <sup>2</sup> )	Generation (Gwh)	Emissions Reduction (CO <sub>2</sub> /a)
Nam Sim 9 MW	Lao PDR	0.6184	0.4889	0.5537	306	32.500	17,995
Muong Hum 32 MW	Vietna m	0.6540	0.4920	0.5733	145	121.860	68,841
Xekaman 3 250 MW	Lao PDR	0.6465	0.5064	0.5764	48	977.500	499,481

Table 26: Avoided emissions from three CDM hydropower projects for the Vietnamese market<sup>138</sup>

The table above also lists the power density for each project. The CDM Executive Board has decided that hydroelectric reservoirs must meet certain power density thresholds to minimize the risks associated with scientific uncertainty concerning GHG emissions from reservoirs. Hydroelectric plants with power densities (calculated from installed power generation capacity divided by the flooded surface area) of:

- less than or equal to 4 W/ m<sup>2</sup> cannot use current methodologies;
- greater than 4 W/ m<sup>2</sup> but less than or equal to 10 W/ m<sup>2</sup> can use the currently approved methodologies, with an emission factor of 90 gCO<sub>2</sub>e/kWh for project reservoir emissions; and

<sup>137</sup> ibid

<sup>138</sup> Project design documents to be found at <http://cdm.unfccc.int/>

- greater than 10 W/ m<sup>2</sup> can use current approved methodologies and the project emissions from the reservoir may be neglected.

GHG emissions are addressed in more detail in the following session 5.2.

A second example for calculating emissions displacement is from a utility with a comprehensive climate change strategy, Manitoba Hydro (MH).<sup>139</sup> MH currently manages 5,000 MW of hydroelectric generation, and is preparing to add 2,500 MW of capacity through the development of three new hydropower facilities: Wuskwatim, Keeyask and Conawapa.

It is estimated that these projects would displace GHG emissions of ca. 8.7 million tons CO<sub>2</sub>e annually (based on typical emissions values from the US Environmental Protection Agency). US values are applied because hydropower projects in Canada are often large, sometimes exceeding several hundred megawatts. These increments are much larger than current load requirements in Manitoba, and MH needs to find export markets until Manitoba can grow into their full utilization or to take advantage of export opportunities.

Electricity exports from Canada have contributed to significant GHG reductions outside of Canada. Since 2005, annual electricity exports by MH have averaged over 10,000 GWh per year. MH also considers additional emerging electricity technologies in its generation planning and actively researches and supports their concept development, as well as energy efficiency programs and the rehabilitation of existing facilities.

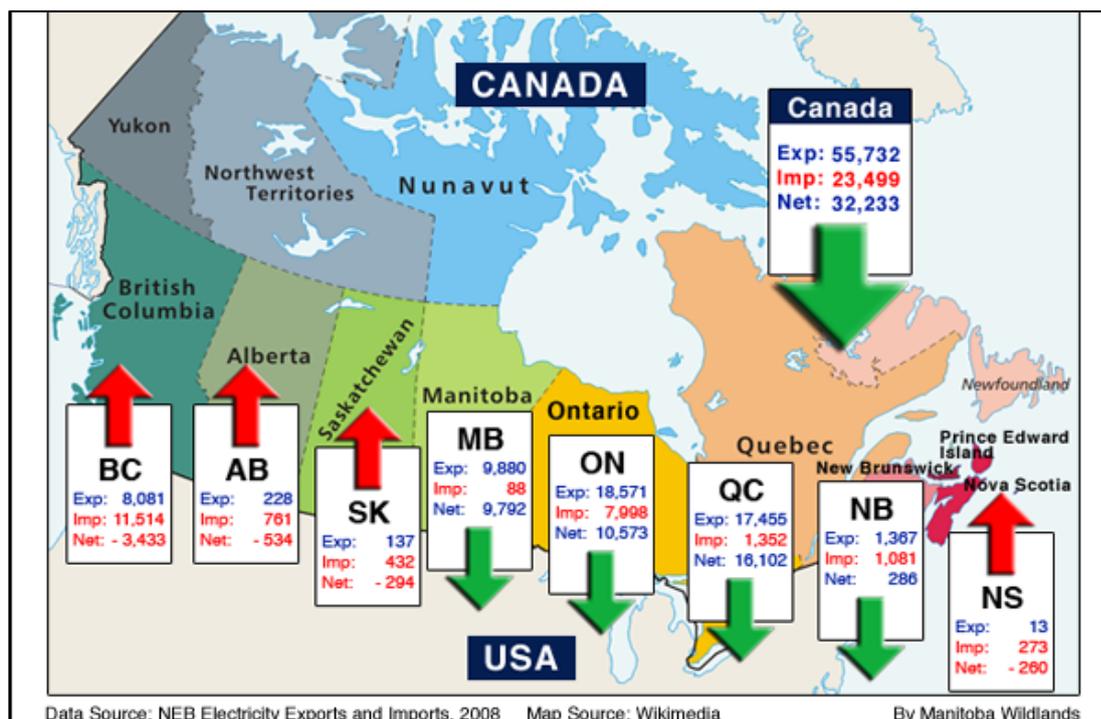


Figure 119: Canadian electricity exports and imports 2008<sup>140</sup>

MH is currently in public hearings about alternatives for its expansion planning, and the GHG implications of the different alternatives play an important role. Four major alternatives are being compared, from a preferred scenario with full hydro development, to an all-natural gas

<sup>139</sup> Manitoba Hydro (2013) Manitoba Hydro Climate Change Report

<sup>140</sup> NEB Electricity Exports and Imports (2008)

scenario. The chart below shows which major components would be commissioned in which year under the four scenarios.

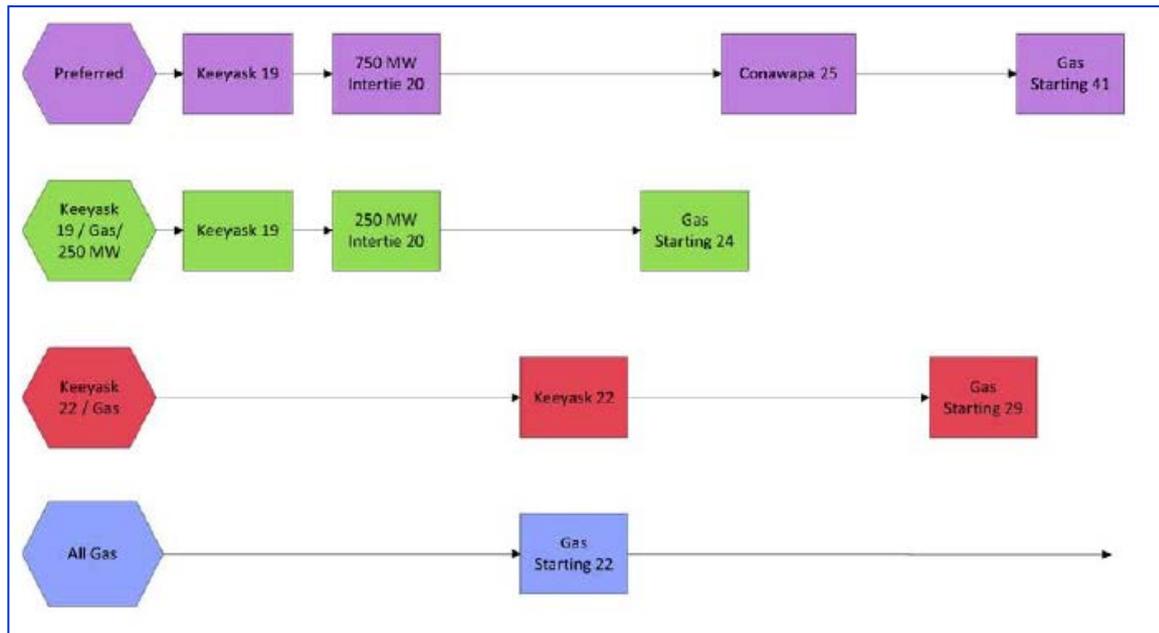


Figure 120: Four Manitoba Hydro expansion scenarios<sup>141</sup>

For all four scenarios, the chart below shows the reduction in GHG emissions against a hypothetical 'no project' alternative. (The reduction in GHG displacement over the long term in all scenarios is due to the fact that as demand grows in Manitoba, less power is exported.)

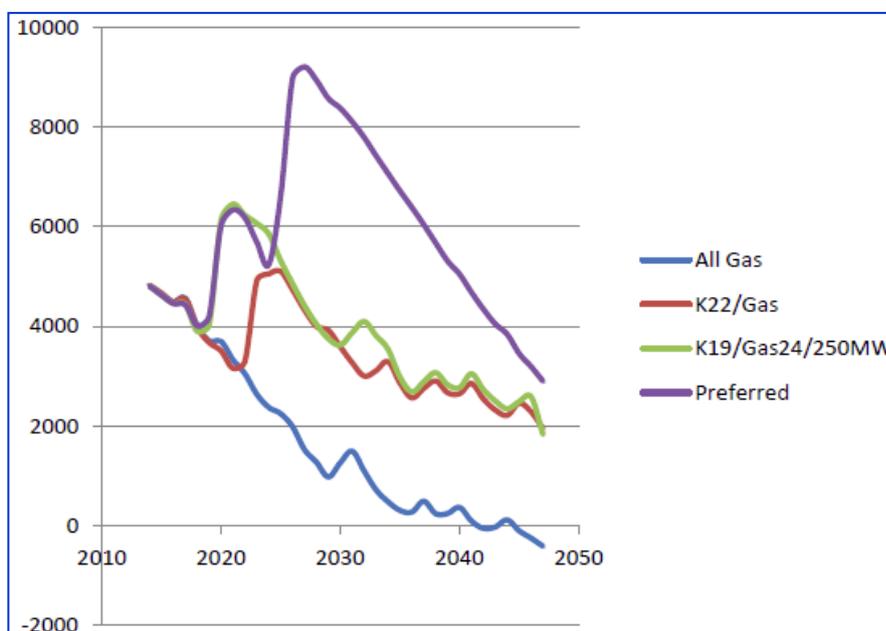


Figure 121: Reduction of thermal generation-related GHG emissions over time ('000 t of CO<sub>2</sub>)<sup>142</sup>

<sup>141</sup> Manitoba Hydro (2013) Needs For and Alternatives To (NFAT) report.

<sup>142</sup> *ibid*

In the valuation of the different scenarios, it was assumed that MH would have to pay for its carbon emissions. The timing and level of charges depend on future policies in Manitoba and Canada with respect to new emission taxes, or membership in a cap and trade system. In the absence of defined policies, the carbon pricing from other regions was considered. For the reference scenario analysis, the GHG emissions charge for natural gas-fired thermal generation was assumed to be ca. CAD 5/ton CO<sub>2</sub> in 2015 rising to approximately CAD 25/ton CO<sub>2</sub> by 2048. These assumed charges, however, do not reflect the full social cost of GHG emissions. Recent estimates of the social cost are higher than the assumed carbon charge.<sup>143</sup>

The four scenarios were finally compared with regards to (a) expected financial costs and (b) expected external costs of GHG emissions. Table 26 shows the savings from the preferred scenario compared to the three others.

	Preferred Development Plan	K19/G24/250MW	K22/Gas	All Gas
Estimated social cost of GHG emissions	188.8	472.6	427.6	620.4
Estimated coal tax and carbon charge payments	38.6	113.8	103.1	149.9
External Cost of GHG Emissions	150.2	358.8	324.5	470.5
Difference from Preferred Development Plan	-----	208.6	174.3	320.3

NFAT REFERENCE SCENARIO ASSUMPTIONS (2014 PRESENT VALUE IN MILLIONS 2014\$)

Table 27: External cost of Manitoba thermal generation-related GHG emissions

So far, we have looked at the direct displacement of emissions. But the benefits of hydropower for GHG mitigation can also be indirect, by allowing other renewables to enter the market. The table below from the IPCC shows characteristics of different renewable technologies. A key concept in the table is the capacity credit, which is another way of expressing 'firm capacity'. For example, if 10 GW of wind power plants are installed in a region, and their capacity credit is 10%, then there will be a reduction of 1 GW in the amount of other plants required, compared to a situation without wind capacity.

<sup>143</sup> Manitoba Hydro NFAT report: "Environment Canada has estimated that the social cost of GHG emissions, based on the present value of expected climate change costs is currently over \$28/ ton CO<sub>2</sub>, rising to almost \$60/ ton CO<sub>2</sub> by 2050 (in constant 2011\$). Including consideration of the willingness to pay to avoid uncertain, but potentially catastrophic, climate change impacts raises the estimated cost to over \$112/ ton CO<sub>2</sub>. Similarly, a U.S. government inter-agency team recently estimated the social cost of GHG emissions at \$38/ ton CO<sub>2</sub> in 2015 rising to \$71/ ton CO<sub>2</sub> in 2050 (in constant 2007\$ US), and recognized that the cost would be much greater the more that people are willing to pay to avoid damages in the future (the lower the discount rate), and the more that people are willing to pay to avoid uncertain, catastrophic risks."

