International Commission on Large Dams – ICOLD

Commission Internationale des Grands Barrages – CIGB

Bulletin on:

"Global Climate Change, Dams, Reservoirs and Related Water Resources"

Bulletin portant sur :

"Changement Climatique, Barrages, Réservoirs et Ressources en eau Associées"

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1. EXECUTIVE SUMMARY

The purpose of this bulletin is to assess the role of dams and reservoirs in adapting to the effects of global climate change, determine the threats, and potential opportunities, posed by global climate change to existing dams and reservoirs, and then recommend measures to mitigate against or adapt to the effects of global climate change.

- The climate change risk to dams, reservoirs and related water resources results from a combination of water hazards and water systems vulnerability, it is site specific and highly variable from one region to another one.
- Dams and reservoirs can also play a significant role in the adaptation to the climatic change: basins with significant reservoir capacity of regulation are more resilient to water resource changes, less vulnerable to climate change, and storage acts as a buffer against climate change.
- Hydropower, as one energetic use of dams and reservoirs, can also stand as a crucial tool in climate change mitigation.

In general, together with a global warming and general average air temperature increase, it is predicted that higher latitudes will get more precipitation and lower latitudes will get less. Therefore, higher latitudes should prepare for more runoff and lower latitudes less. However, the predication is, for some locals, to have to deal with more frequent significant extremes, greater flooding and longer more severe dry periods, though evolution in extreme conditions is still characterized with high uncertainty. Indeed, if trends on drought events can be stated with significant confidence (more intense, more frequent), trends on floods must be announced with caution: higher precipitations at short time scales may also be compensated by dryer soils (particularly for large watersheds), resulting in an uncertain run-off change. This mechanism will be highly dependent on watershed size and climatic region of concern.

This bulletin is organized in chapters that include the following:

- a description of what is at risk when considering dams, reservoirs and related water resources (chapter 3)
- facts and uncertainties with climate evolution, mainly based on past observations analysis (chapter 4)
- framework and method for assessing climate induced impacts and risk at watershed scale (chapter 5)
- other drivers besides climate change that can affect the balance between resources and needs: demography, technology, sedimentation, ... (chapter 6)
- climate-driven opportunities for new storage (chapter 7)
- emissions of greenhouse gases associated to reservoirs and water resources (chapter 8)
- adaptation strategies and case studies from different regions of the world, and illustrating different water resources systems situations (chapter 9)
- recommendations (chapter 10)

For each chapter, information provided are based on ICOLD members experience, knowledge and references but also on the most recent – hopefully – publications and knowledge from outside the ICOLD community, especially for matters about climate science (e.g. analyses provided by the IPCC community).

Given the remaining uncertainty in climate projections (especially for precipitation patterns) and long time horizons of concern, the exact impact of climate change on specific water resources projects cannot be accurately predicted. Therefore, the successful implementation of an adaptive management strategy recognizes the uncertainties and allows for a staged process. It is for this reason that a "No Regrets" approach to adaptation is recommended, though some situations would require anticipation in adaptation decision-making, particularly for large water systems. The "No Regrets" approach, as illustrated in Figure 9.1, involves undertaking some form of intervention or action to reduce a current or perceived future risk, and at the completion of that intervention modeling future possible outcomes, then monitoring system performance. In this way, the adaptive measures can be undertaken when needed, but not before needed.

ICOLD recommendations (chapter 10) address three broad themes:

Recommendation 1: Adopt a whole-of-system approach

- take into account the appropriate multiple needs / objectives at the river basin scale,
- establish what is really at risk in your water resources system, using risk-based approaches (see chapter 3),
- establish priorities in water usages and needs, and ensure that sufficient water for the environment is secured to sustain natural environments and healthy river systems through extremely dry periods,
- ensure that sufficient water of adequate quality is secured for critical human needs for dependent communities to get them through extremely dry or extremely wet periods.

Recommendation 2: Apply an adaptive management process

- identify expertise / information gaps in understanding (see chapter 4),
- consider multiple likely scenarios that cover the range of potential climate evolution ; do not only rely on one single scenario to avoid misleading conclusions (too pessimistic or too optimistic) - (see chapters 4 and 5),
- develop and share appropriate methods and approaches (deterministic, probabilistic) to :
    - (i) assess climate risk on your water resources system, and
    - (ii) adapt to climate change in the water sectors

  (see chapter 5),
- establish an integrated basin management organization with an aim to develop / transfer best practices in river basin management (see chapter 9 and case studies).

Recommendation 3: Collaborate with a wide range of disciplines, interest and stakeholders (including engineers alongside decision makers, politicians, natural resource scientists, social scientists, economists and the greater community) in the assessment of enduring and effective adaptation options

- Identify and explain how dams and reservoirs can mitigate climate change impact in your watershed (see chapter 7)
- Explain how – and how much - GHG emissions are linked to dams and reservoirs (see chapter 8)
- Engage, involve the public and stakeholders actively and early on and ongoingly
- Communicate and educate clearly, concisely and simply, on the role of dams and reservoirs in climate change risks and opportunities management.

2. OBJECTIVE OF ICOLD BULLETIN

2.1 TERMS OF REFERENCE

This bulletin has been developed in response to the Terms of Reference for the Committee on Global Climate Change and Dams, Reservoirs and the Associated Water Resources, April 7 2008.

The terms of reference are:

- Collect and review the guidance and policies currently used in planning for the impacts of global climate change on dams, reservoir, and the associated water resources.
- Assess the role of dams and reservoirs in adapting to the effects of global climate change, and determine the threat posed by global climate change to existing dams and reservoirs.
- Recommend measures designed to mitigate against or adapt to the effects of global change on water storage facilities. Such recommendations would be developed in light of : scientific predictions of future climate changes; possible impacts from factors such as: increased or decreased precipitation, a change in the rate of evapo-transpiration, water quality, erosion, and siltation, prolonged drought, flooding.
- Publish an ICOLD position paper and guidelines for 'climate change and dams, reservoirs and the associated water resources".
- These documents would be used by the ICOLD membership, governments, the United Nations, the World Bank and other organizations in need of guidance with respect to water resource protection and development.

At the beginning of its work, our Technical Committee has recognized the importance to add the following objective to the bulletin:

- Provide up-to-date information about the potential of Green-House-Gas emissions associated to reservoirs and related water systems existence and operation.

In this first formal ICOLD technical bulletin related to climate change issues, the authors recognize that some specific issues are not yet dealt with, such as the particular situation of tailing dams, the issue of stability of dams in permafrost areas, etc.

The issues related to sedimentation are by themselves a full topic of interest, with a wide range of activity covered by a specific Technical Committee. However, some of these sediment load issues are also covered in thie present, in section 6.5 and chapter 7, as sedimentation can play a significant role in the sustainability of dams and reservoirs along with climate impact, or climate change can may also exacerbate sediment load in some basins.

2.2 WORK ORGANIZATION

2.2.1 Contributions of ICOLD Members

The Committee on Global Climate Change and Dams, Reservoirs and the Associated Water Resourses gratefully acknowledge the contribution of members of the Committee as well as the support by their sponsoring organizations.

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3. WHAT IS AT RISK ?

Climate and climate change impact are often seen as threats for existing water uses and water needs, but these threats are seldom well defined and handled. The present chapter aims at providing a framework to water resources engineers and managers, to help them assess and define their climate-related exposure and risks.

3.1 CLIMATE RISK FOR WATER RESOURCES: NEED TO DEFINE A BASELINE AND RISK INDICATORS

Step 1: Define what risks are or may be ?

It is perhaps not useless to remind some key basics of risk analysis concept.

A climate-induced risk that a given water resources system or function may fail, involves both climatic and non-climatic factors. Such a risk is resulting from the combination of:

- a climate hazard, which is characterized by a certain probability of occurrence associated to an intensity and duration ; this is the climatic driver ;
- a vulnerability exposure of the water system to this hazard : how sensitive is the system to a climatic action ; this is a non-climatic factor ;
- and the consequences of the water system failure : this is again a non-climatic factor.

Thus, the risk chain can be described as following:

Risk = Hazard occurrence ⊗ System exposure to hazard ⊗ Consequence of system failure

Chapter 4 will provide the knowledge about the climatic component of the risk chain, mainly coming from IPCC community (see for example ref.[4.9], [5.13]). In Chapter 5, methods to assess impact of climate on water resources system will be given, involving all components of the risk chain. Chapter 6 will develop non-climatic factors (e.g. demography and technology factors, social and regulatory conditions, ...) whose change can affect risk level, even without any change in the climatic driver.

Step 2: Establish a baseline to which future climate-driven scenarios will be compared.

Future climate scenarios must be considered in relation to existing conditions. Changes must be assessed against a given existing and known reference that we will define here as a *baseline*. It is then fundamental to establish such reference scenario - or scenarios - for a given water resources system, that will serve as a *baseline* to which any possible future scenarios will be compared.

Changes in climatic factors characteristics from a baseline may consist of (a) a shift in average values, (b) a change in the variability of the parameters, or (c) both, as schematically depicted on Figure 3-1.