Technology	Plant size range	Variability: Characteristic time scales for power system operation	Dispatchability	Geographical diversity potential	Predictability	Capacity factor range	Capacity credit range	Active power, frequency control	Voltage, reactive power control
	(MW)	Time scale	See legend	See legend	See legend	%	%	See legend	See legend
Bioenergy	0.1–100	Seasons (depending on biomass availability)	+++	+	++	50–90	Similar to thermal and CHP	++	++
Direct solar energy	PV	0.004–100 modular	Minutes to years	+	++	12–27	<25–75	+	+
	CSP with thermal storage*	50–250	Hours to years	++	++	35–42	90	++	++
Geothermal energy	2–100	Years	+++	N/A	++	60–90	Similar to thermal	++	++
Hydropower	Run of river	0.1–1,500	Hours to years	++	+	20–95	0–90	++	++
	Reservoir	1–20,000	Days to years	+++	+	30–60	Similar to thermal	++	++
Ocean energy	Tidal range	0.1–300	Hours to days	+	+	22.5–28.5	<10	++	++
	Tidal current	1–200	Hours to days	+	+	19–60	10–20	+	++
	Wave	1–200	Minutes to years	+	++	22–31	16	+	+
Wind energy	5–300	Minutes to years	+	++	+	20–40 onshore, 30–45 offshore	5–40	+	++

Table 28: Characteristics of different renewables for grid integration<sup>144</sup>

For illustration, the chart below shows the output of two wind farms over a week, with periods of no generation at all. It also shows that the two farms have slightly different generation profiles. The more wind farms are connected in a broader geographical region, the higher their capacity credit can be:

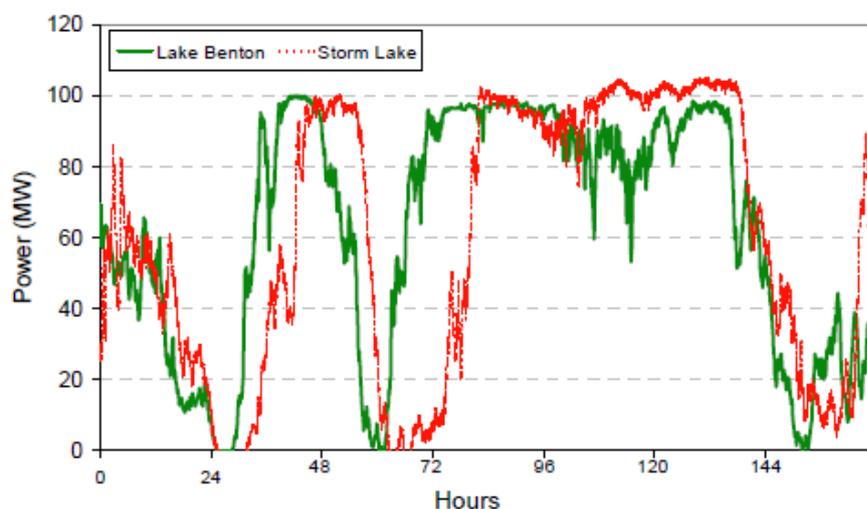


Figure 122: Wind power output over a week at two wind farms in the Midwestern US (CEATI 2011)

The variability of wind is important in terms of voltage regulation (within seconds to minutes), load following (over tens of minutes to hours), and days (with regards to generation scheduling). At all these time scales, hydropower can support wind integration.

In Denmark, for example, the high level of variable wind generation is managed in part through strong interconnections (1 GW) to Norway, where there is substantial storage hydropower. Technically, Norway alone has a long-term potential to add pumped storage

<sup>144</sup>Kumar et al (2011)

facilities in the 10 to 25 GW range, and to enable energy storage over periods from hours to several weeks in its reservoirs.<sup>145</sup>

	Total	Wind	Hydropower	Thermal
Denmark	35	10	-	19
Norway	128	1	122	5

Table 29: Power generation in 2011 in Denmark and Norway (TWh)

How relevant are these considerations for the LMB countries or, in other words, how much potential for GHG emissions reductions through hydropower exists in the LMB countries?

The three most relevant factors to answer this question are:

- the higher the share of fossil fuels in the existing energy mix (OM), the more can be replaced by a given addition of renewables (i.e. most in the Cambodian and Thai markets, almost nothing in the domestic Lao market)
- the higher the demand growth, the quicker new capacity (BM) will be introduced (i.e. most in Cambodia and Laos, while it is more difficult to replace existing gas capacity in Thailand)
- the higher the remaining potential for renewables, the more feasible are capacity additions (i.e. most in Laos)

	High share of fossil fuels in energy mix	High demand growth	High potential for hydropower
Thailand	~ 93%	+	+
Vietnam	~ 59%	++	++
Cambodia	~ 95%	+++	++
Lao PDR	~ 5%	+++	+++

Table 30: Potential avoided emissions from hydropower in LMB countries

In the future, not just hydropower but also 'new renewables' may reduce GHG emissions in the LMB countries. This will depend on a number of factors, including the following:

- Solar generation is quite predictable and peaks when demand for cooling is highest. It therefore can be built as soon as commercially feasible.
- Wind generation is lower cost, but the wind potential in the region appears to be limited and wind is less predictable. However, some wind could easily be integrated in the present LMB electricity system, due to its high share of hydropower and gas.

<sup>145</sup> IEA - ENARD (2010)

- Only at much higher levels of market penetration would wind and solar integration require detailed grid integration analysis and management, and might cause additional costs for back-up from dispatchable hydropower and natural gas capacity, or system modification.

In summary, avoided emissions from hydropower depend on the specific characteristics of the served electricity system, usually described by the operating and build margin, as in the CDM. The benefits of avoided emissions can be estimated through economic analysis, and may also provide financial revenue. Benefits also include support for the expansion of new renewables, which may require back-up and energy storage.

## 5.2 Session 5.2 Life-Cycle Emissions from Hydropower

Purpose and Learning Objectives	<p>The session provides an introduction to greenhouse gas emissions caused by hydropower projects, in a life-cycle perspective. Examples from northern and tropical hydropower projects are provided, and the key greenhouse gas emission impact (emissions from reservoirs) is reviewed in more detail.</p> <p>Trainees will gain a sense of scale of such emissions compared with those of other sources of electricity.</p>
Key Reading	<p>Item 5.1.2 - Manitoba Hydro (2012) Climate Change Report. Chapter 3: GHG Measurement and Reporting.</p> <p>Item 5.2.2 – Liden (2013) Greenhouse Gases from Reservoirs Caused by Biochemical Processes. World Bank Interim Technical Note.</p> <p>Item 5.2.3 – Deshmukh (2012) Greenhouse gases (CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>O) emissions from a newly flooded hydroelectric reservoir in subtropical South Asia: case of Nam Theun 2 Reservoir, Lao PDR- Chapters 7 and 8.</p>
Content	<p>What kinds and quantities of greenhouse gas emissions does hydropower produce?</p> <p>How does this apply to the Mekong region?</p>
Key Aspects	<p>While greenhouse gas emissions from hydropower construction, operation and decommissioning are often low, they are not negligible, particularly in warm climates.</p> <p>Techniques exist to predict and to partially mitigate emissions.</p>
Discussion Topics and Exercises	<p>Group discussion:</p> <p>How can/should siting, design and operational decisions take GHG emissions from reservoirs into account?</p>
Additional Resources	<p>Manitoba Hydro's Climate Change Report (2012) provides a good overview of a range of climate change issues for a hydropower utility, including issues beyond greenhouse gas emissions.</p>

A life-cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through

materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). LCAs can help to avoid a narrow outlook on environmental concerns by:

- Compiling an inventory of all relevant energy and material inputs and environmental releases;
- Evaluating the potential impacts associated with identified inputs and releases;
- Interpreting the results to help make more informed decisions.

Sometimes LCA is integrated into environmental impact assessments. LCA can also be applied to the product 'electricity'. Its life cycle impacts are then usually measured per unit (such as a kWh). The one impact that is of most interest is often the GHG emissions. The table below shows the range of recent data on the life cycle GHG emissions from various electricity technologies.

Values	Bio-power	Solar		Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
		PV	CSP								
Minimum	-633	5	7	6	0	2	2	1	290	510	675
25th percentile	360	29	14	20	3	6	8	8	422	722	877
50th percentile	18	46	22	45	4	8	12	16	469	840	1001
75th percentile	37	80	32	57	7	9	20	45	548	907	1130
Maximum	75	217	89	79	43	23	81	220	930	1170	1689
CCS min	-1368								65		98
CCS max	-594								245		396

Note: CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.

Table 31: Life cycle GHG emissions from electricity generation technologies in gCO<sub>2</sub>e/kWh<sup>146</sup>

The phases of a hydropower project that would be considered in an LCA include construction, operation and maintenance, and (sometimes) decommissioning. In the construction phase, primary GHGs emissions are from the production and transportation of materials (e.g., concrete, steel etc.) and the use of civil work equipment and materials for construction of the facility (e.g., diesel engines). In the operation and maintenance phase, GHG emissions can be generated by operation and maintenance activities, for example, building heating/cooling systems, auxiliary diesel generating units, or onsite staff transportation for maintenance activities. Furthermore, land use change induced by reservoir creation and the associated modification of the terrestrial carbon cycle must be considered, and may lead to net GHG emissions from the reservoir during operation. Dams can be decommissioned for economic, safety, or environmental reasons. Until now, only a few relatively small dams have been removed, mainly in the United States. Emissions related to this stage have rarely been included in LCAs.

The different activities in the stages of the various hydropower methods (reservoir, run-of-river, and pumped storage) will result in different LCA values (Figure 123).<sup>147</sup> In addition, the lifetime of a project strongly influences over how many years the construction and dismantling emissions are amortized.

<sup>146</sup> [http://srren.ipcc-wg3.de/report/IPCC\\_SRREN\\_Annex\\_II.pdf](http://srren.ipcc-wg3.de/report/IPCC_SRREN_Annex_II.pdf)

<sup>147</sup> Kumar et al (2011)

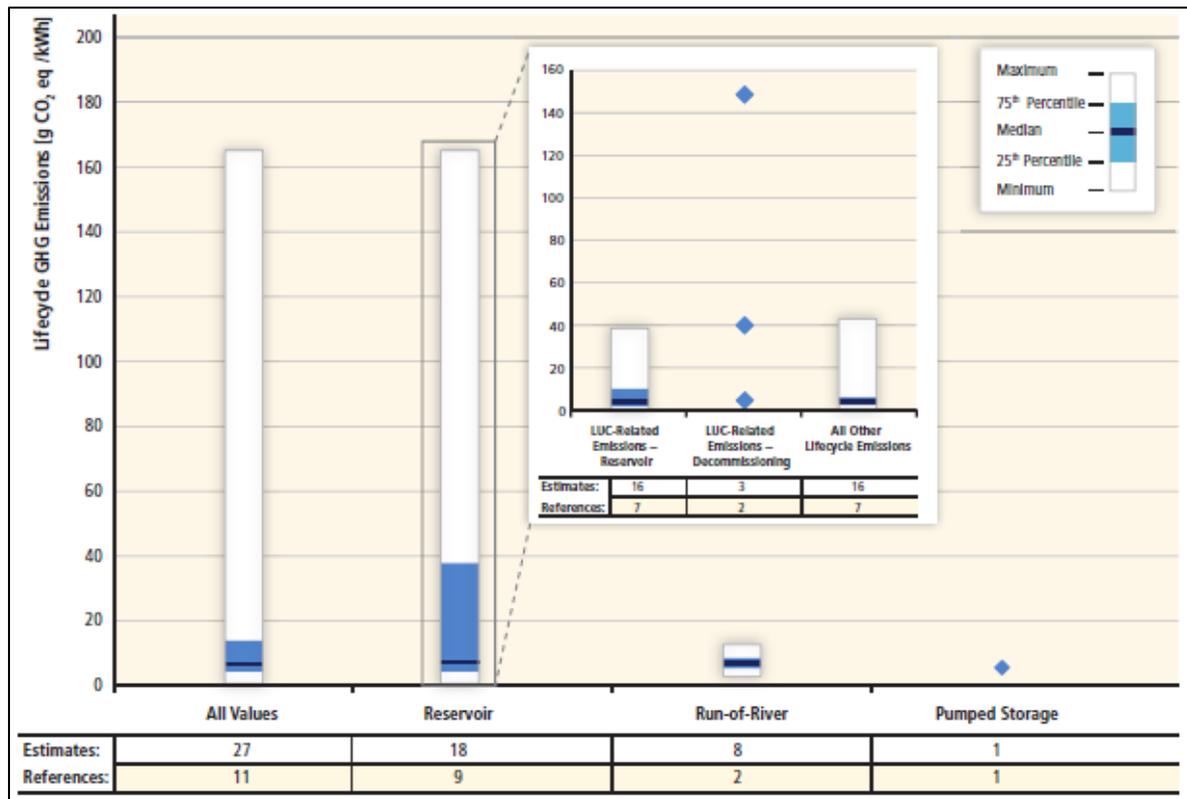


Figure 123: Hydropower life-cycle emissions: empirical data

Manitoba Hydro shows a specific example of their GHG emissions at the Keeyask and Wuskwatim hydropower projects in comparison to wind, gas, and coal technologies:

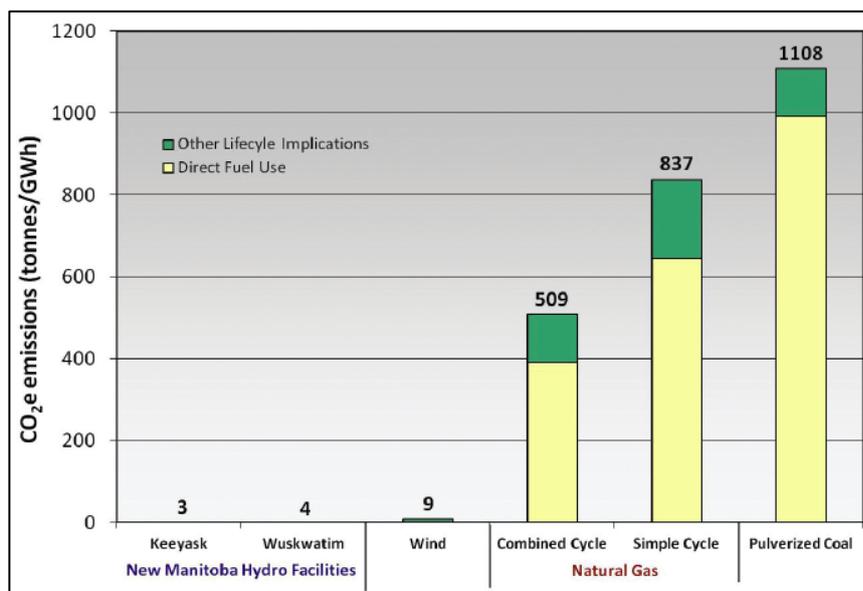


Figure 124: Life-cycle emissions for various generation technologies<sup>148</sup>

<sup>148</sup> Manitoba Hydro (2013) Manitoba Hydro Climate Change Report

Analyzing the Keeyask facility's GHG emissions further shows that more than half of these emissions are due to land-use change and almost another half are from the construction phase alone.<sup>149</sup>

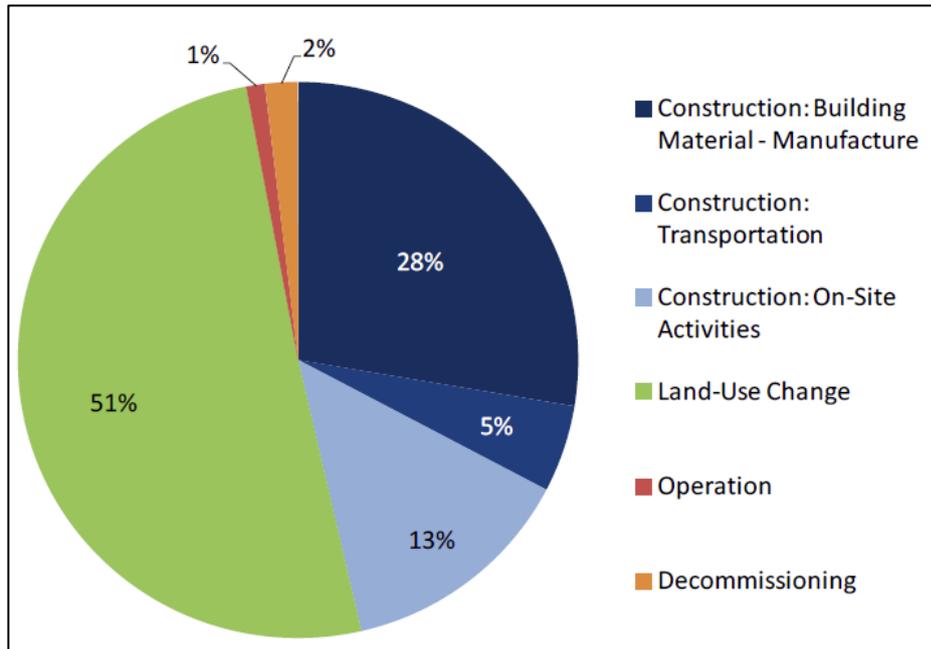


Figure 125: Breakdown of Keeyask life-cycle emissions

Other infrastructure associated with Manitoba Hydro's projects is also subjected to GHG analysis. For example, the life-cycle emissions for a new major transmission line are reported (Figure 126).<sup>150</sup> Again, the building and construction phase and land-use changes account for approximately three quarters of the total GHG emissions.