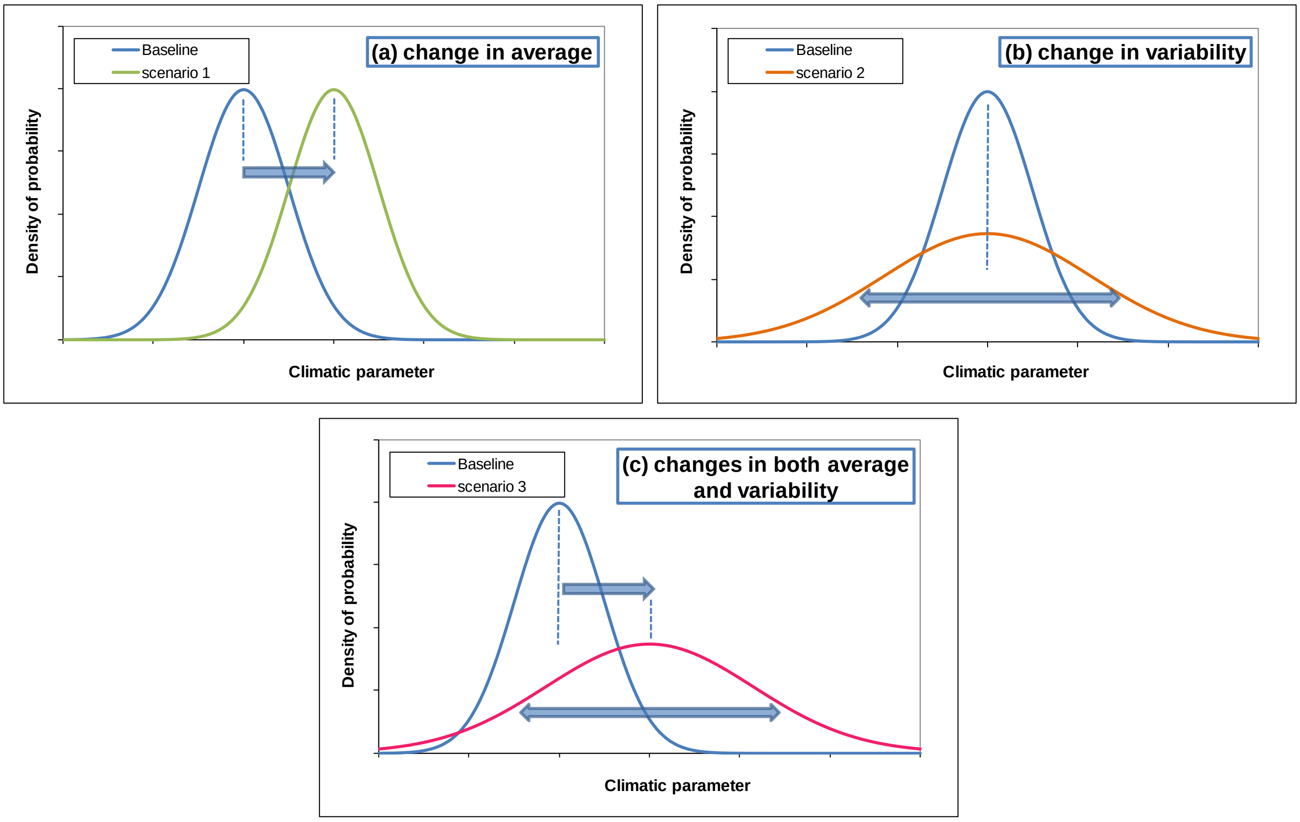

Figure 3-1 – Types of climatic parameters changes through schematic change of their density of probability: (a) shift of the average, (b) change in the variability, and (c) combination of both.

Water resources systems might be more sensitive and exposed to a change in average values (case a), or a change in variability of climatic factors which especially affect extreme values (case b), or both (case c).

Reference scenario(s) can be constructed by averaging parameters characterising the water system over a given period (e.g. a decade), or on typical historical situations (examples: the drought of year YYYY; the flood and related inundations of year YYYY; etc ...).

The baseline must also clearly define the water resources system under consideration: functional relationships between all components of the system; boundaries of the system; connections with factors/actors out of the system ; ...

Step 3: Define relevant risk indicators

Risk indicators must be defined to reflect, through quantitative assessment, situations where uses of the water resources system under consideration may become critical, or may even fail. These indicators must be associated with different thresholds, corresponding to different level of alert or criticity.

These indicators must cover all components of the risk chain, e.g. hazard aspects, water use aspects, and consequences of failure. Thus risk indicators definition cannot be restricted to classical hazard parameters like $Flood\_{100\text{-}yr}$, $Drought\_{100\text{-}yr}$, minimum flows, etc ...

Risk indicators have to be initialized for the baseline situation(s), to serve as quantitative baseline for comparison with future scenarios.

Examples of risk indicators are given in next sub-sections, for different nature of water uses and needs under consideration.

3.2 RISKS FOR WATER RESOURCES

A water use-based or function-based classification of climate risks is proposed in this section, with a non-exhaustive list of possible indicators reflecting the nature and level of risk.

- **Irrigation**

Examples of nature of risks: water unavailability, over time and space; competition with other water uses; water usage conflicts

Examples of risk indicators:

- yearly or seasonal supply of water, per unit of water use (m3/ha)
- sustainability of minimum upstream reservoir level or volume

- **Water supply**

Examples of nature of risks: water unavailability, over time and space, during specific seasons; competition with other water uses; water usage conflicts ; water quality decrease

Examples of risk indicators:

- Yearly or seasonal supply of water, per unit of water use (m3/capita)
- Exceedance of critical water quality criteria

- **Power generation**

Beforehand, it is necessary to distinguish risk of water unavailability over time and space depending on nature of power generation:

- Hydropower : water is the "fuel" of the process ; competition is expected with other water needs around reservoirs
- Thermal power (fossil-fired or nuclear) : water is used for cooling (water withdrawals) ; a small part of water is consumed ; water quality may be affected (temperature, ...)

It is also important to identify that risk of water unavailability for power generation can cover:

- A physical unavailability : water is not physically available;
- A regulatory unavailability: water is there but it is not permitted to use it due to regulatory requirements (ex. water withdrawal restriction to comply with thermal release constraints in rivers).

Examples of nature of risks: physical or regulatory unavailability of water, over time and space; competition with other water uses; water usage conflicts; loss of cooling for generation or even safety (nuclear power)

Examples of risk indicators:

- Loss of yearly or seasonal hydropower generation
- Loss of yearly or seasonal thermal-power generation
- Exceedance (by lower values) of reservoir levels thresholds

- **Other industry needs**

Other industries like pulp production, oil and gas production, steel and aluminium production, chemical treatment, ... rely on more or less significant amount of water use and/or consumption.

Their activities might be affected by a lack of physical or regulatory availability of water. Nature of risks and indicators are thus more or less identical to those identified for power generation needs.

- **Flood control**

Examples of nature of risks: Increase of flood intensity and frequency : inadequacy of existing flood control capacities (reservoir volumes, spillway capacities); variation of seasonality of extreme events

Examples of risk indicators:

- Probability that critical reservoir safety levels might be exceeded
- Loss of protection in areas downstream reservoirs with a flood control function – which can also result as a combined increase of vulnerabilities within these areas (urbanization development)

- **Environmental functions and needs**

Water uses and needs for aquatic ecosystems protection or improvement, for water quality control or improvement, may be challenged under climate change.

Due to the complexity of the question, it is also important here to mention that a large number of non-climatic factors can affect environmental functions, directly or indirectly (ex. pollution).

Examples of nature of risks:

- water unavailability, over time and space (minimum flows conditions)
- water quality change (temperature, pH, N and P concentrations, ...)
- competition with other water uses ; water usage conflicts
- morphological changes and perturbation of habitats

Examples of risk indicators:

- hydro-morphological indicators
- biological indicators (fish population structures, biodiversity, ...)

- **Inland navigation**

For inland navigation, the consequences of the observed and expected climate change can be a question of fundamental existence or survival. Already today commercial users of the inland waterways are asking for safe predictions of how many days a year the waterways can be used without restrictions. These questions result of the recent experiences of years with increased extreme low and high water levels. For the plans of those industries using navigation as the primary mode of transportation for their goods, it is a fundamental question for the future location of their production facilities (PIANC, 2007).

Example of nature of risks:

- decrease or increase of inflows in the navigable reaches, depending of watershed conditions
- changes of navigable reaches morphology and siltation rates;

Examples of risk indicators:

- Frequency of dredging to guarantee ship clearance;
- Unavailability or intermittency of waterways use due to lack or variability of inflows;

3.3 RISKS FOR CIVIL-ENGINEERING STRUCTURES

Albeit possibly playing at a second order of concern compared to effects on water resources themselves, attention may be paid to long term behavorial response of civil-engineering structures to changes in climatic loading, both on an average trend perspective, and also in extreme conditions.

Examples of nature of risks:

- Effects of air/water average or extreme temperature changes on structural behaviour of dams and appurtenant structures (concrete structures, geotechnical structures, tightness and drainage systems performance, ...);
- Design flood changes;
- Landslide in reservoirs occurrence changes;
- Impacts of debris yielded with floods on dams and structures (gates);
- Variability of reservoir level change that may affect structural behaviour of dams.

Examples of risk indicators:

- Changes in precipitation and flow regimes in the catchment area;
- Evolution in and long-term prediction of dam safety monitoring parameters (displacements, stresses, cracking, leakages, ...).

3.4 RISKS OR OPPORTUNITIES ?

Climate variability or change is not only a potential source of risks, but can also create new opportunities for new water resources systems. Additional or modified systems can be necessary to correct a deficiency of existing water resources systems functions, but can also stand as an alternative to other industrial options.