<sup>149</sup> Manitoba Hydro (2013) Needs For and Alternatives To report, Appendix 7.3

<sup>150</sup>

[https://www.hydro.mb.ca/projects/bipoleIII/eis/BPIII\\_Greenhouse\\_Gas\\_Lifecycle\\_Assessment\\_Technical\\_Report\\_November%202011.pdf](https://www.hydro.mb.ca/projects/bipoleIII/eis/BPIII_Greenhouse_Gas_Lifecycle_Assessment_Technical_Report_November%202011.pdf)

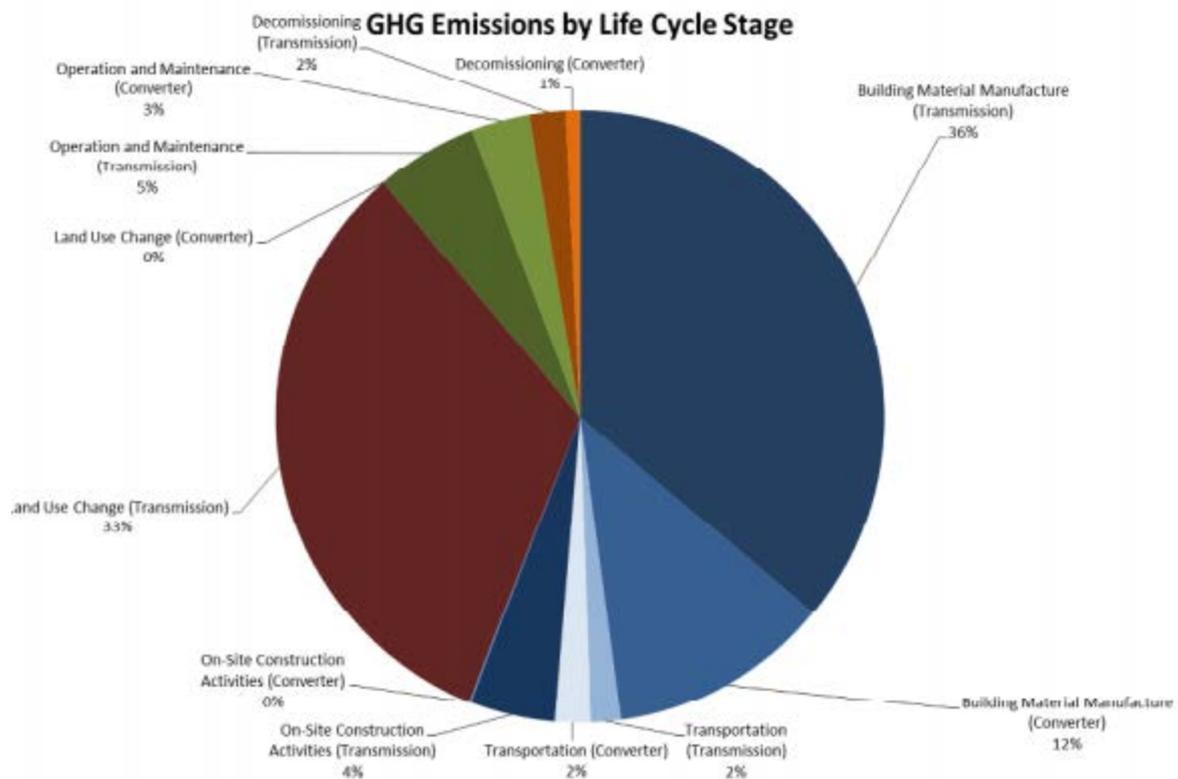


Figure 126: Life-cycle emissions for new Manitoba Hydro transmission line

For reservoir projects, typically the biggest components in LCAs are the activities involving the reservoir itself. We now turn to better understand those emissions. Pathways for GHG emissions to the atmosphere from reservoirs, as shown in Figure 127, include:<sup>151</sup>

- Diffusive flux: Discharge of GHGs from the air-water interface of a water body. Diffusion of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O can be observed from the water surface of the reservoir;
- Bubbling: Discharge in the form of gas bubbles, which result from carbonation, evaporation or fermentation bubble fluxes. This is an important pathway for CH<sub>4</sub>, through anaerobic decomposition of organic matter in the sediments, mainly in shallow water;
- Degassing: an emission that happens on discharge from low-level outlets (including turbine tailwaters) induced by dramatic pressure changes just downstream of the reservoir outlet(s);
- Increased diffusive fluxes along the river course downstream of a reservoir.

<sup>151</sup> IHA (2010) Greenhouse gas emissions related to freshwater reservoirs

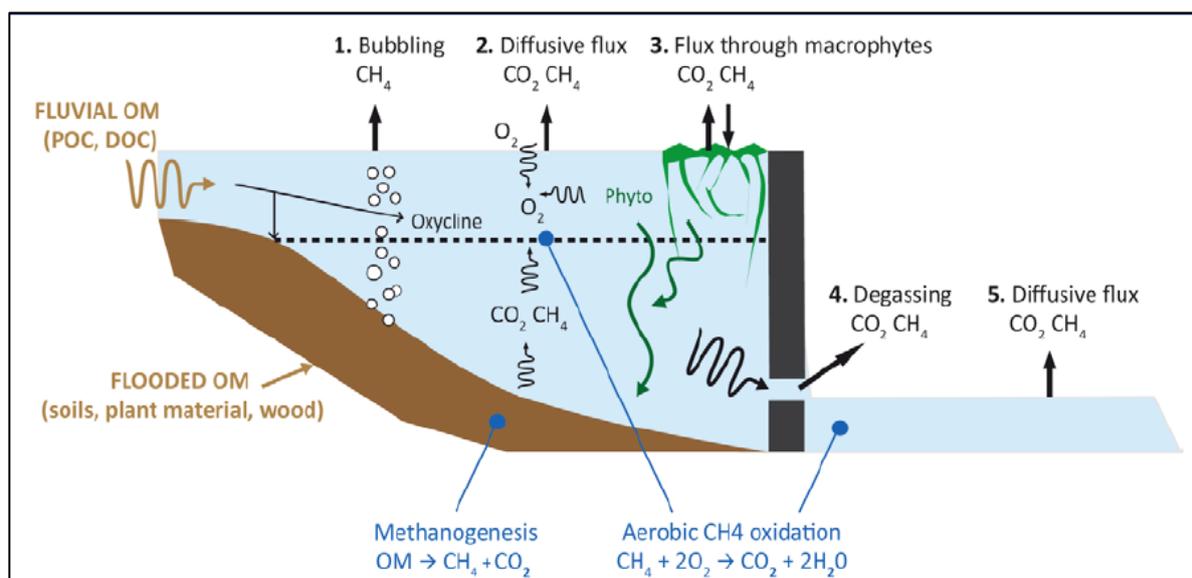


Figure 127: GHG pathways in a freshwater reservoir with an anoxic hypolimnion

Some of the main parameters or factors affecting GHG production are:

- Carbon and nutrient loaded into the reservoir;
- Rainfall;
- Soil type and land use;
- Biomass of plants, algae, bacteria and animals in the reservoir and in drawdown zone;
- Water temperature;
- Residence time;
- Stratification of the reservoir body;
- Reservoir age;
- Drawdown zone exposure (changes in water depth);
- Wind speed and direction;
- Presence of low level outlets;
- Increased turbulence downstream of the dam associated with ancillary structures, e.g. spillways and weirs;
- Reservoir shape (shoreline/surface ratio);
- Water depth.

For well-oxygenated reservoirs, pathways (2), (4), and (5) in the above chart are reduced.

Significant debate persists over the significance of contributions of GHGs from reservoirs. The country with the most in-depth research may be Canada. In one study, measurements of carbon fluxes from 57 hydroelectric reservoirs in four different Canadian provinces (Québec, Manitoba, British Columbia, and Newfoundland/Labrador) were evaluated. Out of these measured reservoirs, a subset of 25 was selected to develop a national emission curve for the 50-year period following impoundment (Figure 128).<sup>152</sup> This would indicate that emissions fall over time and that reservoirs may become a carbon sink eventually.

<sup>152</sup> Canada (2011) National Inventory Report

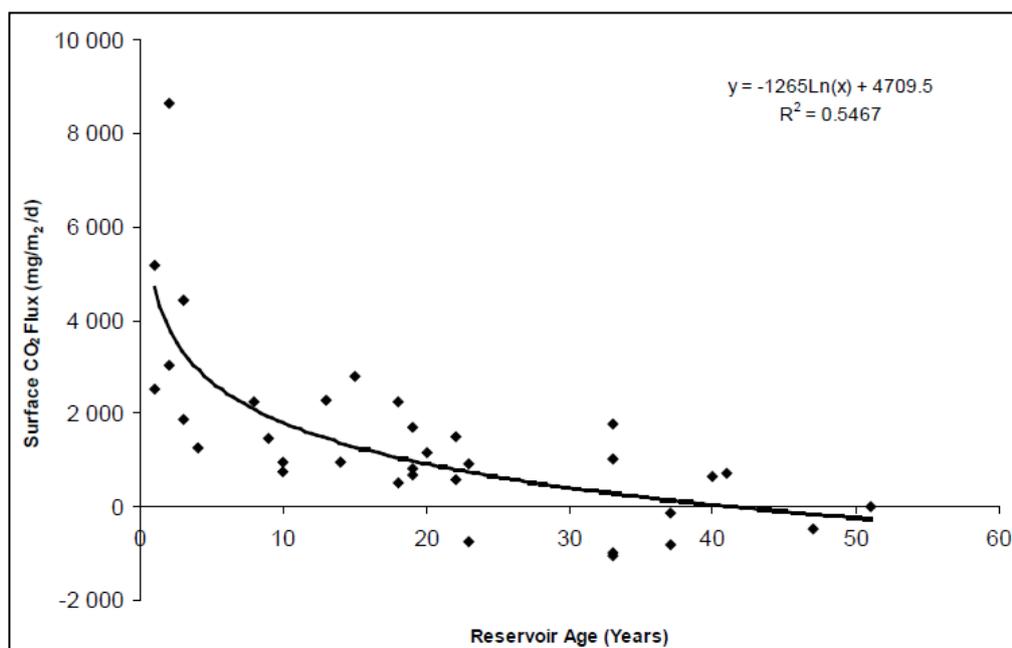


Figure 128: GHG emissions from reservoirs in Canada over time

In an example from the LMB region, the GHG emissions from the Nam Theun 2 reservoir in Laos were examined. Dam construction was completed in 2008 and filling of the reservoir was completed by 2010. This was one of the first studies that systematically assessed GHG emissions from the reservoir area before impoundment, in order to be able to provide net instead of gross emissions data. Table 27 provides both pre- and post-impoundment GHG values for the reservoir area.<sup>153</sup> Emissions significantly increased (by almost 10 times) after impoundment. The GHG emission factors per kwh were 310 and 300 gCO<sub>2</sub>e for the years 2010 and 2011. In comparing these values with Table 30 and Figure 124 above, it should be taken into account that (a) these are values for the first years after impoundment, when exceptionally high emissions are expected which are probably not representative for the whole life of the reservoir, (b) higher than average emissions would be expected from a tropical shallow reservoir like Nam Theun 2.

GHG	Pre-impoundment exchange	Post-impoundment exchange		Net GHG footprint	
	2008	2010	2011	2010	2011
Total CO <sub>2</sub>	-73 ± 225	1307 ± 244	1551 ± 197	1380 ± 332	1624 ± 299
Total CH <sub>4</sub> -CO <sub>2</sub> eq	7 ± 11	768 ± 206	473 ± 91	761 ± 206	466 ± 92
Total N <sub>2</sub> O-CO <sub>2</sub> eq	345 ± 258	93 ± 162	109 ± 170	-252 ± 305	-236 ± 309
Total CO <sub>2</sub> eq	279 ± 343	2168 ± 358	2133 ± 276	1889 ± 496	1854 ± 440

Table 32: GHG emissions from Nam Theun 2 reservoir

<sup>153</sup> Deshmukh et al (2012) GHG budget in a young subtropical hydroelectric reservoir: Nam Theun 2 case study

Since predictive quantitative models for GHG emissions do not yet exist, a risk analysis may be performed to predict the GHG emissions from new reservoirs. The first step must include the factors that determine the carbon supply. These include:

- Organic material in the catchment
- Land use in the catchment
- Biomass in reservoir and drawdown areas
- Agricultural practices (that influence both carbon and nutrient stocks, and carbon and nutrient ability)
- Rainfall

The second step includes factors that impact the ability to create GHGs:

- Residence time
- Temperature
- Stratification
- Drawdown zone exposure
- Reservoir age

The third step includes factors that influence the ability to release GHGs such as:

- Wind
- Water depth
- Reservoir shape (surface/shoreline ratio)
- Low level outlets

Siting, design, and operational choices influence all of these factors.