Examples:

- New reservoirs and storage capacities for sustaining water supply demand increase in coastal areas, as an alternative to desalination technologies;
- New pumped storage facilities coupled with large amount of intermittent power technologies (solar, wind), developed to counter GHG emissions from fossil-fired power units;
- etc ...

These issues will be addressed in chapter 7.

4. CLIMATE EVOLUTION: FACTS, UNCERTAINTIES

4.1 BACKGROUND

There is little doubt that a changing climate will have profound impact on the distribution and availability of water resources both as concerns average conditions and its variability. Therefore the prospect of climate change has become a key issue for the dams & reservoirs operation and safety community.

In its 5th assessment report from 2013 the Intergovernmental Panel on Climate Change (IPCC) expressed great concern about the risks for global warming due to increasing emissions of greenhouse gases into the atmosphere. In the report on The Physical Science Basis (IPCC, 2013) the following statements concerning observations can be found:

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased".

And further on:

"Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system." – see Figure 4-1 from IPCC (2007) which illustrates the evidence of anthropogenic activity on global average temperature change.

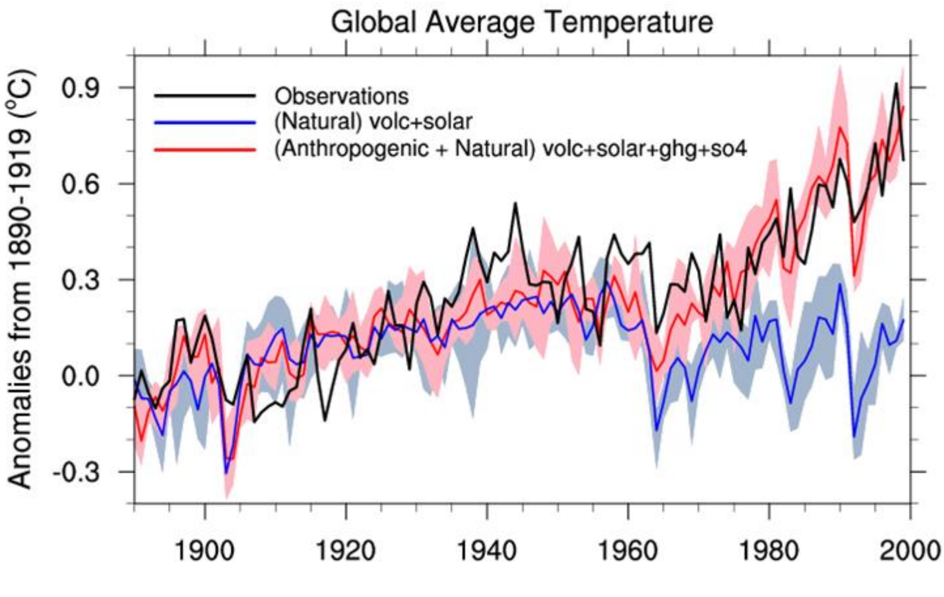

Figure 4-1 – Evidence of anthropogenic activity on global average temperature change (from IPCC 2007 – 4th assessment)

In 2008 IPCC launched its Technical Paper on Climate Change and Water (IPCC, 2008) and in 2011 the Special Report on Renewable Energy Sources and Climate Change Mitigation appeared (IPCC, 2011). In 2012 the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation was published (IPCC, 2012). All these reports express concerns about the impacts of climate change on the hydrological cycle and available water resources.

Also, the climate impact community, e.g. the agriculture and water resources sectors, have recently joint efforts in order to provide global climate impact projections based on an ensemble of impact models (Hagemann et al., 2013; Rosenzweig et al., 2014; Warszawski et al., 2014).

4.2 THE ROLE OF CLIMATE MODELLING

Simulations by climate models have become the most important tool for analysis of our future climate and its impacts. General Circulation Models (GCMs) give a broader picture while various techniques for downscaling give more details for a specific region or catchment. The climate models are driven by radiative forcing from space and assumptions about future emissions of green-house gases and aerosols, so called emissions scenarios. So far most studies are based on emissions scenarios from the IPCC storylines as described in Nakićenović et al. (2000), but they are now being replaced by a new family of scenarios, the so called Representative Concentration Pathways (Moss, et al., 2010). These latter scenarios are used by IPCC in its fifth assessment report published in 2013.

Climate modelling has developed rapidly. Comprehensive global climate projections have been carried out in the framework of Coupled Model Intercomparison Project phase 5 (CMIP5, Taylor et al., 2012), which provides a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models. The international CORDEX project produces an ensemble of multiple dynamical and statistical downscaling models considering multiple forcing GCMs from the CMIP5 archive, and e.g for Europe the project has delivered data for regional impact studies (Jacob et al., 2013). The access to sets of several regional climate scenarios has opened the possibility to make more detailed regional and even local impact and adaptation studies and to look at the uncertainty in more depth.

4.3 AIR TEMPERATURES

Much of the debate on climate change has focused on air temperatures, even though the most obvious impacts on dam operations and safety are related to precipitation and changes in available water resources. Air temperatures are, however, a logical and physical indicator and the most commonly used variable when describing climate change. Observations of air temperatures are abundant, but there are pitfalls. Observational homogeneity is affected by measuring techniques and local conditions, such as urbanisation, and the quality of older records can often be questioned. Therefore great efforts have been spend on quality control and assurance in the IPCC process.

The climate models are normally judged by the way they describe the historical temperature climate. Temperatures are also easier to model compared to precipitation and the different climate models therefore show a more consistent pattern for changes in air temperatures than for precipitation.

4.3.1 Observations of trends in temperatures

Observations and reconstructions of global temperatures reveal a pronounced warming during the past 150 years. According to IPCC (2013) "The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880–2012, when multiple independently produced datasets exist. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] °C, based on the single longest dataset available".

Notice, however, that the global air temperature has not increased much during the last 15 years (1998--2012), and that this warming hiatus is possibly related to natural climate variability affecting ocean heat uptake (Meehl et al., 2011).

According to IPCC (2012), there is evidence from observations gathered since 1950 of change in some extremes. The report says that it is *very likely* [1]that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights on the global scale, i.e., for most land areas with sufficient data. It is *likely* that these changes have also occurred at the continental scale in North America, Europe, and Australia. There is *medium confidence* of a warming trend in daily temperature extremes in much of Asia. Confidence in observed trends in daily temperature extremes in Africa and South America generally varies from *low* to *medium* depending on the region. In many regions over the globe with sufficient data there is *medium confidence* that the length or number of warm spells, or heat waves, has increased.

4.3.2 Scenarios of future temperatures

Regarding future temperatures IPCC (2013) delivers the following key message among others:

"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 RCP scenarios except RCP2.6. It is likely to exceed 2°C for RCP6.0 and RCP8.5, and more likely than not to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform."

And further on:

"It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is very likely that heat waves will occur with a higher frequency and duration. Occasional cold winter extremes will continue to occur".

4.4 PRECIPITATION

As for air temperatures there are many pitfalls in precipitation records, which have to be avoided in the search for trends. Again measuring techniques and local conditions play a role and older records are generally less reliable that more recent ones. Initial rigorous homogeneity controls is therefore of utmost importance in any trend analysis related to precipitation.

Modelling precipitation by climate models is a more difficult task than to model air temperatures and the different models therefore show a greater span in the results. Modelling extreme precipitation on a relatively small catchment scale is a still more difficult task. This supports the use of ensembles of climate models in climate change impact studies related to precipitation and water resources.

4.4.1 Observations of trends in precipitation

According to IPCC (2013) "*Confidence* in precipitation change averaged over global land areas since 1901 is *low* prior to 1951 and *medium* afterwards. Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudes area-averaged long-term positive or negative trends have *low confidence*."

Concerning heavy precipitation IPCC (2013) states that "There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has *likely* increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most *medium*"

Regarding tropical cyclones, which cause torrential rains affecting the design and operation of dams as well as water resource management in specific regions, robust detection of trends is significantly

[1] IPCC terminology is used here on purpose for qualifying climate evolution trends. See ref. [4.10] and IPCC glossary referred to in Chapter 13 for explanations on this terminology

constrained by data heterogeneity and deficient quantification of internal variability (Kunkel et al., 2013).

4.4.2 Scenarios of future precipitation

Concerning the future global water cycle development IPCC (2013) states that:

"Changes in the global water cycle in response to the warming over the 21st century 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."

In more detail IPCC (2013) specifies the impacts of climate change on the water cycle as follows:

- *"Projected changes in the water cycle over the next few decades show similar large-scale patterns to those towards the end of the century, but with smaller magnitude. Changes in the near-term, and at the regional scale will be strongly influenced by natural internal variability and may be affected by anthropogenic aerosol emissions.*

- *The high latitudes and the equatorial Pacific Ocean are likely to experience an increase in annual mean precipitation by the end of this century under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase by the end of this century under the RCP8.5 scenario.*

- *Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases.*

- *Globally, it is likely that the area encompassed by monsoon systems will increase over the 21st century. While monsoon winds are likely to weaken, monsoon precipitation is likely to intensify due to the increase in atmospheric moisture. Monsoon onset dates are likely to become earlier or not to change much. Monsoon retreat dates will likely be delayed, resulting in lengthening of the monsoon season in many regions.*

- *There is high confidence that the El Niño-Southern Oscillation (ENSO) will remain the dominant mode of interannual variability in the tropical Pacific, with global effects in the 21st century. Due to the increase in moisture availability, ENSO-related precipitation variability on regional scales will likely intensify. Natural variations of the amplitude and spatial pattern of ENSO are large and thus confidence in any specific projected change in ENSO and related regional phenomena for the 21st century remains low."*

Kunkel et al. (2013) have analyzed the latest climate simulations regarding probable maximum precipitation (PMP) and shown that PMP will increase in the future due to higher levels of atmospheric moisture content and consequent higher levels of moisture transport into storms. The increase of atmospheric moisture content is consistent with temperature changes with an approximate Clausius-Clapeyron relationship, which is the differential equation relating pressure of a substance (water vapor in this case) to temperature in a system, in which two phases of the substance are in equilibrium.