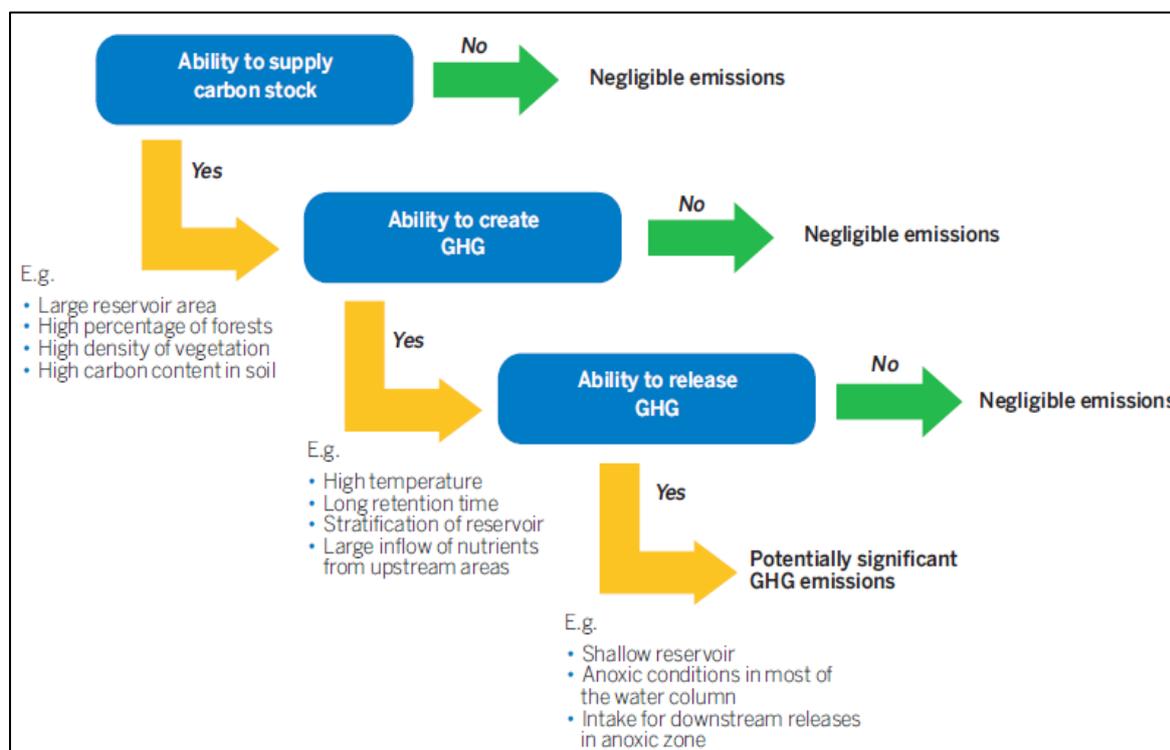


Figure 129: Risk analysis for GHG emissions<sup>154</sup>

<sup>154</sup> WB (2013) based on IHA (2010) Greenhouse gas emissions related to freshwater reservoirs.

## 6 MODULE 6. IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT IN THE MEKONG REGION

### 6.1 Session 6.1 Sustainable Power Systems

Purpose and Learning Objectives	<p>This session addresses sustainability at an intermediate, sector-level scale, between the individual project and the macro-level of the entire society. It looks at projections of power sector development in the Mekong region to the year 2035, and considers policy options to influence the directions the power sectors will take. The quantitative and qualitative role of hydropower within sustainable power sectors will be discussed.</p> <p>Trainees will learn to appreciate the complexities of power investment decisions in a context where not just the climate but also many other factors are uncertain.</p>
Key Reading	Item 6.1.1 - International Energy Agency (2013) Southeast Asia Energy Outlook. World Energy Outlook Special Report.
Content	<p>What policies can be used to promote sustainability in a power sector?</p> <p>Which scenarios are projected for the power sectors in South-East Asia?</p> <p>What is the expected role of hydropower in these sectors?</p>
Key Aspects	<p>Power generation in the Mekong countries will expand quickly.</p> <p>Investment decisions are made under multiple uncertainties.</p> <p>Sector policies can influence growth paths.</p>
Discussion Topics and Exercises	<p>Group discussion (for each country):</p> <ul style="list-style-type: none"> <li>- How ambitious should sector policies be to achieve a low-carbon, qualitatively transformed power sector, by 2035?</li> <li>- How would this affect the competitive position and the role of hydropower in the power systems?</li> </ul>

This session addresses sustainability at an intermediate, sector-level scale, between the individual project and the macro-level of the entire society. A sustainable power system is more than just a collection of sustainable power projects; it must include sustainable policies as well.

Typical policy objectives of the power sector include:

- Providing universal access to service, to make available the socio-economic benefits of rural electrification
- Guaranteeing security of supply, as reliability increases incentives to invest and reduces the costs of supply interruptions
- Using indigenous resources in order to reduce dependence on imports
- Minimizing direct costs of supply through least-cost planning or through competition
- Minimizing negative externalities (indirect costs)

These policy objectives may differ depending on the location (i.e., developing versus developed nations) and timing (i.e., stage in power sector development). For example, the importance of using indigenous resources is amplified in countries with difficult security situations. In Israel, energy security and independence comes before all other objectives.<sup>155</sup>

Hydropower can support but also presents challenges for some of these policy objectives. For example, supply security depends on the reliability of flows, availability of storage, and sufficient generation capacities. Hydropower is an indigenous resource, but transboundary rivers present some limits on independence. Negative externalities can be high, even if there are low GHG emissions.

Standard policy objectives may be modified under climate change scenarios. Instead of just providing universal access to heating, a modified objective may be to provide electricity for heating, instead of fossil fuels. To guarantee security of supply, diesel emergency generators may be replaced with strengthened transmission lines. Indeed, many countries have updated their energy sector policies in recent years to take climate change into account.

Several policy instruments can be used in the power sector to encourage renewable technologies growth and overcome barriers to implementation:

- Planning (indicative or binding)
- Structural and competition policies
- Regulation of power companies
- Licensing of power plants and transmission lines
- Taxes, subsidies, and funding to companies and consumers
- Investment by state-owned companies
- Measures to secure and expand fuel supplies

The following Table 32 shows some specific examples for possible sector policies in developing countries, and a number of barriers to overcome:

Policy reform	Barriers to overcome
Remove subsidies to ensure more efficient use of electricity; allow generation companies to charge competitive rates	Social concerns that raising tariffs will impact access to affordable energy
Reforming planning system so that it does not disadvantage clean energy	Historic reliance on fossil sources; concern over reliability of renewable sources
Carbon tax or feed-in tariffs to increase renewable competitiveness	Political opposition to increasing consumer bills; requirement to get levels correct to induce change
Capacity for long term planning	Capital constraints and supply bottlenecks mean short term outlooks dominate
Reduce losses in T&D system, including reduction in unauthorized use	Capital constraints to upgrade; lack of administrative capacity to deal with non-

<sup>155</sup> Israeli Ministry of National Infrastructures, Energy, and Water Resources. 2014. <http://energy.gov.il/English/Subjects/RenewableEnergy/Pages/GxmsMniRenewableEnergyAbout.aspx>

	payment / theft
Promotion of decentralized renewables e.g. through subsidies	Capital requirements; issues around technology maintenance capacity
Enhance regional grid connections to ensure supply reliability and flows of low carbon power	Multi-national agreements need to be in place; large capital
Reduce risks of energy prospecting e.g. provide geothermal drilling assessments or ensure good wind monitoring data available	Cost outlay without guarantee of investment

Table 33: Steps towards transformation to a low carbon power sector<sup>156</sup>

Prior to considering how to transform to a low-carbon power sector, it is helpful to first establish the current status of a power sector. One of the key indicators in this regard is the 'energy intensity' of a nation. This is the electricity required to produce a unit of GDP, and is a measure of the energy efficiency of the economy. This relationship is partly correlation and partly causality. For example, Singapore has approximately two times the GDP per capita as South Korea but less per capita electricity demand, so a much higher energy efficiency, or lower energy intensity. These nations serve as two different examples of where LMB nations could be in the future.

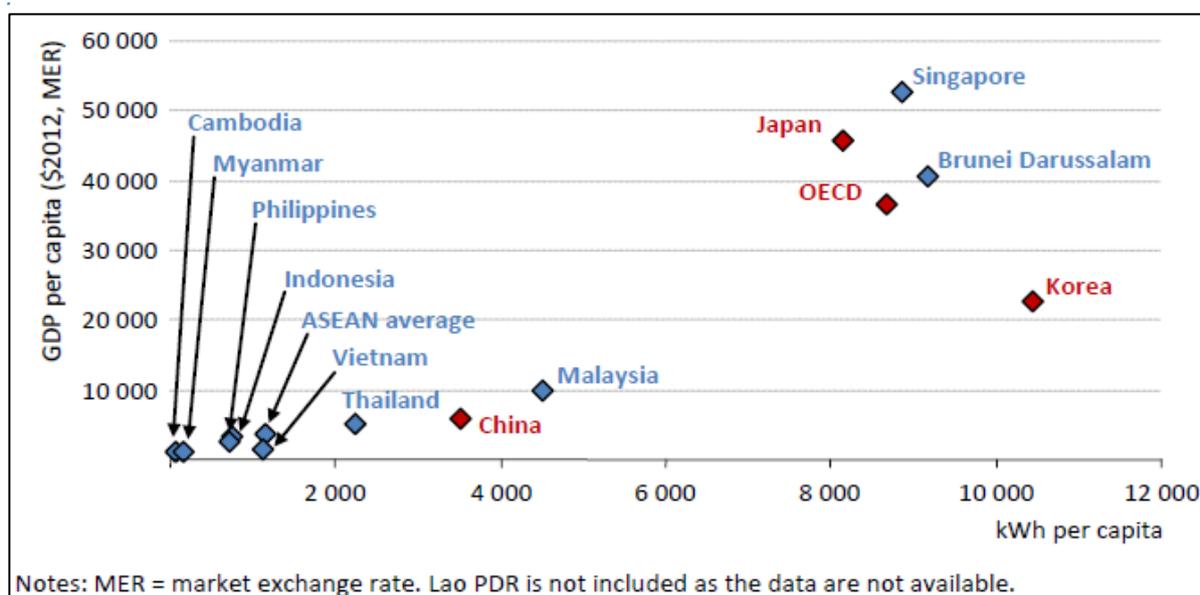


Figure 130: Per capita electricity demand and GDP per capita in ASEAN (blue) and other countries for comparison (red), 2011<sup>157</sup>

<sup>156</sup> Pye et al (2010) The Economics of Low Carbon, Climate Resilient Patterns of Growth in Developing Countries: A Review of the Evidence. Report for DFID.

<sup>157</sup> International Energy Agency (2013) Southeast Asia Energy Outlook

Another key indicator is the current status of access to modern energy services, as given in Table 33 below. In the Association of Southeast Asian Nations (ASEAN), in 2011 134 million people were still without electricity and 279 million people used traditional biomass methods for cooking. In the LMB, 14 million people were without electricity and 84 million people without modern cooking fuels.

	Population without access to electricity		Population relying on traditional use of biomass for cooking*	
	Million	Share (%)	Million	Share (%)
Brunei Darussalam	0	0%	0	0%
Cambodia	9	66%	13	88%
Indonesia	66	27%	103	42%
Lao PDR	1	22%	4	65%
Malaysia	0	1%	1	3%
Myanmar	25	51%	44	92%
Philippines	28	30%	47	50%
Singapore	0	0%	0	0%
Thailand	1	1%	18	26%
Vietnam	3	4%	49	56%
<b>Total ASEAN</b>	<b>134</b>	<b>22%</b>	<b>279</b>	<b>47%</b>

\* Preliminary estimates based on IEA and World Health Organization (WHO) databases. Final estimates for 2011 will be published online at [www.worldenergyoutlook.org](http://www.worldenergyoutlook.org).

Table 34: Access to modern energy services in ASEAN, 2011<sup>158</sup>

From these starting points, policy makers can begin to examine their choices in creating a future low-carbon power sector. Costs are generally the most significant factor in the choice of power technology. Figure 131 shows that diesel-fired electricity is usually the most expensive of all choices. Fossil fuel costs in OECD countries are around 10 US cent/kWh, which is broadly comparable to LMB countries, as there is a world market in fossil fuels and generation technologies. The costs of renewable technologies - except offshore wind and solar - are broadly similar to those of fossil fuels. Renewables in the OECD are slightly more expensive than outside the OECD; and several renewables (biomass, hydro, geothermal) are actually cheaper than fossil fuels outside the OECD.

<sup>158</sup> *ibid*

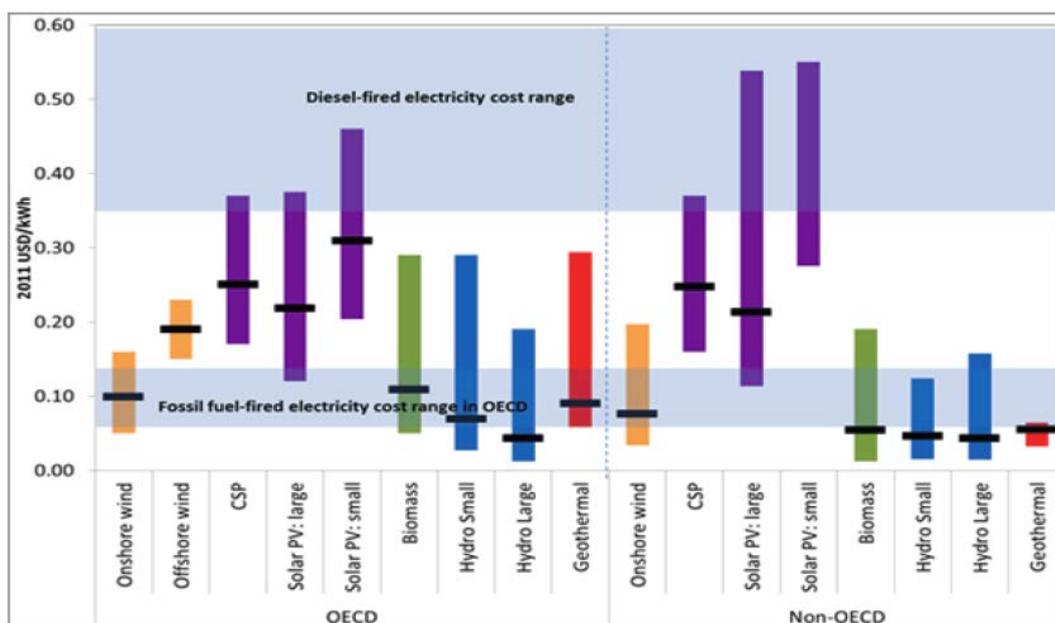


Figure 131: Current direct costs of fossil and renewable power technologies<sup>159</sup>

The indirect costs of power technologies should also be compared, in addition to the direct costs. The table below shows the range of costs from the literature, indicating that the indirect costs are ranked descending from coal and oil, then nuclear and gas, biomass and hydro (site-specific), and finally wind and solar.

	Coal	Oil	Nat. Gas	Nuclear	Hydro	Wind	Solar	Biomass
N	36	20	31	21	16	18	11	22
Min	0.01	0.04	<0.01	<0.01	0	0	0.00	0
Max	90.61	53.43	17.69	86.23	35.14	1.18	2.94	29.56
Mean	18.75	16.48	6.17	9.53	4.50	0.41	1.12	6.62
Median	8.54	12.19	3.51	1.08	0.43	0.43	1.02	3.59

Table 35: Indirect costs of competing power technologies (cents/kWh)<sup>160</sup>

An important element of indirect costs is the social cost of carbon. The social cost of carbon is a measure of the benefit of reducing greenhouse gas emissions now and thereby avoiding costs in the future. As a very simple example, if emissions damage coral reefs, which in turn discourage tourists from visiting Australia, one cost incurred will be lost revenue to the tourist industry. Avoiding that cost is a benefit.<sup>161</sup> Another indirect cost is the local pollution and health problems near coal plants and coal mines. Some indirect costs, including the social cost of carbon, are felt globally, and for an individual small country there may be little incentive to reduce such externalities.

<sup>159</sup> IRENA (nd) Factsheet: Renewables Becoming More Competitive Worldwide at <http://www.irena.org/DocumentDownloads/factsheet/costing%20factsheet.pdf>

<sup>160</sup> Sundqvist and Soderholm (2002) in Resources for the Future (2012) The True Cost of Electric Power.

<sup>161</sup> WRI (2011) More than meets the eye: the social cost of carbon.

In the following, some projections for the ASEAN region for the period 2011-2035 are presented. These have been developed by the International Energy Agency, and assume certain cost developments and choices by policymakers. Total electricity demand in ASEAN is expected to increase, with broader access and urbanization increasing the share of residential demand:

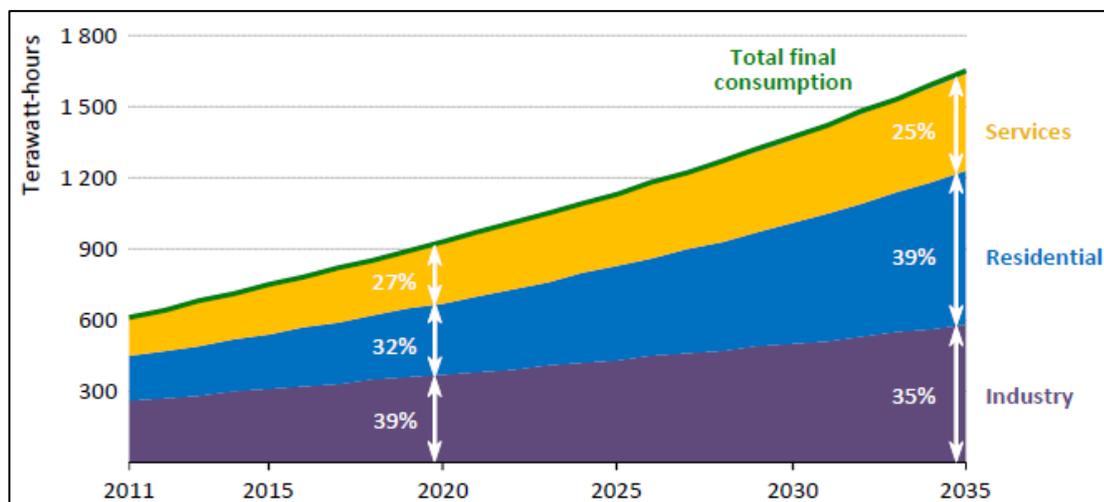


Figure 132: Projections to 2035: Total electricity demand in ASEAN<sup>162</sup>

High investments in the order of about USD 150 bn will be required to satisfy this increase in demand, providing a chance to create a very modern capital stock. Most investments are currently projected in coal and hydro, as well as transmission and distribution networks.

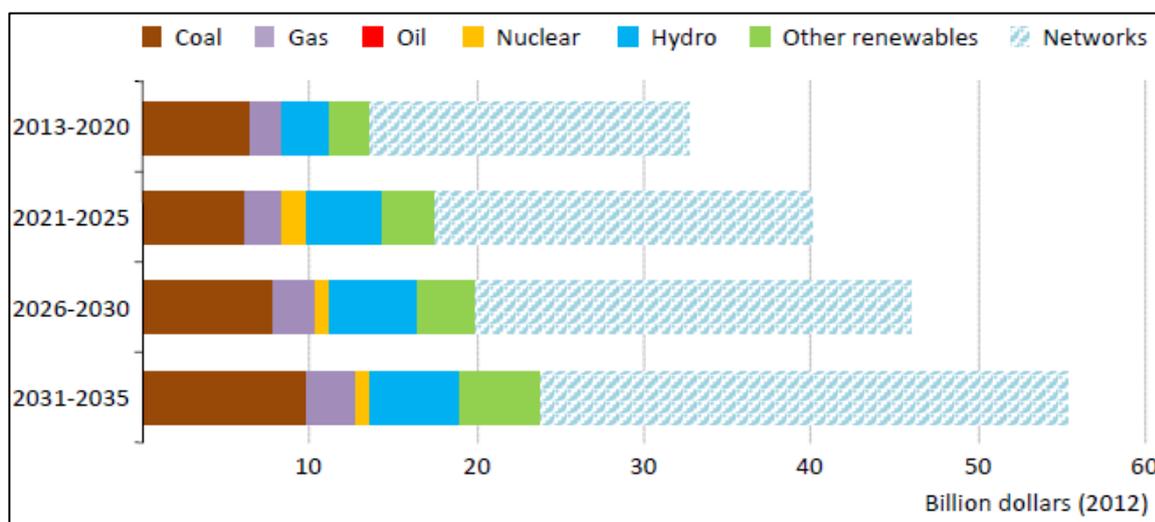


Figure 133: Projections to 2035: Power sector investments in ASEAN<sup>163</sup>

Generation capacity will grow accordingly, with gas and coal continuing to contribute the highest capacities. Renewables and nuclear will also continue to grow, but they are starting from very low levels:

<sup>162</sup> International Energy Agency (2013) Southeast Asia Energy Outlook

<sup>163</sup> *ibid*

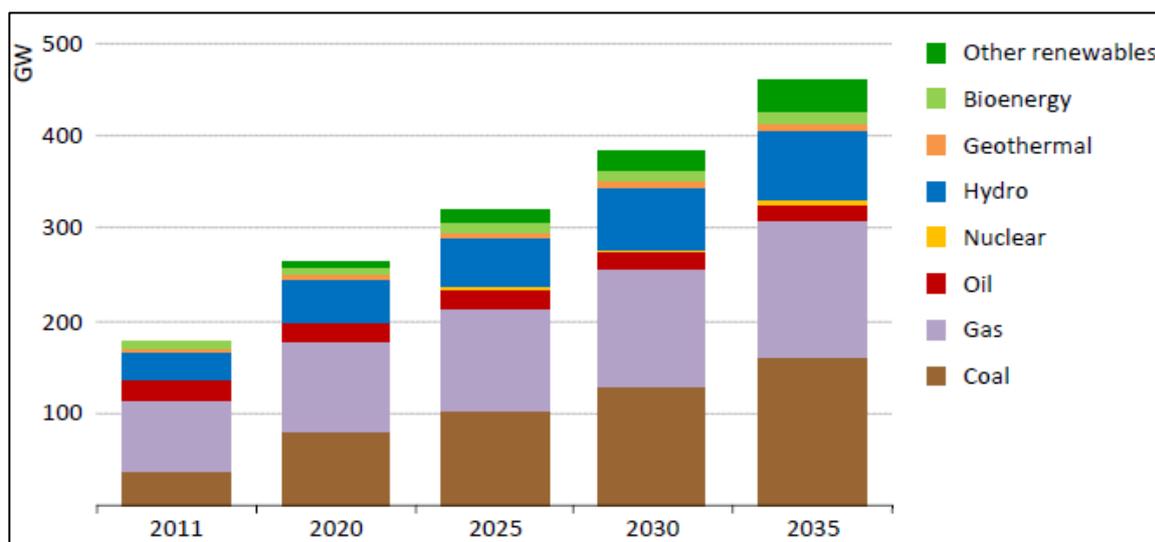


Figure 134: Projections to 2035: Generation capacity in ASEAN<sup>164</sup>

Total generation from different sources is shown in the table below. The growth of coal outpaces most other technologies; nuclear and renewables also show strong growth. Gas has a slower rate of growth, and oil continues to be phased out.

	1990	2011	2020	2035	2011-2035**	Share	
						2011	2035
<b>Fossil fuels</b>	<b>120</b>	<b>596</b>	<b>880</b>	<b>1 470</b>	<b>3.8%</b>	<b>86%</b>	<b>78%</b>
Coal	28	217	439	914	6.2%	31%	49%
Gas	26	307	394	523	2.2%	44%	28%
Oil	66	72	47	34	-3.1%	10%	2%
<b>Nuclear</b>	<b>-</b>	<b>-</b>	<b>-</b>	<b>31</b>	<b>n.a.</b>	<b>0%</b>	<b>2%</b>
<b>Renewables</b>	<b>34</b>	<b>100</b>	<b>184</b>	<b>378</b>	<b>5.7%</b>	<b>14%</b>	<b>20%</b>
Hydro	27	73	122	214	4.6%	10%	11%
Geothermal	7	19	28	51	4.1%	3%	3%
Bioenergy	1	8	23	63	9.2%	1%	3%
Other	0	0	11	50	24.0%	0%	3%
<b>Total</b>	<b>154</b>	<b>696</b>	<b>1 063</b>	<b>1 879</b>	<b>4.2%</b>	<b>100%</b>	<b>100%</b>

\* Inter-regional trade in electricity (*i.e.* from the ASEAN region to/from other regions) is assumed to be zero.  
 \*\* Compound average annual growth rate.

Table 36: Projections to 2035: Generation in ASEAN (Twh)<sup>165</sup>

As mentioned above, these energy sector projections are based on model assumptions (e.g., population and income growth, costs of fuels and power technologies) and policy scenarios that are uncertain. It is quite possible that policy changes may occur in major emitting countries, at the global policy level, or at the national level in South East Asia, that would alter these projections. An effective global carbon market might be created between

<sup>164</sup> ibid

<sup>165</sup> ibid

now and 2035, which would create much larger incentives for renewables. Southeast Asian countries may introduce major demand management or energy efficiency policies. As an illustration of sensitivities, the following graph shows the impact of different fossil fuel costs on the competitiveness of different technologies.

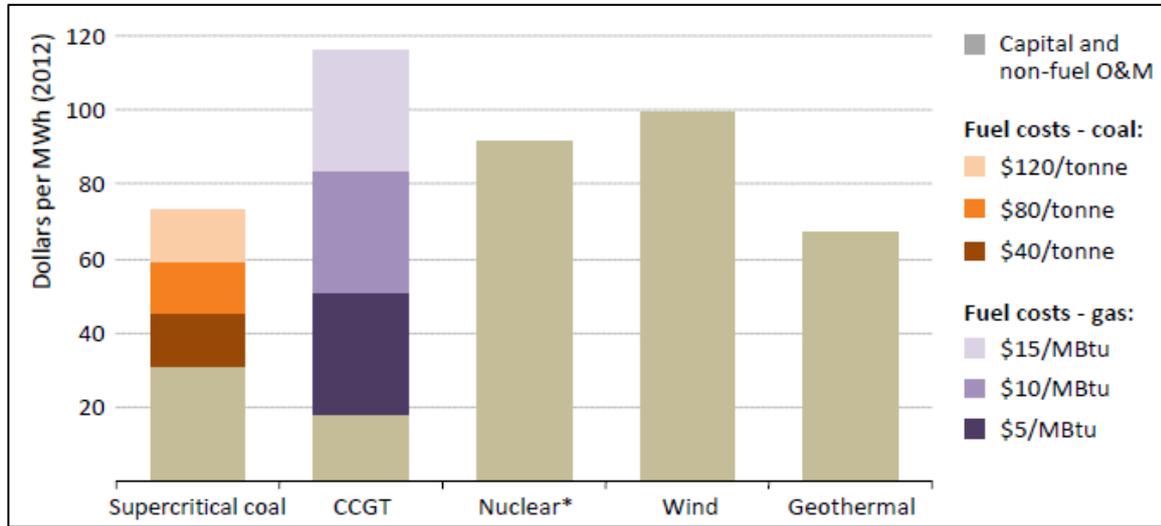


Figure 135: Impact of fuel costs on competing power technologies in ASEAN (2020-2035)<sup>166</sup>

Another major uncertainty is the future energy intensity. Countries like China, India and Vietnam have already significantly improved their energy intensity, measured in ‘toe’ or tons of oil equivalent per unit of GDP. However, Malaysia and Thailand have increased theirs as they industrialized. The goal of many ASEAN countries will be to continue to improve their levels to that of OECD or other Asian countries. This depends on their role in the world economy. Producers of manufactured goods – especially where these involve heavy industries – have a higher energy intensity than service-oriented industries.