In some regions, climatologists even found evidence that precipitation amounts in strongly convective events may be even more sensitive to temperature than the Clausius-Clapeyron relationship would indicate - see Lenderik *et al.* (2009) for an example in the North Sea.

4.5 GLOBAL WATER RESOURCES

Observations of river runoff and other variables related to water resources are organized differently around the world. Most countries have national hydrological services, sometimes as a part of their hydrometeorological service. But there are also data collected by industry branches like the hydropower industry and companies working with water supply. On the global scale there are a few centralized data centres, like the German Global Runoff Data Centre, where sets of high quality hydrological data can be found. As for air temperatures and precipitation homogeneity problems have to be considered in any trend analysis of river runoff. This is an even greater problem for the runoff records as they are affected by land use changes in the catchment, river regulation and abstraction for irrigation and water supply.

4.5.1 Observations of trends in water resources

At the global scale, there is evidence of a broadly coherent pattern of change in annual runoff (IPCC, 2008). High latitudes and large parts of the USA have experienced an increase in runoff (e.g. Peterson et al., 2002; McClelland et al., 2004; Dai et al., 2009; Lins and Slack, 1999) and others, such as parts of West Africa, southern Europe and southernmost South America, have experienced a decrease in runoff (Milly et al., 2005). Stahl et al. (2010) studied trends in streamflow in Europe for the period 1962-2004. They found a regionally coherent picture of annual streamflow trends, with negative trends in southern and eastern regions, and generally positive trends elsewhere. Hamlet et al. (2007) found that in the Western USA, runoff is occurring earlier in spring, a trend that is related primarily to increasing temperatures and snowmelt. There have been significant decreases in water storage in mountain glaciers and Northern Hemisphere snow cover (IPCC, 2008).

In many areas no trends in runoff have been found, or studies have been unable to separate the effects of variations in temperature and precipitation from the effects of human interventions in the catchment, such as land-use change and reservoir construction (IPCC, 2008).

According to IPCC (2012) special report, there is *limited* to *medium* evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scales because the available instrumental records of floods at gauge stations are limited in space and time, and because of confounding effects of changes in land use and engineering. Furthermore, there is low agreement in this evidence, and thus overall *low confidence* at the global scale regarding even the sign of these changes.

4.5.2 Scenarios of future water resources

Following chapters give details on how to assess climate change impacts at watershed scale. But one gives in the present section some insights about possible future projections at the global scale.

The global-scale studies that have been conducted using both runoff simulated directly by climate models and hydrological models run off-line show that runoff increases in high latitudes and the wet tropics, and decreases in mid-latitudes and some parts of the dry tropics (IPCC, 2008). By the middle of the 21st century, annual average river runoff and water availability are projected to increase as a result of climate change at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics. Many semi-arid and arid areas (e.g., the Mediterranean Basin, western USA, southern Africa and northeastern Brazil) are particularly exposed to the impacts of climate change and are projected to suffer a decrease of water resources due to climate change (*high confidence*). Results from the recently ended WATCH project indicate that when using a multi-model ensemble of climate models and hydrological models, there is a large spread in projected changes in water resources for some regions of the world (Hagemann et al., 2013).

However, at high latitudes and in some mid-latitude regions the models agree on the sign of projected hydrological changes, indicating higher confidence in the results (Hagemann et al., 2013). According to IPCC (2011) projected precipitation and temperature changes imply possible changes in floods, although overall there is *low confidence* in projections of changes in fluvial floods. Confidence is *low* because the causes of regional changes are complex, although there are exceptions to this statement. There is *medium confidence* (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding, in some catchments or regions. People living in snowmelt-fed basins experiencing decreasing snow storage in winter may be negatively affected by decreased river flows in the summer and autumn (Barnett et al., 2005).

According to IPCC (2011) there is *medium confidence* that droughts will intensify in the 21st century in some seasons and areas, due to reduced precipitation and/or increased evapotranspiration. This applies to regions including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Elsewhere there is overall *low confidence* because of inconsistent projections of drought changes (dependent both on model and dryness index).

5. CLIMATE-INDUCED IMPACT AND RISK ASSESSMENT ON DAMS, RESERVOIRS, AND WATER RESOURCES SYSTEMS

This chapter aims at describing different methods and approaches allowing dam and reservoir owners to analyse potential impacts of climate change on their water resources systems.

The first section (5.1) reviews the recommendations of IPCC with respect to regional impact analyses. Section 5.2 recaptures the main elements justifying dam and reservoir managers and designers to revisit their activities in light of climate evolution and describes the overall analysis process leading to the evaluation of the benefits associated to adaptation measures. Section 5.3 focuses on the description of different methodologies commonly used to perform climate change impact analyses. Section 5.4 deals with uncertainties and probabilistic approaches, and finally section 5.5 brings examples of impacts analyses and adaptation measures adopted to cope with climate change consequences.

5.1 IPCC RECOMMENDATIONS FOR REGIONAL IMPACT ANALYSIS

The IPCC has summarized and published the state of knowledge with respect to the assessment of climate change impacts, adaptation and vulnerability in the assessment reports of the IPCC Working Group II (Carter et al., 1996; Ahmad et al., 2001; IPCC, 2007) and in a special report on impacts and adaptation (IPCC, 1994). The earlier assessment reports from 1996 and 2001 provide detailed descriptions of impact assessment methods while the fourth assessment report (2007) provides an update focussing on improvements of methods. Many assessment methods make use of climate scenarios derived from climate model simulations. This is particularly true for hydrological studies that have a strong quantitative component. The IPCC treats the topic of climate scenarios in dedicated chapters in WG I and WG II reports (see Carter et al., 2001; Mearns et al., 2001; Carter et al., 2007; or more recent IPCC Assessment Reports) and has recently summarized IPCC guidelines on how to make adequate use of available climate model projections (Knutti et al., 2010). A IPCC technical paper with a focus on climate change impacts on water resources (Bates et al., 2008) can serve as a good reference for dam operators and owners both in respect to different water resources sectors as well as regional contexts.

The IPCC recommends a standard approach to climate change assessment, which is based on seven basic steps:

1. Define problem
2. Select method
3. Test method/sensitivity
4. Select climate scenarios
5. Assess biophysical/socio-economic impacts
6. Assess autonomous adjustments
7. Evaluate adaptation strategies

This approach is driven by climate model generated scenarios and has early been defined in the special report on impacts and adaptation (IPCC, 1994) and refined in TAR, AR4 (IPCC, 2001; IPCC, 2007), and more recently in AR5 IPCC reports. It has been used in a wide range of applications and can be modified according to particularities of a study.

Hydrological impacts will need to be quantified in the majority of cases and should therefore rely on quantitative climate scenarios. In order to make quantitative predictions of regional climate change effects on hydrology, it is recommended to analyse both changes in average flow at different time scales and changes in the temporal distribution of flow. Direct runoff output from climate models allows for the assessment of changes in surface runoff but lacks the routing and transformation into stream flows. Thus, to achieve the transformation of climate scenarios into stream flow scenarios hydrological models should be employed. Hydrological regimes governed by snow and/or ice are particularly susceptible to shifts in peak flows and winter conditions (Kumar et al. 2011).

5.2 REQUIREMENTS FOR ADAPTING DAM AND RESERVOIR DESIGN AND OPERATION TO CLIMATE CHANGE

Dams, reservoirs and water resources systems largely contribute to human well-being. However, the performance of their design and operations under climate change conditions may change. In order to identify the potential initiatives that the dam, reservoir and water resources systems owners and operators may undertake to cope with this important issue, it is essential to determine the current state of knowledge of the impacts of climate change on hydrological variables at regional and local scales. This section (i) defines the problem we have to cope with and (ii) describes roughly the analysis process to be realized in order to quantify the benefits of possible adaptation measures applied to dam and reservoir management and design.

(i) define the problem we have to cope with:

The problem to be addressed arises from the potential change to the connection between climate and the hydrological regime on one side and the physical configuration and the operation of a dam or reservoir on the other. It implies that:

1. Hydraulic structures were designed and are operated according to past climate and hydrological conditions
2. In the light of potential climate and hydrological changes, it is recommended to revisit the adequacy of the hydraulic structures and their operations

Based on this definition of interaction of climate change and dams/reservoirs the analysis process to be realized in order to evaluate the necessity of adapting equipment design or operations can be implemented.

(ii) describe the analysis process leading to a decision whether to adapt or not:

Prior to any adaptation the potential climate change impacts and the benefits that might lie in adaptation need to be investigated for any particular dam and reservoir systems. This can be done by studying the performance of the system under different climate scenarios. The analysis design is illustrated in Figure 5.1. In order to evaluate the interest for adaptation, the (virtual or numerical) analysis to perform is to compare the known performance of the system to the performance under new hydro-climatic conditions. Four cases can be examined:

1. Assess the current equipment's performance (performance 1)
2. Evaluate the equipment performance under new hydro-climatic conditions without modifying either operational rules or the equipment physical configuration (performance 2)
3. Evaluate the equipment performance under new hydro-climatic conditions and improved operational rules without modifying the equipment physical configuration (performance 3)
4. Evaluate the equipment performance under new hydro-climatic conditions and both improved operational rules and adapted equipment physical configuration (performance 4)

Benefits associated with any given functional or structural adaptation measure can be evaluated by comparing performances 1 to 4. Examples of possible functional and structural adaptation measures are presented in Chapter 9.