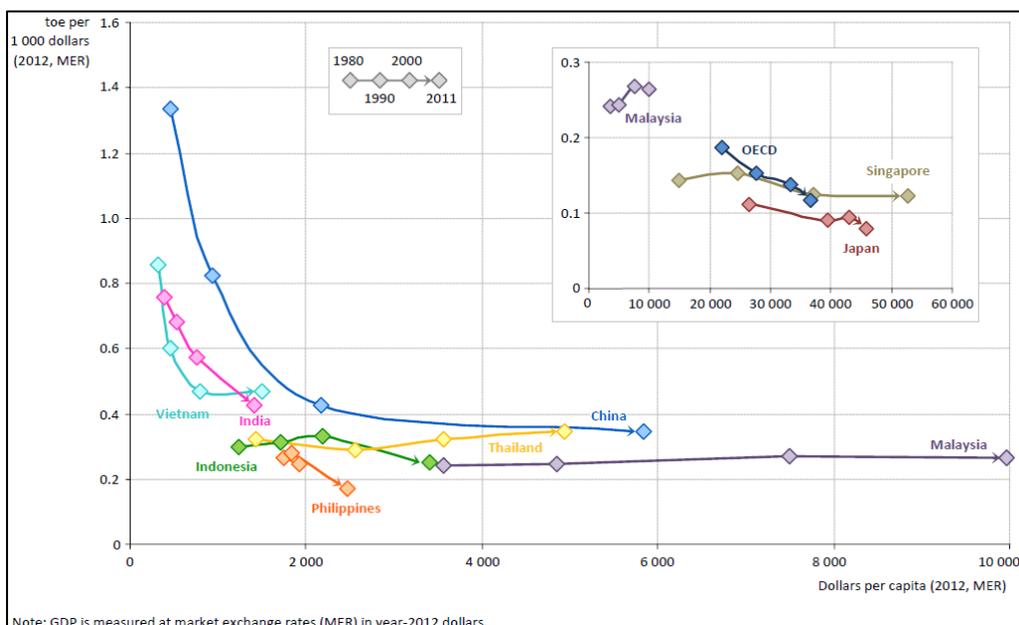


Figure 136: Trends in energy intensity and GDP per capita, 1980-2011<sup>167</sup>

<sup>166</sup> ibid

Finally, expected changes in the sector are not just quantitative (i.e. one source of power replacing another) but they are also qualitative. Some emerging qualitative trends are listed in the table below, and may change the future role of hydropower in energy systems. While they are more speculative, to some extent they could undermine hydropower's role as a large, centralized, and dispatchable source of power.

Traditional power systems	Future power systems
Power flows from large generators into a high voltage transmission grid and passes multiple transformation substations until it reaches consumers in the low voltage grid.	A large number of decentralized renewables plants feed in power on the low voltage levels of the distribution grid.
Power demand cannot be controlled. All generators together can meet the demand in any place and anytime.	Consumption is influenced via demand side management technology, thereby adapting it to the generation of power.
Power cannot be stored effectively.	There is a variety of cost-effective storage technologies (such as the batteries of electric vehicles) for balancing of generation and load.

Table 37: Potential major long-run changes in power systems<sup>168</sup>

<sup>167</sup> ibid

<sup>168</sup> AlpEnergy (2011) Sustainable Power Systems for the Alpine Space - Guidelines for Decision Makers and Practitioners

## 6.2 Session 6.2 Sustainable Societies and Ecosystems

<p>Purpose and Learning Objectives</p>	<p>This session draws some conclusions on the impacts of hydropower development and climate change on economic development, livelihoods, ecosystems, and biodiversity. It will review how positive and negative impacts of hydropower are modified in a changing climate, and how societies can use that understanding to achieve more sustainable development.</p> <p>Trainees will reflect on the complex relationships that have been explored in the course, and relate them to the ultimate policy goal of sustainable development.</p>
<p>Key Reading</p>	<p>Item 6.2.1 - Zhuang et al (2011) The Economics of Climate Change in SE Asia.</p> <p>Item 6.2.2 – Brown (2010) The End of Reliability.</p> <p>Item 6.2.3 – WWF (2010) Flowing Forward: Freshwater ecosystem adaptation to climate change in water resources management and biodiversity conservation. WB Water Working Note 28.</p>
<p>Content</p>	<p>What does sustainable development under climate change look like? How do climate change and hydropower jointly impact natural resources in the LMB countries? What are the implications for development planning?</p>
<p>Key Aspects</p>	<p>The future climate is uncertain, and we can reduce the uncertainty only partially by investing more in research.</p> <p>Reliable water and power infrastructure is an important element of sustainable development. In an uncertain future climate, reliability is more difficult to achieve.</p> <p>There are complex relationships between climate, ecosystems and the economy that have to be managed well to achieve sustainable development.</p> <p>Climate change is an additional challenge on top of other difficult problems, but some robust or win-win solutions may be available.</p> <p>Hydropower can help achieve sustainable development. But current planning is often too short-sighted, relies on narrow and deterministic planning methods, and does not take climate change into account.</p>
<p>Discussion Topics and Exercises</p>	<p>Group discussion:</p> <ul style="list-style-type: none"> <li>- Compared to your opinion before the beginning of the course, are you more or less in favour of hydropower?</li> <li>- What could be some first practical steps towards more climate-aware hydropower development in your country?</li> </ul>

This manual has examined the impacts of hydropower development and climate change on economic development, livelihoods, ecosystems, and biodiversity. This last session will review how positive and negative impacts of hydropower are modified in a changing climate, and how societies can use that understanding to achieve more sustainable development.

Sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.<sup>169</sup> While this has proven to be a useful definition, there are major interpretation issues. In particular, ‘needs’ are potentially unlimited. Is the level of consumption in the OECD really needed?

Some basic concepts from economics may be helpful. Income is defined as the “amount that people can consume without impoverishing themselves”.<sup>170</sup> This can be applied to an individual, to a family, to a business, and even to an individual nation. Societies need to manage three types of capital: economic, social, and natural. Some of these capital stocks may be non-substitutable. Using up some parts of natural capital, for example, may damage the ability to generate income from the other parts. Consumption of some capital stocks may be irreversible, while others can be replaced.

An example of this concept is of the independent state of Nauru, a 21 km<sup>2</sup> island in the Pacific with about 10,000 people.<sup>171</sup> The people of Nauru were largely dependent on phosphate mining for their income. For a while, the state had some of the highest per capita income in the world. Today, 80% of the island has been mined and their reserves are exhausted. The people of Nauru are living off of the interest of a (badly managed) trust fund; income is declining, unemployment rates are high, social problems (e.g., obesity) are rampant. Other income options are few; they include detention centers for Australian refugees or the sale of fishing and overflight rights. Climate change is now further reducing its options, by threatening the remaining habitable coastal parts of the island. Yet, most people want to stay on their island.

Even if their mining efforts were well executed, could Nauru’s strategy to replace natural capital with financial capital have been sustainable? Is ‘weak’ sustainability, which allows substitution (e.g., replacing Nauru’s soil with financial assets), enough? Or is ‘strong’ sustainability required, i.e. maintaining all components of capital (economic, social, and natural) at least at the current level? If strong sustainability were required, replacing a natural river with a hydropower reservoir may not be feasible.

One way of looking at the compatibility of socio-economic quality of life and environmental quality is to compare relevant indices. Quality of life has long been measured by combining indicators of life expectancy, educational attainment, and income into a composite human development index (HDI). The HDI shows where each country stands, expressed as a value between 0 and 1. The HDIs of nations in the LMB are<sup>172</sup>:

- Thailand: 0.690
- Vietnam: 0.617
- Lao PDR: 0.543
- Cambodia: 0.543

One way to measure environmental quality is the ‘ecological footprint’, a measure of human demands on the Earth, which is expressed in ‘global hectares per capita’. It is a standardized measure of demand for natural capital that may be contrasted with the Earth’s ecological capacity to regenerate. It represents the amount of biologically productive land and sea area necessary to supply the resources a human population consumes, and to assimilate

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<sup>169</sup> Brundtland Commission (1987)

<sup>170</sup> Hicks (1946)

<sup>171</sup> <http://en.wikipedia.org/wiki/Nauru>

<sup>172</sup> Wikipedia. [http://en.wikipedia.org/wiki/List\\_of\\_countries\\_by\\_Human\\_Development\\_Index](http://en.wikipedia.org/wiki/List_of_countries_by_Human_Development_Index)

associated wastes. Simply, it represents “how many Earths” would be needed to support humanity, given a certain lifestyle. The ecological footprints of nations in the LMB are:<sup>173</sup>

- Thailand: 2.37
- Vietnam: 1.40
- Lao PDR: 1.28
- Cambodia: 1.03

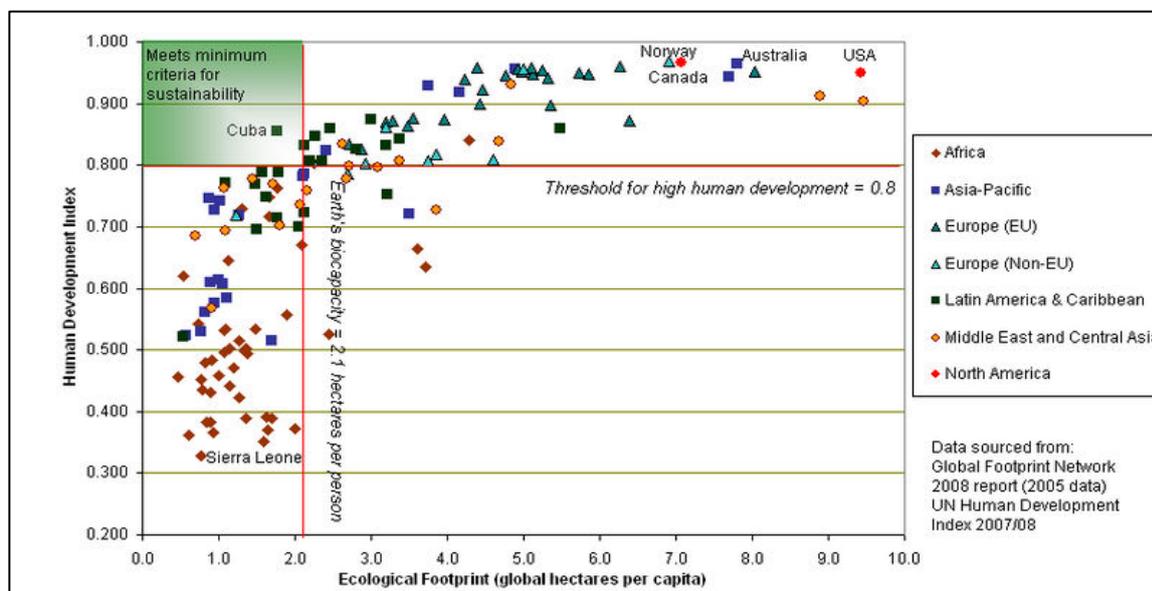


Figure 137: Human welfare and ecological footprints compared

Looking at the global comparison in Figure 137 above, at first glance it seems almost inevitable that increasing human welfare will increase the ecological footprint at the same time. However, there seem to be distinct areas in this chart, with weaker or stronger relationships between human welfare and ecological footprint. There are certainly countries which achieve the same human welfare at much lower ecological cost than others. This is perhaps because there are win-win options, in which the impact on Earth is minimized while human welfare is increased.

For example, McKinsey & Company constructed a cost analysis of carbon abatement options, available for the world and individual large countries, to identify win-win options. Each curve identifies total available volume and unit cost per ton CO<sub>2</sub>e. India, for example, could reduce its emissions by ~ 800 million tons per year in the year 2030 (compared to a business-as-usual scenario with no mitigation policies) while saving money at the same time.

<sup>173</sup> Wikipedia. [http://en.wikipedia.org/wiki/List\\_of\\_countries\\_by\\_ecological\\_footprint](http://en.wikipedia.org/wiki/List_of_countries_by_ecological_footprint)).

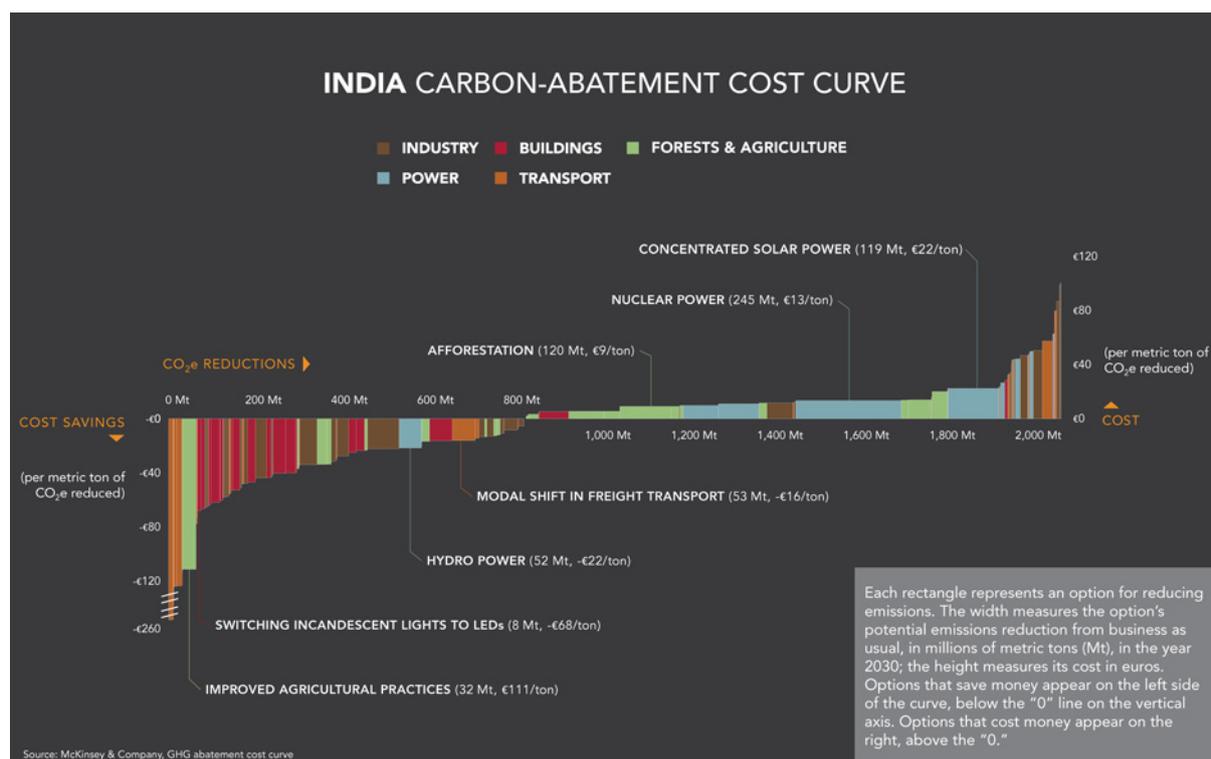


Figure 138: India carbon-abatement cost curve<sup>174</sup>

For example, expanding hydropower would reduce emissions by 52 million tons and at the same time reduce electricity costs by EUR 22 for every ton CO<sub>2</sub>e. Switching light bulbs to LEDs would reduce emissions by 8 million tons and at the same time reduce electricity costs by EUR 68 for every ton CO<sub>2</sub>e. Only after the win-win options are exhausted, and depending on its level of ambition, does a country need to start actually spending additional money on mitigation.