Care must be taken to clearly separate climate driven changes to a water management system from non-climatic factors that have an impact of the system performance in the four cases. A review of non-climatic drivers can be found in Chapter 6.

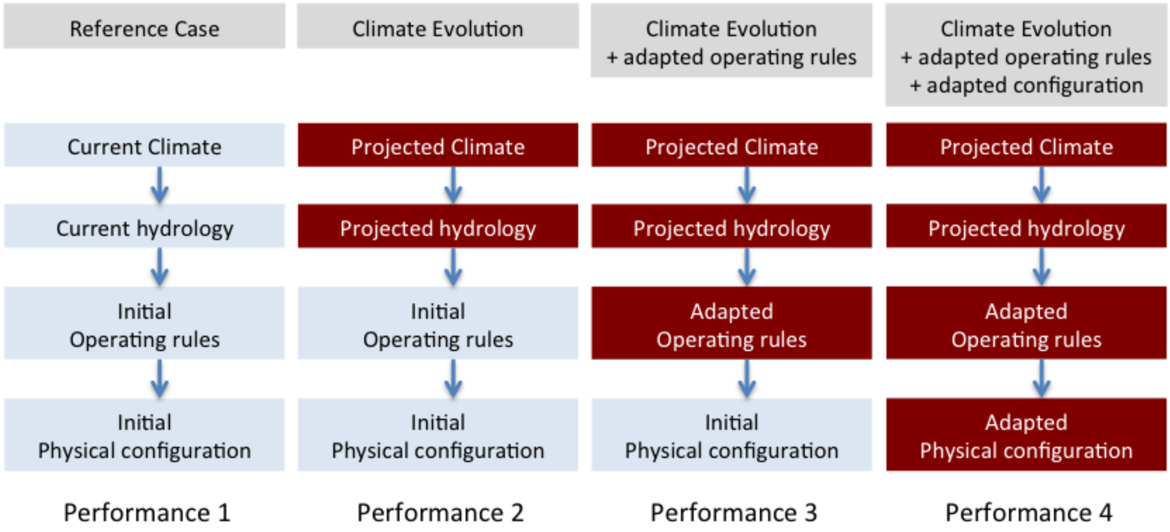

Figure 5-1 – Illustration of the analysis design quantifying the benefits for adaptation (modified from Roy et al., 2008)

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This section describes a general framework in order to perform climate change impact analysis on water resources systems. We will introduce a range of different known and improved methods from relatively simple and low-cost analyses to more expensive and sophisticated ones. The simpler ones being considered when only limited information is available, a broad evaluation of impacts is sufficient or the risk of failure are not associated with important damages. The more complete and complex ones could be preferred by users having access to more climatological and hydrological information and/or having to deal with major hydraulic infrastructures at risk. More complex procedures might involve larger uncertainty thus simpler approaches could still be effective and considered although more complex methods are available.

The simplest and most accessible method to analyse dams/reservoirs climate sensitivity relies on "what if scenarios". According to this approach, the climate and hydrological scenarios could be based on historical data analysis (for either specifically unusual conditions, or disturbed observations) or taken from available general circulation models (GCMs). When affordable, more accurate methods involving dynamical, empirical or statistical downscaling of global climate model output could be used. Since climate models include the modelling of the hydrological cycle at the land surface, runoff taken directly from climate simulations may be used, with caution due to coarse resolution and potential biases. Regional Climate Models (RCM) may provide higher resolution simulations where available. When suitable, hydrologic models should be employed to simulate the effects of climate change at regional and local scales. In this case climate model information needs to be adapted to hydrological modelling scales. Hydrological model outputs simulated for future conditions can then serve as inputs to water management models that shed more light on potential impacts. If expected impacts are of substantial magnitude this latter information can be used to adapt the design or the operations of any given hydraulic structure. If impacts are insignificant no adaptation is necessary. The following sub-sections describe briefly the proposed stepwise approach moving from the most simplistic to the most elaborated one. Figure 5.2 provides a schematical illustration of the sequence of approaches.

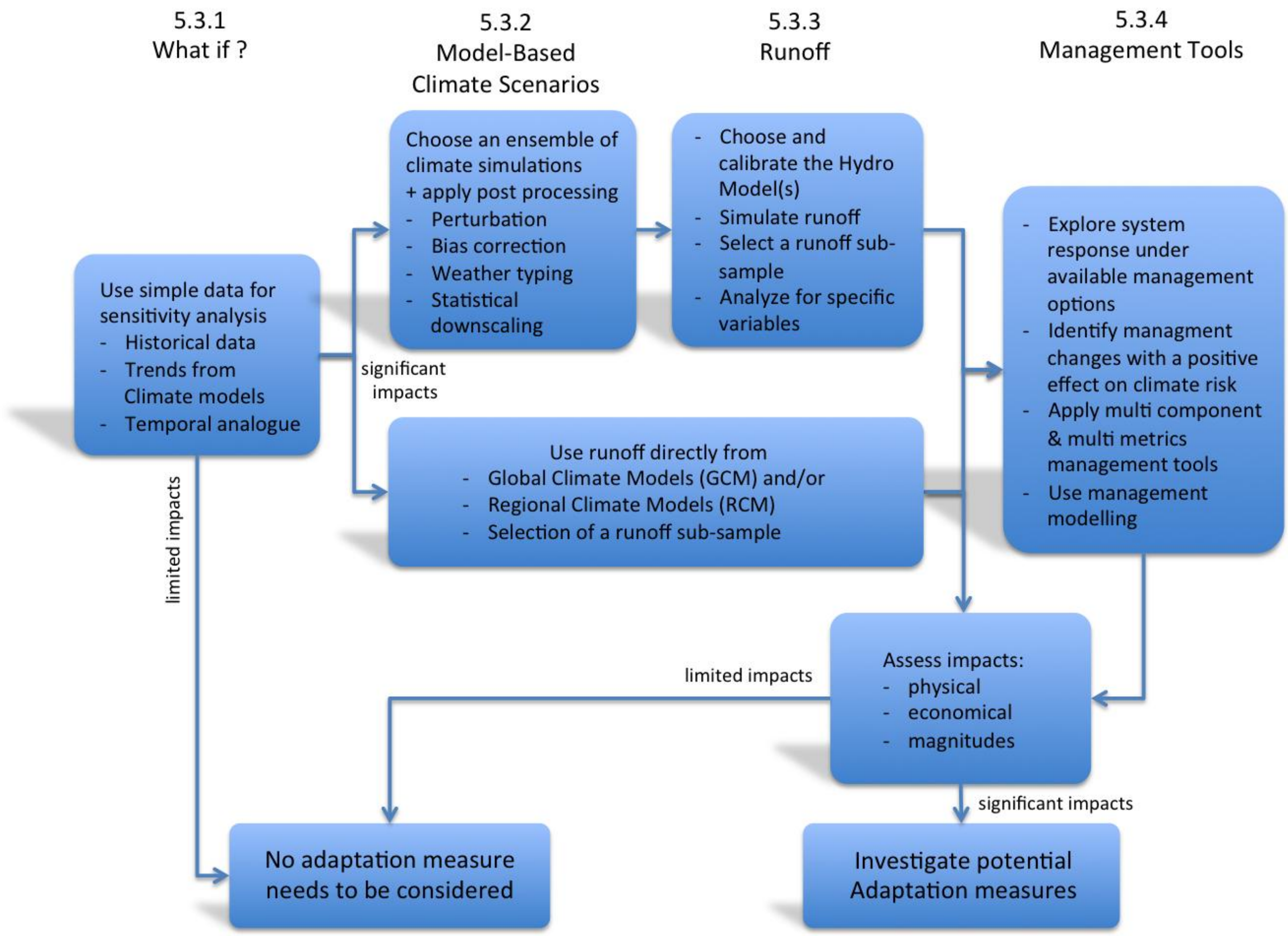


Figure 5-2 – Different pathways for hydrological climate impact assessments

5.2.1 “What if” scenarios

To construct « What if ? » scenarios:

a. either exploit historical climatological and hydrological information on events general trends obtained from easily available deltas of change from GCM simulations, putting emphasis on extreme conditions, that could even be inflated. Such events based on temperatures and/or precipitation can be selected on scatter plots giving a wide range of potential future climate conditions. For instance, a typical “what if scenario” can be based on:

   - the repetition of a past historical drought period, but assuming for example a longer duration or harsher conditions during the event ;
   - an average air temperature increase for a range of plausible values ;
   - an annual or seasonal precipitation average change for a range of plausible values;
   - etc ...

b. evaluate roughly the potential impacts of these climatological/hydrological conditions on dam operations and design by using temporal analogues of extreme climatic conditions

c. assess the significance of impacts. If they are not significant, there is no need to adapt and the exercise may stop here

d. If the expected impacts are significant, then the approach described in 5.3.2 should be followed

5.2.2 Climate model-based scenarios

This category of scenarios include the use of climate models outputs and post-processing to serve as inputs to regional basin hydrological models.