Starting with the lowest cost options for mitigation should make mitigation politically more acceptable. Unfortunately, all mitigation options have side effects, and in the McKinsey analysis, their indirect costs are not counted. A two-dimensional relationship between development and nature is too simplistic. Policies are needed that not only address climate change, but jointly address sustainable development and climate change, recognizing the feedbacks and trade-offs between the two.

The following chart attempts to show the relevant relationships more fully. Climate adaptation refers to how ecosystems and the economy receive and respond to influences from the climate system. For example, ecosystems that receive lower stress from the economy, may be more resilient or better able to withstand climate stress.

<sup>174</sup> McKinsey & Company (2009) Environmental and Energy Sustainability: An Approach for India.

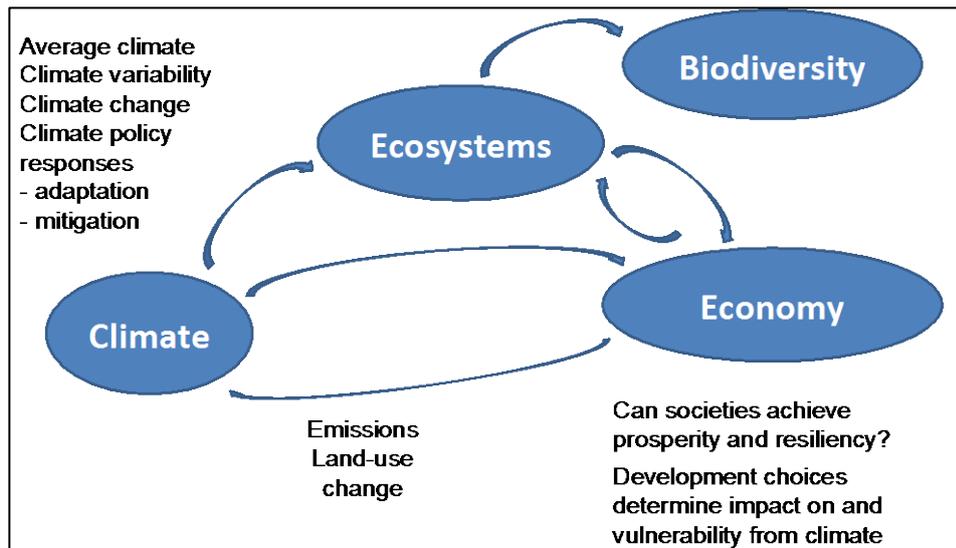


Figure 139: Relationships between the climate, the economy, ecosystems and biodiversity

Hydropower as part of the economy interacts both with the climate and with ecosystems. Very roughly speaking, it is good for the climate and bad for aquatic and riparian ecosystems. Since biodiversity depends on ecosystems, which provide the habitat for plants and animals, it will also be impacted by hydropower. Through its positive impact on the climate, however, hydropower reduces other stresses on ecosystems – for example on forests and coral reefs. From a policy perspective, one would want to strengthen positive feedbacks and reduce negative feedbacks in a system like this.

Figure 140<sup>175</sup> below shows one of these complex pathways in more detail. Climate variability, increased by anthropogenic climate change, results in interrelated kinds of droughts that cause economic, social, and environmental impacts:

<sup>175</sup> <http://www.nws.noaa.gov/om/brochures/climate/DroughtPublic2.pdf>

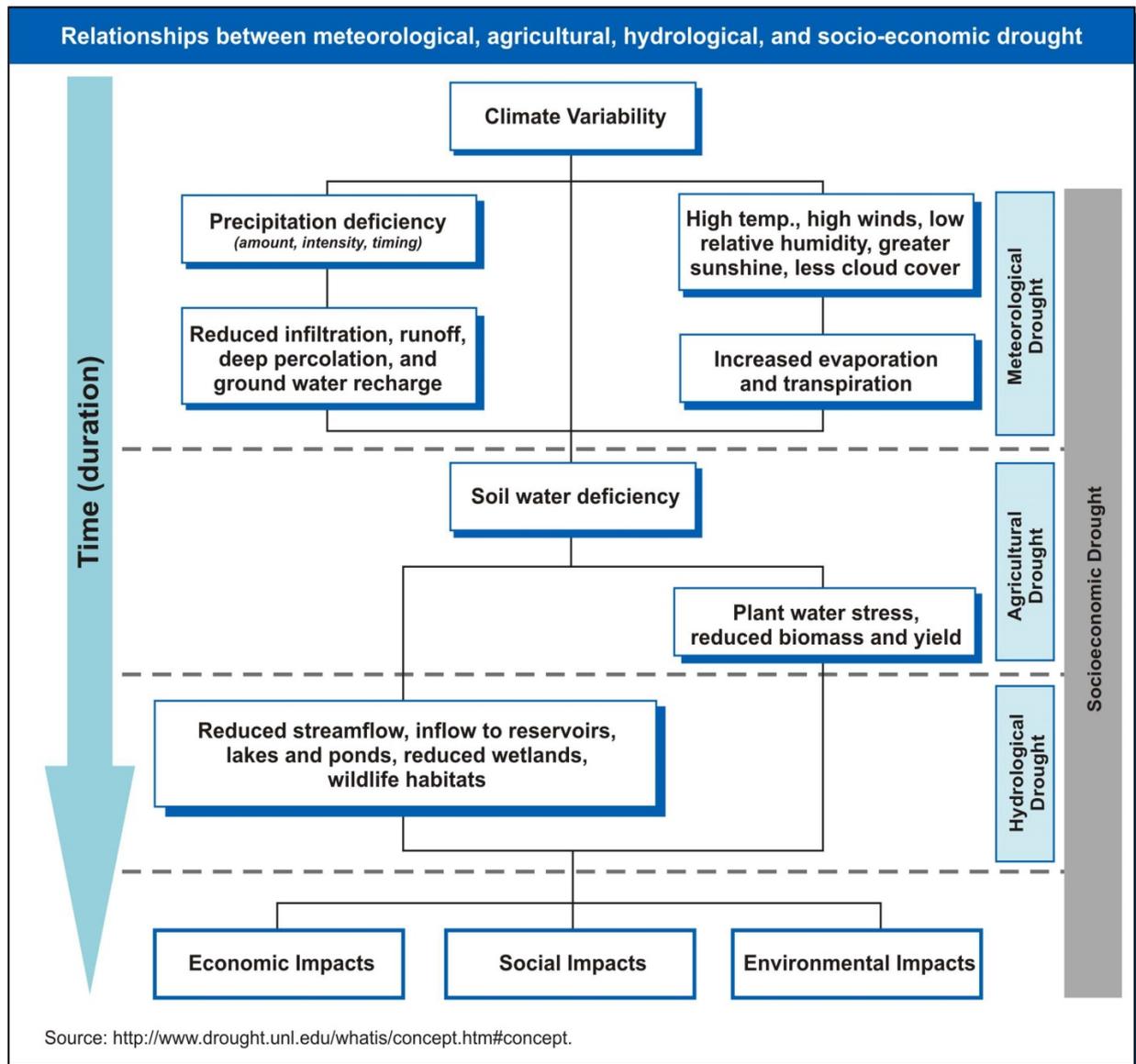


Figure 140: Direct and indirect impacts of drought

Another way of looking at this, is to analyze the impact pathway from climate change on a specific ecosystem. Aquatic ecosystems are known to be the most stressed among all ecosystems globally, losing their ability to deliver ecosystem services in many places. It is important to understand these losses in order to conduct proper impact analysis of human water management. The impact of a hydropower project on downstream flows, for example, is in addition to pre-existing pressures and underlying climate change already occurring in the ecosystem.

Impacts of climate change	Eco-hydrological impacts	Impacts for ecosystems and species
Changes in volume and timing of precipitation Increased evapotranspiration Shift from snow to rain, and/or earlier snowpack melt Reduced groundwater recharge Increase in the variability and timing of monsoon Increased demand for water in response to higher temperatures and climate mitigation responses	<b>1. Increased low-flow episodes and water stress</b>	Reduced habitat availability Increased temperature and pollution levels Impacts on flow-dependent species Impacts on estuarine ecosystems
Shift from snow to rain, and/or earlier snowpack melt Changes in precipitation timing Increase in the variability and timing of annual monsoon	<b>2. Shifts in timing of floods and freshwater pulses</b>	Impacts on spawning and emergence cues for critical behaviors Impacts on key hydrology-based life-cycle stages (e.g., migration, wetland and lake flooding)
Increased temperatures Reduced precipitation and runoff	<b>3. Increased evaporative losses from shallower water bodies</b>	Permanent water bodies become temporary/ephemeral, changing mix of species (e.g., from fish-dominated to fairy shrimp-dominated)
Increased precipitation and runoff More intense rainfall events	<b>4. Higher and more frequent storm flows</b>	Floods remove riparian and bottom-dwelling organisms Changes in structure of available habitat cause range shifts and wider floodplains Less shading from near-channel vegetation leads to extreme shallow water temperatures
Changes in air temperature and seasonality Changes in the ice breakup dates of lakes	<b>5. Shifts in the seasonality and frequency of thermal stratification (i.e., normal seasonal mixing of cold and warm layers) in lakes and wetlands</b>	Species requiring cold-water layers lose habitat Thermal refuges disappear More frequent algal-dominated eutrophic periods from disturbances of sediment; warmer water Species acclimated to historical hydroperiod and stratification cycle are disrupted, may need to shift ranges in response
Reduced precipitation and runoff Higher storm surges from tropical storms Sea-level rise	<b>6. Saltwater encroachment in coastal, deltaic, and low-lying ecosystems</b>	Increased mortality of saline-intolerant species and ecosystems Salinity levels will alter coastal habitats for many species in estuaries and up to 100 km inland
Increase in intensity and frequency of extreme precipitation events	<b>7. More intense runoff, leading to increased sediment and pollution loads</b>	Increase of algal-dominated eutrophic periods during droughts Raised physiological and genetic threats from old industrial pollutants such as dioxins
Changes in air temperature Increased variability in temperature	<b>8. Hot or cold-water conditions and shifts in concentration of dissolved oxygen</b>	Direct physiological thermal stress on species More frequent eutrophic periods during warm seasons Oxygen starvation for gill-breathing organisms Miscues for critical behaviors such as migration and breeding

Table 38: Climate impacts on aquatic biodiversity<sup>176</sup>

From a human perspective, another pathway that should be considered is the reliability of water and power infrastructure, as an important element of sustainable development. Reliability is the probability that failures do not occur. Failure could be due to lack of water in a reservoir, which then forces water or energy services to be cut. Failure could also be too much water, resulting in wasted use of the resource. Traditionally, planners try to optimize between the cost of failure and the cost of reliability. The cost of droughts and floods can be

<sup>176</sup> WWF (2010) Flowing forward

extremely high (several % of GDP), but 100% reliability is technically and economically not feasible either. In an uncertain future climate, reliability is more difficult to achieve.

If anthropogenic climate change leads to reduced reliability, what does this mean for water resources planning and management? Planners need to be proactive about climate change. They can first try to find out as much as possible about future conditions. Forecasts, in conjunction with real-time observations, should then be used to alter operational rules in an adaptive manner. Planners should also design systems to manage the consequences of failure. This may mean including extra safety margins, designing robust systems to have no single point of failure, or designing systems in a modular approach, using components only as needed. Finally, planners should incorporate innovative non-structural elements, such as communications, information technology, and the application of economic mechanisms to enhance water system performance.<sup>177</sup>

There are direct implications of these concepts for sustainable development in the LMB. The economy of the region is strongly linked to its natural resource base (e.g., through agriculture, forestry, fisheries, hydropower) and reliable infrastructure. The ecosystems in the region are vulnerable to the concurrent changes of climate and economic activity. The significance of the impact on the LMB countries will depend on baseline economic performance, costs and benefits of climate change as compared to this baseline, and international burden sharing, i.e. the extent to which other countries may help with climate change adaptation and mitigation.

Climate change may also bring some benefits to the LMB, for example, in increased productivity of agriculture. But it will not be without its costs: direct costs of mitigation (e.g., increased cost of generation) and adaptation (e.g., increased cost of cooling), and indirect costs (e.g., costs imposed on fisheries due to increased hydropower development). The impacts of climate change will also be unequally distributed in the region. Rural economies are more dependent on natural resources than urban economies, and may therefore experience larger impacts. These impacts could include displacement in coastal or rural areas, and moves to urban areas.

Fisheries is one sector where climate change will simultaneously have human and ecological dimensions. The LMB region is one of the most productive fishing regions in the world, from capture fisheries and aquaculture. Rising seas, more severe storms, and saltwater intrusion in the deltas may bring increased risks to coastal fishing communities and aquaculture systems. Climate change will alter the distribution and production of fish (i.e., migration routes, spawning and feeding grounds, and fishing seasons), impacting the quantity and quality of available fish. Impacts will vary depending on the habitat inhabited by each group (e.g., upland, migratory, wetland, estuarine, inland aquaculture). It is impossible and unnecessary to study the life cycles and vulnerabilities of ca. 1200 individual species of fish in the Mekong system. Rather, more detailed assessments can be made at the group level.<sup>178</sup>

Upland species are highly vulnerable; but impacts may be mitigated through the replanting or protection of forest cover to provide shade habitat and to prevent flash flooding. Migratory fish will benefit from improving the connectivity of refuge areas, spawning grounds, and nursery areas. Wetland fish appear to be “climate-resilient” and may increase in the proportion of fish catches due to their survivability in low water quality areas and their lack of need for connectivity for migrations. Estuarine fish, particularly the sedentary species, will be

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<sup>177</sup> Brown (2010)

<sup>178</sup> <http://www.cakex.org/virtual-library/usaaid-mekong-arcc-climate-change-impact-and-adaptation-study-fisheries-report>

highly vulnerable but could benefit from planting of mangrove forests in coastal areas to protect against storms and erosion resulting from sea level rise, increased storm events, and increased rainfall. Several invasive species are likely to increase their range under the changing conditions; intensive and effective monitoring and eradication programs should be implemented to control their spread. A recent survey of climate change impacts on fisheries in 130 countries concluded that Cambodia and Vietnam are among the 30 most vulnerable because of their dependence on fisheries, exposure to climate risks, and limited coping capacity. Aquaculture is more exposed than capture fisheries, but with more adaptive capacity. These risks from climate change are concurrent to those already present, such as barriers to migration, changes to river morphology, and overfishing.<sup>179</sup>

In the fisheries sector, and in others as well, concurrent pressures, cumulative impacts, synergies, and feedbacks need to be studied in more detail. The possibility exists that in some cases, pressure on aquatic ecosystems from climate change may be reduced through positive synergies with hydropower development. If climate change increases water temperature, perhaps the release of cooler reservoir waters could maintain or restore historic temperatures. If climate change increases erosion, perhaps retention of sediment in reservoirs could maintain or restore historic sediment loads. If climate change increases salinity intrusion, perhaps dry season releases from reservoirs could maintain or restore the historic saltwater boundary. And, if climate change increases flood peaks, perhaps retention of water in reservoirs could maintain or restore historic flood peaks.