A critical point in any quantitative scenario-based impact assessment is the selection of future climate scenarios. Following IPCC recommendations, analysis must rely on ensembles of simulations for climate impact analysis and a number of issues should be considered in the selection of climate scenarios:

- Due to model complexity and model response no 'best model' for a given region or application can be identified. Quality metrics are not unequivocal. An ensemble of multiple models should be used to represent a range of realistic responses.
- Be aware that differences in the climate model simulations are to be observed and must be understood (variations between simulations and models, type of ensemble, internal variability, etc.).
- Overrepresentation of models with multi-member simulations must be considered by averaging model members first before combining different models
- Observational uncertainty and internal variability should be taken into account to identify a significant climate change signal
- Ranking and weighting models is a critical issue. If applied it needs to be fully documented and compared to un-weighted results.
- Agreement of models is not an indicator of likelihood
- Uncertainty should be assessed combining Global and/or Regional Climate models and different downscaling techniques
- Uncertainty in future climate scenarios increases with decreasing scale
- More recent simulations should not be considered more reliable than older ones (e.g. CMIP5 ensemble does not mean that the CMIP3 ensemble should be discarded)
- Consider non-climatic regional factors (e.g. land use change, atmospheric pollutants, see Chapter 6)

This list includes the most important issues to consider when using climate scenarios for regional impact analysis. The detailed description of issues and currently unresolved questions in building multi-model ensembles found in Knutti et al. (2010) is highly recommended.

In order to bring climate simulation data to effective use in hydrological modelling data can be treated by using methods of statistical downscaling to bring climate scenarios to an appropriate scale for hydrological models. This is particularly the case for GCM data at coarse scales unfit for direct use in watershed impact analysis. Options for statistical downscaling include

- applying a "Perturbation" method to produce future climate scenarios usable by hydrological models. Perturbation methods will use the difference between simulated future climate and simulated reference climate to perturb observed time series. Different approaches based on monthly deltas or percentiles of daily data's distributions are available. Perturbation methods create a future time series with similar characteristics as observed time series. They do not make use of the different climate dynamics represented in climate model simulations (Mpelasoka and Chiew, 2009; Themessl et al., 2010; Maraun et al. 2010).
- applying a "Bias Correction" approach to produce future climate scenarios usable by hydrological models. Bias correction methods use the biases between reference climate observations and reference climate simulations to correct a future simulation. They assume neglectable biase differences between climate simulations for a reference period and a future period. Different approaches to address climate model deviation from observed climate may be employed. This group of methods preserves the climate dynamics generated by climate

models but might lack some of the characteristics known from observations (Mpelasoka and Chiew, 2009; Themessl et al., 2010; Maraun et al. 2010).

- building climate scenarios by "weather Typing". Weather typing involves a classification of large-scale synoptic patterns of air pressure, humidity, etc. that are statistically linked to local and regional weather. These relationships are applied to future large scale patterns obtained from GCM simulations. It involves the risk that the relationships between weather type and site weather may not be stationary over time (IPCC, 2001a).
- creating climate scenarios using "statistical downscaling". Statistical downscaling derives statistical relationships between observed small-scale variables (predictand from station observations) and larger scale variables (predictor from reanalysis) using multivariate regression analysis or neural network methods. Then, the statistical relationships are applied on GCM or RCM variables to generate the future local or regional climate (IPCC, 2007a).

As the next step we can proceed with the approach described in 5.3.3 (application of a hydrological model).

5.2.3 Run-off determination

State of the art runoff determination usually involves the application of a specific hydrological model. Fundamental steps in following this approach involve:

a. Choose a hydrological model ;
b. Calibrate the hydrological model ;
c. Simulate the future hydrological regime (driving the HM with climate scenarios) ;
d. Select a sub-sample of hydrological simulations that covers the uncertainty ;
e. Analyse the impacts on specific variables of interest (mean annual volume, flood volume, flood peak, timing of the flood peak, etc.) ;
f. If expected impacts are not significant, there is no need to adapt and the exercise stops here
g. If the expected impacts are significant, you may or may not go through management tools (c.f. 5.3.4)

In the case of using direct GCM/RCM runoff :

a. Extract the runoff simulated by climate models. Higher resolution model outputs (RCMs) should be preferred over lower resolution model output (GCMs) ;
b. Select an ensemble of hydrological scenarios;
c. If expected impacts are not significant, there is no need to adapt and the exercise stops here

5.2.4 Management tools

All previous steps in the impact assessment process regard natural responses to varying climate conditions. These steps can be sufficient to evaluate whether situations become critical and require remediation. But when water resources systems are highly regulated and controlled, or when water needs and water uses are complex and diverse, the impact assessment process must also rely on "management tools" that reflect the way installations and projects may be (i), affected by changed climate conditions, and (ii) operated in a different manner where the change in management has a positive effect on the risks identified (Brekke et al, 2004). These management tools must include different components that model physical processes, economical aspects, human and environmental needs, safety objectives, etc. Such tools often include an operational optimizer, but the complexity of situations and the variety of objectives to meet also call for multi-metrics management tools. The use of water resources management tools in combination with stakeholders participation, coordination and negotiation may lead to an "optimum" new way of managing and operating the system.

In this light, responding to climate change challenges might as well drive forward the necessity to move towards fully "Integrated Water Resources Management" (IWRM).

5.3 MANAGING UNCERTAINTY. TOWARDS PROBABILISTIC APPROACHES

As already stated in this guide, the arbitrary selection of one or two GCMs can lead to confounding results and conclusion, with no handy or even misleading use for decision-makers at the end. Examination of multiple scenarios (multi model, multi GHG emission scenario) can thus provide bounds of future possibilities. It shall be noted that probabilities cannot be formally associated to either GHG emissions scenarios or GCM output scenarios.

However, as mentioned in the IPCC guidelines for climate impact studies (IPCC, 1999), there are ways to account for uncertainty associated with climate change projections, which can provide a more comprehensive evaluation of risks. In particular, Jones (2000) developed an interesting statistical method, inspired from surrogate model or response surface statistical concept (De Rocquigny et al., 2008), and based on 3 major steps conceptually summarized and described on Figure 5.3:

1. Establish the intrinsic climatic sensitivity of the water resources system of concern, through appropriate risk indicators α (see chapter 3), to arbitrary incremental changes in air climatic parameters (temperature ΔT and precipitation ΔP). Practically, the response of risk indicators α to constant arbitrary ΔT and ΔP changes can be plotted as shown by schematic α-isolines on Figure 5.3. As ΔT is increasing, or as ΔP is decreasing, risk indicator α is usually increasing;
2. Estimate the likelihood or probability density function (pdf) of these ΔT and ΔP changes at the time horizon of interest, by post-processing outputs from GCM scenarios to calculate a rough estimation of ΔT and ΔP pdf's, simply assuming that each climate scenario is equiprobably "wrong", and granting each GCM scenario with a similar uniform weight. A schematic distribution of such a calculated (ΔT, ΔP) pdf is plotted in shaded pink circles on Figure 5.3;
3. Combine risk response mapping (step 1) and (ΔT, ΔP) pdf estimation (step 2), to calculate the probability that a given risk threshold might be exceeded at the given time horizon. For example, when considering a risk indicator threshold α2 on Figure 5.3, it is possible to evaluate the climate occurrence probability that this threshold would be exceeded at the given time horizon, by calculating the integral of pdf curves over the blue cross-hatched domain delineated by α2 risk isoline. Scanning the whole range of risk α value allows to assessing an entire risk range.

Typically, this approach can lead to a final output as described on Figure 5.4 from Jones (2000): by 2030, the probability that the risk indicator (here, the annual likelihood that a water farm cap for irrigation falls below a critical threshold) exceeds the value 20% is about 5%; by 2070, the same risk level has a probability which grows at about 80%.

Aelbrecht et al. (2007) tested this approach to the Navajo reservoir in the 4-corner region in the USA, where balance between irrigation needs, hydropower generation and cooling needs downstream the reservoir, is already currently challenged in dry conditions, and might become even more difficult to guarantee in future climate conditions.

The ultimate difficulty in this kind of approach remains in the capacity or possibility of water resources managers for making decisions based on probabilistic criteria, which are maybe not in use in water resources risk assessment and management culture.

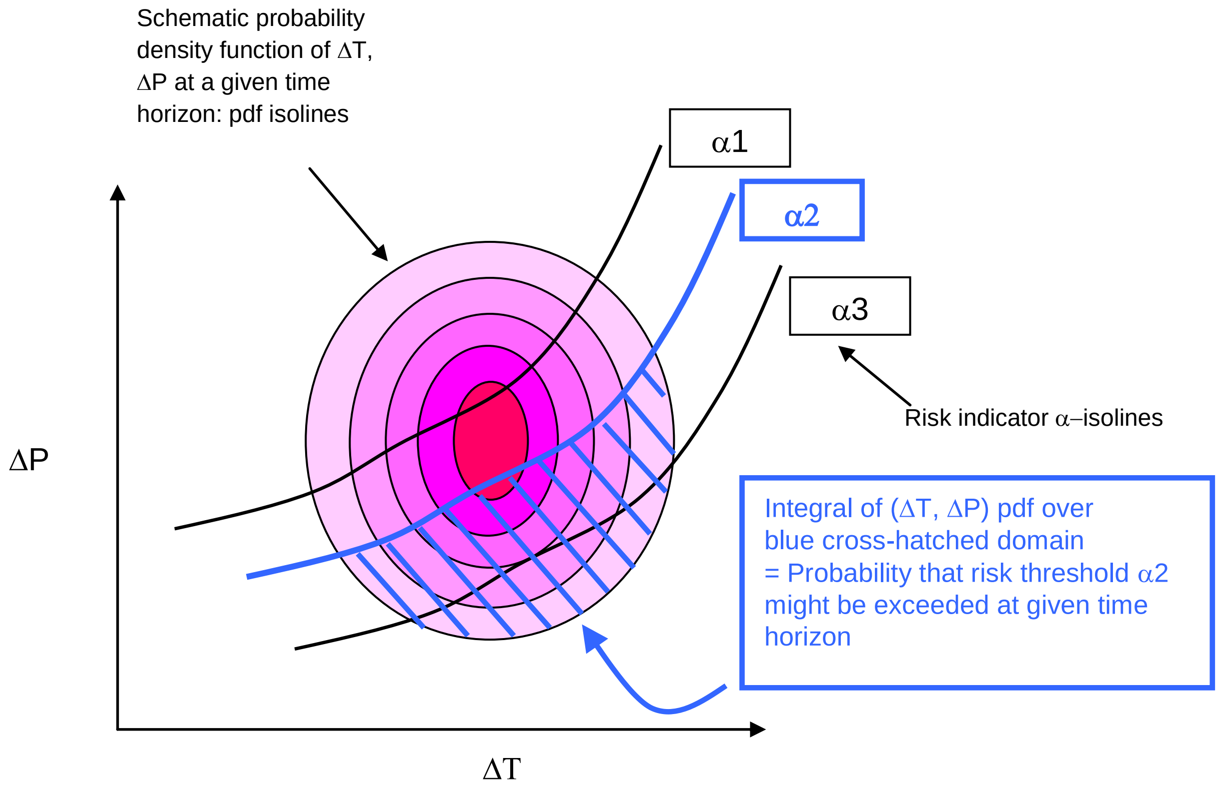


Figure 5-3 – Probabilistic risk estimation schematic diagram

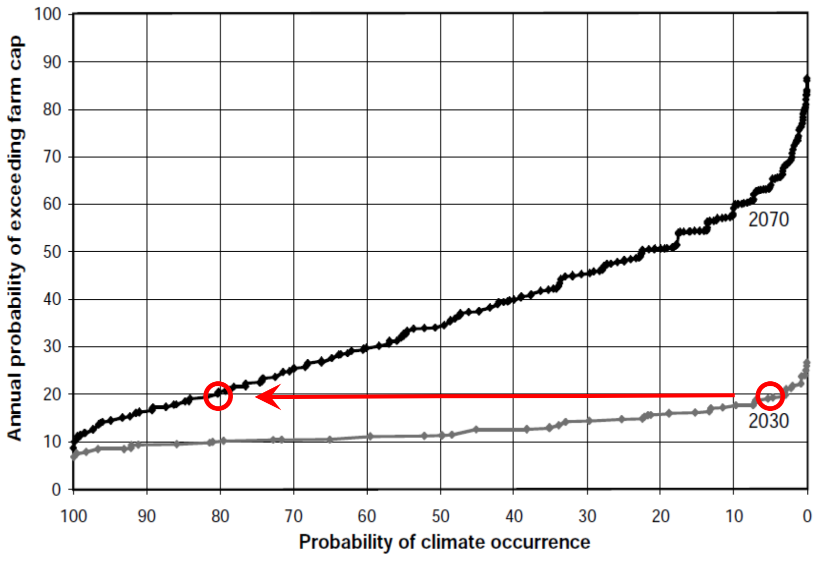


Figure 5-4 – Example of probabilistic analysis output (from Jones, 2000)

5.4 EXAMPLES OF REGIONAL CLIMATE IMPACT ANALYSIS

This section lists selected examples where climate model simulations were used to produce climate change scenarios for regional impact analysis.

Example 1: Does assessment of design floods for dams hold in a changing climate? – Sweden

In a collaboration of the national dam safety authority (SVK, Swedish National Grid Agency) with the Swedish Meteorological and Hydrological Institute (SMHI) and players in the hydro and mining industry, design flows were revisited for 1001 watersheds throughout Sweden. The basins of 11 high hazard risk basins were studied in more detail by employing 16 scenarios from regional climate models for two future time horizons (2050, 2100). The scenarios were bias corrected to integrate seamlessly with a hydrological model to obtain future stream flow scenarios. Analysis revealed that decreases in future floods corresponded to decreasing design snow packs and higher rates of evapotranspiration in a warmer climate. However, an increase in design floods volume was found in southern Sweden, where climate projections are dominated by a large increase in precipitation (Bergström, et al. 2012)

Example 2: Are climate change impacts large enough to be considered in the refurbishment of hydro power generation equipment? – Québec, Canada

After several decades of operation hydro power station installations routinely undergo refurbishment for optimal operation and safety. However, such effort in turn has a multi-decade planning horizon. The effects of increasing green house gas concentrations in the atmosphere are very likely to affect future hydrological regimes at that time scale, particularly in northern regions of Québec. The operational management of Hydro Québec therefore initiated a cost benefit study to establish whether economical impacts of changes in the hydrological cycle of their dammed watersheds called for a consideration of climate change impacts in long term planning routines. In collaboration with the Ouranos Consortium on regional climatology and adaptation to climate change a study was conducted for 10 watersheds in northern Québec. A total of 81 climate scenarios from a multi model ensemble were employed. The ensemble covers the uncertainty from climate model imperfection, natural climate variability, greenhouse gas emission scenarios and different approaches of post processing. The operational hydrological model of Hydro Québec's research centre was fed with the climate scenarios to produce future stream flow scenarios. The 81 scenarios had to be further filtered in order to select a set of scenarios that could adequately be integrated in a decision making process. To this end, a cluster analysis approach was used to combine multiple hydrological and economical criteria critical to operation planning. The approach successfully conveyed the consideration of climate uncertainty in the decision making process. The results showed that in the region of interest climate change impacts are at a magnitude that calls for more in depth and site specific assessment of changes on hydrological regimes. (Braun et al., 2013)

Example 3: Can a water transfer system be managed under climate change conditions? - Bavaria, Germany

A water transfer system composed of multiple reservoirs, pumping stations and river flow constraints is used to maintain defined minimum flows in the (dryer) Main river system by transferring water from the (wetter) Danube river system. Multiple interest of various stakeholders are involved: a power plant that requires cooling water, tourism and recreational activities that depend on water levels of the reservoirs, pumping capacities, minimal flows to be maintained for ecological reasons in two rivers and the additional waters transferred by the Main-Danube water way. In order to assess climate change impacts on this complex system, three simulations from a regional climate model were used to drive a hydrological model to simulate present and future water inputs to the system. The complex water management of the system that needs to take into account the various interests involved was addressed by developing a fuzzy logic based management software. The combination of climate model output, hydrological model results and the water transfer system model allowed to assess the increase in water stress situations in autumn and evaluate adaptation options by modeling various use cases of the system (Schmid et al. 2012) .

Example 4: Is the impact of climate change on river discharge associated with the East Asian rain band assessed based on a high-resolution climate simulation? - Japan

One of the main issues of climate change impact in Japan is changes in precipitation in terms of intensity, amount, and duration. Since heavy precipitation events often occur in a narrow rain band associated with the East Asian summer monsoon, its modulation is the key aspect of future precipitation changes. This rain band cannot be resolved in a conventional coupled atmosphere-ocean GCM, used for future climate projection. As one of the ways to obtain sufficient resolutions, the Japan Meteorological Agency and the Meteorological Research Institute jointly developed a framework of time-slice climate experiments using an extremely high-resolution (grid size of 20 km) atmosphere GCM, driven by prescribed sea surface temperatures as boundary conditions (Kusunoki et al., 2011). The impact of climate change on river discharge was analyzed by feeding future climate projection data from the time-slice experiments into a distributed rainfall-runoff model (Tachikawa et al., 2011), which produces downscaled hourly runoff data over complex Japan river basins with a resolution of 1 km. In this result changes in the annual maximum of hourly runoff were clearly detected under a future climate scenario. The magnitude and sign of the changes are different from regions to regions, depending on local changes in summer rainfall and the tendency of decrease in snowmelt runoff.

6. CLIMATE IS ONE OF THE DRIVERS ... AMONG OTHER

Climate is just one of the drivers for change in the world's water resources. Socio-economic drivers will have as much if not more impact on water resources than climate changes. The most significant socio-economic driver is a growing world population. There is a finite amount of fresh water available and its use will have to be maximized taking into consideration all the uses for fresh water including protecting the environment.

6.1 DEMOGRAPHY EVOLUTION

The world population is increasing. However, some parts of the world have stable populations and the needs for more water are not as great. Growing populations in lower latitudes just add to the future concerns about available water supplies for direct human use, energy production and food production. More storage is definitely needed, but are there enough supplies available even if storage is available? These are regional concerns that must be considered and addressed. In higher latitudes with growing populations, the need for more water can probably be addressed. However, the concern in these higher latitudes is will the new population settle in areas prone to flooding by larger floods. This must be considered and addressed.

6.2 TECHNOLOGY EVOLUTION

Technology advances can reduce the need for water, increase the need, help better manage and maximize the efficient use of existing supplies, and make non-potable water usable.

Technology developments have greatly reduced the amount of water needed to grow food crops by reducing the waste in the system. There are two significant examples:

- Development by bio-engineers of more drought tolerate varieties of basic crops and
- Use of irrigation systems that apply water to the crops when needed instead of the more traditional flooding of crops.