A primary example regarding flood management may be the concurrent effects of climate change and dam development on the Tonlé Sap lake ecosystem.<sup>180</sup> The Tonlé Sap is the largest freshwater lake in Southeast Asia and a prime fishing ground. The lake expands and shrinks dramatically with the seasons. Arias et al. (2012)<sup>181</sup> found opposite trends in flood extent, at similar magnitude: upstream development is expected to reduce flood extent by up to 1,200 km<sup>2</sup> while climate change is expected to increase flood extent by up to 1,000 km<sup>2</sup>. Lauri et al. (2012)<sup>182</sup> suggest that the impact of hydropower on some hydrological characteristics of the Mekong River, such as monthly discharge, flood peaks and dry season flow, is larger than those caused by climate change. This may be because hydropower impacts are expected earlier than climate change impacts. The combined effect of both flood storage in hydropower reservoirs and increased floods may be largely neutral. Hydropower reservoirs could then be interpreted as an adaptation measure.

Several international studies have been conducted on the effects of climate change in the LMB, and may be referenced for additional information. The Asian Development Bank examined the water resources, agriculture, forestry, coastal and marine resources, and health sectors in Southeast Asia.<sup>183</sup> The World Bank analyzed the agriculture, forestry, coastal ports, and aquaculture sectors in Vietnam.<sup>184</sup> World Wildlife Fund looked at water resources, agriculture, biodiversity, coastal resources, and fisheries in the Greater Mekong

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<sup>179</sup> Allison et al. (2009) Vulnerability of national economies to the impacts of climate change on fisheries; WWF (2009).

<sup>180</sup> Beilfuss & Triet (n.d.) Climate change and hydropower in the Mekong River Basin: a synthesis of research. A scoping study prepared for the MRC and GIZ. Draft.

<sup>181</sup> <http://www.hydrol-earth-syst-sci-discuss.net/11/2177/2014/hessd-11-2177-2014.pdf>

<sup>182</sup> <http://www.hydrol-earth-syst-sci.net/16/4603/2012/hess-16-4603-2012.pdf>

<sup>183</sup> <http://www.adb.org/publications/economics-climate-change-southeast-asia-regional-review>

<sup>184</sup> <http://www.worldbank.org/en/news/feature/2011/06/06/economics-adaptation-climate-change>

Subregion.<sup>185</sup> USAID reported on socio-economics (health and rural infrastructure), agriculture, natural systems, livestock, and fisheries in the Lower Mekong Basin.<sup>186</sup>

In conclusion, reliable water and power infrastructure is an important element of sustainable development. In an uncertain future climate, reliability is more difficult to achieve. There are complex relationships between climate, ecosystems and the economy that have to be managed well to achieve sustainable development. Climate change is an additional challenge on top of other difficult problems, but some robust or win-win solutions may be available. Hydropower can help achieve sustainable development. But current planning is often too shortsighted, relies on narrow and deterministic planning methods, and does not take climate change into account.

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<sup>185</sup> [http://wwf.panda.org/what we do/where we work/greatermekong/challenges in the greater mekong/climate change in the greater mekong/](http://wwf.panda.org/what_we_do/where_we_work/greatermekong/challenges_in_the_greater_mekong/climate_change_in_the_greater_mekong/)

<sup>186</sup> <http://www.mekongarcc.net/resource/usaids-mekong-arcc-lower-mekong-climate-study-released-download>

## 7 ANNEX 1: RECOMMENDED READING

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Note: This manual draws from a diverse and rapidly evolving literature. During the time of its drafting, the IPCC's Fifth Assessment Report was released in stages, and users may want to consult the original report at <http://www.ipcc.ch/index.htm>. Additional references to the ones in the 'recommended reading' list are given in footnotes. All weblinks in footnotes were accessed in February 2014.

Item 1.1.1 - IEA (2012) Key Findings, in Technology Roadmap Hydropower (p. 5).

Item 1.1.2 - BP (2013) Section 36 (Hydroelectricity) in Statistical Review of World Energy.

Item 1.1.3 - MRC (2013) Section 3.2 (Opportunities and Risks of Water Resources Development) in Basin Development Strategy (pp. 18-22).

Item 1.1.4 - ADB (2013) Assessment of the Greater Mekong Subregion energy sector development: Progress, prospects, and regional investment priorities.

Item 1.2.1 - Bruckner et al (2013) Executive Summary of Chapter 7 (Energy Systems) in Climate Change 2014: Mitigation of Climate Change. Draft Working Group III contribution to the 5th Assessment Report of the IPCC.

Item 1.2.2 - Kumar et al (2011) Executive Summary of Chapter 5 (Hydropower) in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (pp. 441-442).

Item 1.3.1 - UN Water (n.d.) Climate change adaptation is mainly about water.

Item 1.3.2 - Jimenez et al (2013) Chapter 3 (Freshwater resources and their management) in Climate Change 2014: Impacts, Adaptation and Vulnerability. Draft Contribution of Working Group II to the 5th Assessment Report of the IPCC.

Item 1.3.3 - Hijioka et al (2013) Chapter 24 (Asia) in Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the 5th Assessment Report of the IPCC.

Item 1.3.4 - IR graphic on dams and climate change.

Item 1.3.5 - IHA Congress (2013) climate session summary

Item 2.1.1 - Climate article from <http://en.wikipedia.org/wiki/Climate>

Item 2.2.1 - MRC (2009) The Flow of the Mekong. Management Information booklet series No. 2.

Item 2.3.1 - Principles of Hydropower Engineering. Module 5.1 of Water Resources Engineering Course. Indian Institute of Technology Kharagpur.

Item 2.3.2. - Piman et al. (2013) Assessment of Flow Changes from Hydropower Development and Operations in Sekong, Sesan, and Srepok Rivers of the Mekong Basin

Item 2.3.3 - US Army Corps of Engineers (1992) Hydrologic Engineering for Hydropower. Regulation No. 1110-2-1463.

Item 2.4.1 - Stocker et al (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the 5th Assessment Report of the IPCC.

Item 2.4.2 - MRC (2011) Impacts of climate change and development on Mekong flow regimes: First assessment – 2009. Management Information Booklet Series No. 4.

Item 2.4.3 - MRC (2010) Impacts of climate change and development on Mekong flow regimes. First assessment – 2009. Technical Paper No. 29.

Item 3.2.1 - Milly et al (2008) Stationarity is dead.

Item 3.2.2 - Hamadudu and Killingtveit (2012) Assessing Climate Change Impacts on Global Hydropower.

Item 3.2.3 - Vattenfall Power Consultant AB (2007) Addressing Climate Change-Driven Increased Hydrological Variability in Environmental Assessments for Hydropower Projects – a Scoping Study.

Item 3.2.4 - Brown et al (2010) Managing Climate Risk in Water Supply Systems: Materials and tools designed to empower technical professionals to better understand key issues.

Item 3.2.5 - Materials for role play

Item 3.3.1 - Dortch (n.d.) Water Quality Considerations in Reservoir Management.

Item 3.3.2 - Moss et al (2011) Allied attack: climate change and eutrophication.

Item 3.3.3 - UNESCO-WHO-UNEP (1996) Reservoir Water Quality Assessments.

Item 3.4.1 - Major (1998) Climate change and water resources: The role of risk management methods.

Item 3.4.2 - Byer and Yeomans (2007) Methods for Climate Uncertainties in EIAs.

Item 3.4.3 - Hallegatte (2009) Strategies to adapt to an uncertain climate change.

Item 3.4.4 - Pittock et al (2008) Running dry: Freshwater biodiversity, protected areas and climate change.

Item 4.1.1 - Cox (2013) Cooling a warming planet.

Item 4.1.2 - Parkpoom et al (n.d.) Climate Change Impacts on Electricity Demand in Thailand.

Item 4.1.3 – Mekonnen and Hoekstra (2012) The blue water footprint of electricity from hydropower.

Item 4.1.4 - Doell (2002) Impact of Climate Change and Variability on Irrigation Requirements.

Item 4.1.5 - Mideksa and Kallbecken (2010) The impact of climate change on the electricity market.

Item 4.2.1 - REN21 (2013) Global Status Report. Chapter: 4 Policy Landscape.

Item 4.3.1 - The Economist (2010) How to live with climate change.

Item 4.3.2 - Colombo & Byer (2012) Adaptation, flexibility and project decision-making.

Item 4.3.3 - DFID (2010) Water storage and hydropower: supporting growth, resilience and low carbon development. A DFID evidence-into-action paper.

Item 4.3.4 - McCartney & Smakhtin (2010) Water Storage in an Era of Climate Change. IWMI.

Item 5.1.1 - Project Design Document for Xekaman 3 project (2011). Annex 3 (calculation of avoided emissions).

Item 5.1.2 - Manitoba Hydro (2012) Climate Change Report. Chapter 4: Contribute to GHG Emission Reductions.

Item 5.1.3 - CEATI (2011) The Hydroelectric Industry's Role in Integrating Wind Energy.

Item 5.2.2 - Liden (2013) Greenhouse Gases from Reservoirs Caused by Biochemical Processes. World Bank Interim Technical Note.

Item 5.2.3 - Deshmukh (2012) Greenhouse gases (CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>O) emissions from a newly flooded hydroelectric reservoir in subtropical South Asia: case of Nam Theun 2 Reservoir, Lao PDR- Chapters 7 and 8.

Item 6.1.1 - International Energy Agency (2013) Southeast Asia Energy Outlook. World Energy Outlook Special Report.

Item 6.2.1 - Zhuang et al (2011) The Economics of Climate Change in SE Asia.

Item 6.2.2 - Brown (2010) The End of Reliability.

Item 6.2.3 - WWF (2010) Flowing Forward: Freshwater ecosystem adaptation to climate change in water resources management and biodiversity conservation. WB Water Working Note 28.

## 8 MRC-GIZ COOPERATION PROGRAMME BACKGROUND

GIZ is supporting the Mekong River Commission (MRC) in its work in poverty-alleviation and environmentally friendly hydropower development, as well as in protecting the population from the negative impacts of climate change in the Lower Mekong Basin. GIZ is directly supporting experts and managers from the MRC Secretariat, the National Mekong Committees, and the Ministries for water, energy and environment in the member countries. The GIZ programme aims to achieve long-term, sustainable improvement to the livelihoods of more than 60 million people in the Lower Mekong Basin.

The GIZ programme comprises the following components:

(<http://www.giz.de/themen/en/30306.htm>):

- [Supporting the Mekong River Commission in organisational reform](#)
- [Supporting the MRC in pro-poor sustainable hydropower development](#)
- [Supporting the MRC in Adaptation to Climate Change in the Mekong region](#)
- [Adaptation to climate change through climate-sensitive flood management](#)

### **Supporting the MRC in pro-poor sustainable hydropower development**

GIZ is advising the Mekong River Commission (MRC) on developing and implementing instruments for testing and improving the sustainability of hydropower projects. For example, this includes instruments for analysing the impacts of hydropower development in catchment areas as well as approaches for establishing benefit-sharing mechanisms within water catchment areas and beyond borders. In addition, GIZ is promoting the exchange of experiences between various river basin commissions involved in sustainable hydropower development. The project is also developing basic and advanced training measures on sustainable hydropower.

### **Network on Sustainable Hydropower Development in the Mekong Countries (NSHD-M)**

The NSHD-M is integrated in the project 'supporting the MRC in pro-poor sustainable hydropower development' of the Mekong River Commission (MRC) - GIZ Co-operation programme. The Network was established in October 2012 by universities and research institutions in the Mekong countries Cambodia, China, Laos, Thailand and Vietnam. The network aims to

- enhance knowledge and skills on sustainable hydropower development (SHD) at academic and research institutions,
- share knowledge and experiences on SHD in the Mekong countries,
- increase awareness on SHD at all levels of decision making,
- strengthen the capacity of stakeholders, including planners and decision makers, to cope with the challenges of SHD.

The network and its activities in the Mekong River Basin are supported by GIZ on behalf of the Federal Ministry for Economic Cooperation and Development (BMZ).

Further information on NSHD-M goals, activities and partners:

[www.cdri.org.kh/index.php/nshdmekong](http://www.cdri.org.kh/index.php/nshdmekong).

Contacts: [klaus.sattler@giz.de](mailto:klaus.sattler@giz.de) and [thomas.petermann@giz.de](mailto:thomas.petermann@giz.de)

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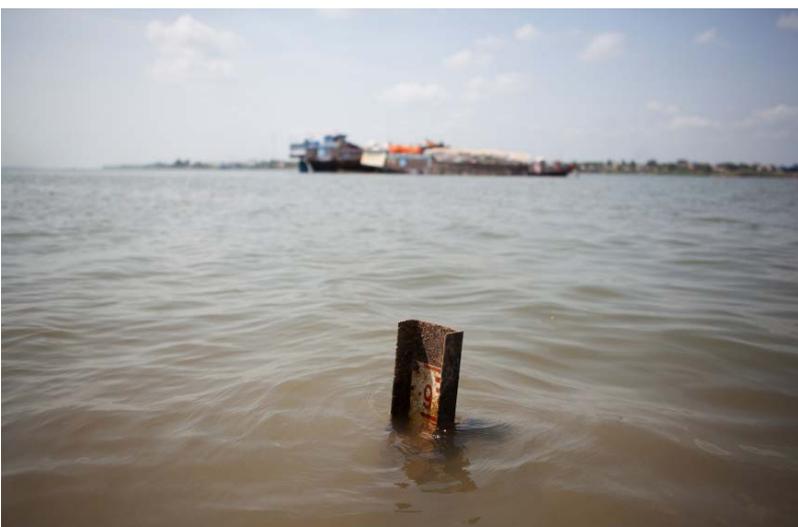
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