As the need for water grows, all water users need to assess the waste in their systems and use technology to reduce the waste.

Technology can also increase water usage as more water is used. A great example is in energy development where new technologies allow fracking, fracturing of formations containing oil and gas, to obtain these energy sources from formations where only limited supplies could previously be obtained.

The advances in data recovery on actual precipitation and runoff coupled with the analytical capacity of modern computer systems helps water resources professionals better manage the available water supplies.

A last example of how technology impacts water supplies is in improvements to water treatment. The economic cost of treating and using non-potable water is decreasing. This is making reuse of wastewater and use of brackish / sea water for water supplies more common.

6.3 SOCIAL AND REGULATORY EVOLUTION

Social and regulatory evolution is changing the way water resources are perceived and managed. Historically, if a need was economical, water resources development could be justified. Today, society's overall needs must be considered and many times these needs are much harder to quantify. This leads to misunderstanding and less trust. Society's needs differ regionally and can only be addressed on a regional basis. Water resources planners need to understand and address these needs.

Regulatory changes are driven by governments trying to accommodate society’s needs. Regulatory changes are needed, but they must be undertaken in such a way as to maximize the overall water resources and meet all of the needs, not just one need at the cost of another. Obviously, regulatory changes must be addressed on a regional basis requiring cooperation between local, regional and national governments as well as cooperation between national governments. As water grows more scarce the need for cooperation increases, but the potential for protectionist approaches increase. How to resolve this age old dilemma is beyond the scope of this document.

6.4 ECONOMIC FACTORS

Economic factors drive water needs and usage. The worldwide need for more energy requires the need for water to produce that energy (hydropower, steam electric, and the newer need for fracking to extract oil and gas) grows. This must be taken into consideration by water planners just as other needs are considered. This water – energy nexus is well documented.

In addition, richer economies tend to use more water. The use of technology to change this trend will help society meet future water needs. There is no reason why richer economies cannot reverse this trend and make water available to their less fortunate neighbours.

6.5 SEDIMENTATION

The deposit of sediment in water supply reservoirs has been the subject of an ICOLD Bulletin, an ICOLD Congress question, and a current ICOLD Technical Committee is preparing a new bulletin on the subject. In summary, sedimentation has a very progressive and subtle impact on water supply storage capacity in existing reservoirs. Annually, there is a small loss of storage and supply capacity. However, over a period of years the impact becomes significant. Figure 7.9 (from Annandale, 2013 - see Chapter 7 references) shows the worldwide impact of sedimentation on reservoir storage. This is even more dramatic because of the decrease in the number of new reservoirs since the 1980”s. Water resource planners need to take sedimentation into consideration and consider measures to reduce the amount both in new and existing reservoirs.

7. OPPORTUNITIES FOR NEW STORAGE AND NEW RESOURCES MANAGEMENT

7.1 INTRODUCTION

Dams are constructed to regulate and store water for purposes of fresh water supply and hydropower generation. The size of a dam and its reservoir is determined by the demand for water and power, the desired reliability of supply, and the hydrologic characteristics of riverflow. Climate change will principally affect the hydrologic characteristics of riverflow, which in turn will affect the size of dams and the magnitude of reservoir volumes.

The impact of climate change on the reliability of fresh water supply and hydropower is considered. This is done by highlighting the uncertainties associated with climate change and how they will impact the reliability of water and power supply. It is concluded that the best way to deal with these uncertainties is to plan, design and construct robust infrastructure, which is characterized as having the least sensitivity to climate change effects.

7.2 THE NEED FOR RESERVOIRS

This section emphasizes the importance of developing rivers for sustained fresh water supply (domestic and irrigation) and power generation. Global demand for water can be divided into water demand required to satisfy agriculture, domestic (municipal) and industrial needs. The largest user of water, worldwide, is agriculture, which uses 70% of supplied fresh water. Industry uses 19% of all supplied water and 11% is provided for domestic use.

Water sources

The two principal sources of fresh water used worldwide are groundwater and river water. Identifying the source with the greatest potential for sustainable development requires consideration of the usage and replenishment rates of these resources. If the rate by which water may be used is greater than the replenishment rate of the resource, it indicates non-sustainable use. Alternatively, if the rate of usage is lower than the rate of replenishment the resource can be sustainably developed.

A proxy that can be used to quantify the relative rate of replenishment of fresh water sources is the residence time of water. Residence time is the time it takes for a drop of water to move through a resource. It is estimated that the average residence time for all fresh groundwater on earth is about 1,400 years, while the average residence time of river water is estimated at about 16 to 18 days (Shiklomanov & Rodda 2003). In practical terms, what this means is that if one were able to suddenly remove all fresh groundwater on earth, it will take about 1,400 years on average to recover. On the other hand, should one suddenly remove all river water on earth, it will take about two weeks to recover.

The usage rate for water is roughly on a daily basis. What this means is that the potential to non-sustainably use groundwater is high. In the case of river water, the usage and replenishment rates are roughly the same. It means that the potential to sustainably develop river water is much greater than the potential to sustainably develop groundwater.

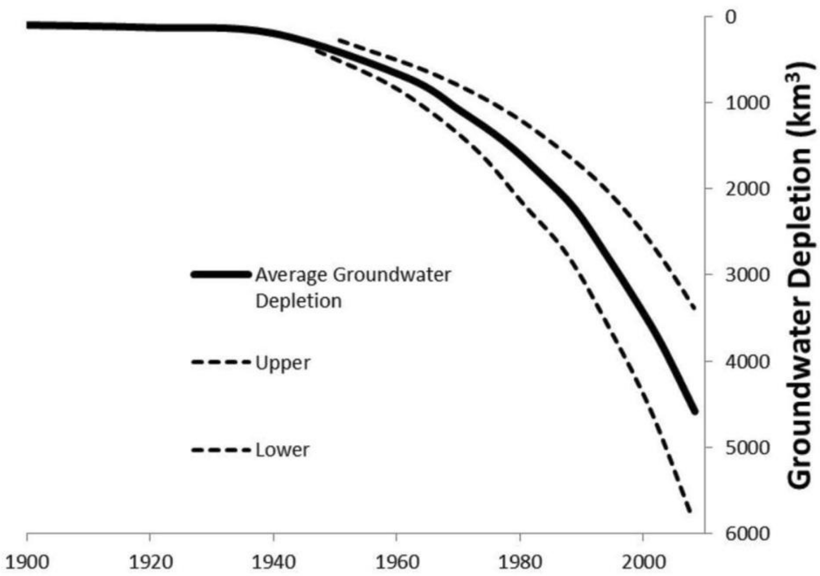


Figure 7-1. Global Groundwater Depletion (data from Konikow 2011).

This high-level assessment of the potential to non-sustainably use groundwater is confirmed by experience. Figure 7.1 presents an estimate of the global depletion of groundwater since 1900, indicating total depletion of about 4,500km^3; a volume that is roughly equal to the net storage space of all large manmade reservoirs on earth. Recent research by Gleeson et al. (2012) confirms this trend, indicating that 3.5 times more groundwater is used worldwide than what is naturally replenished. It is nevertheless noted that site specific conditions may favour groundwater in cases where the replenishment rate is roughly equal to the usage rate, on average.

Consideration of river water as the preferred source of fresh water is therefore in order. One of the main considerations when developing river water relates to the fact that flow in rivers vary between seasons and, in many cases, from year to year. This variability means that the amount of water that is required for use may not always be readily available unless excess amounts of waters occurring during high flow regimes or even floods are temporarily stored for use when riverflow is low.

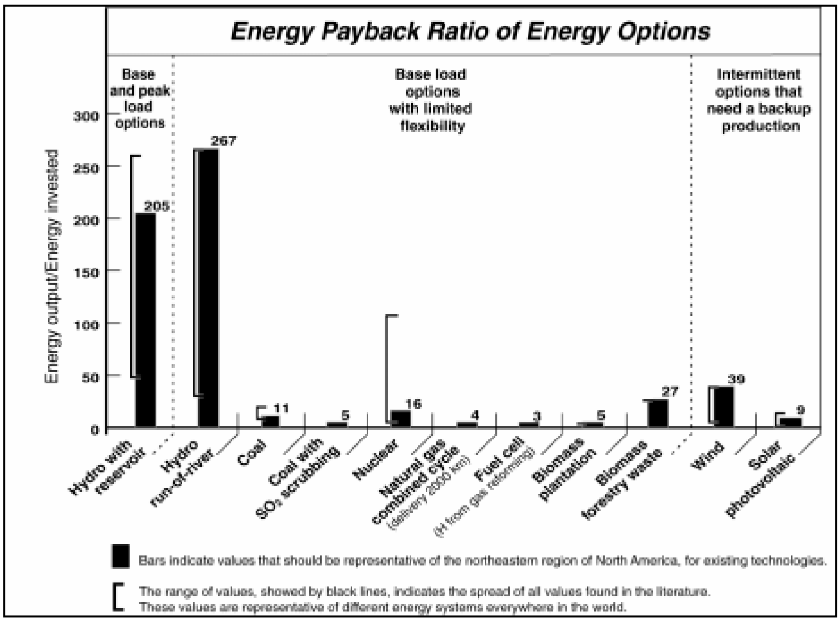
Hydropower

Hydropower is one of the most cost-effective means of generating energy, and by-far one of the less emitting power source. Figure 7.2.a compares the payback ratio, which is the ratio between energy output and the amount of energy invested to develop a resource, for various energy generating options. It indicates that the energy payback ratio of hydropower is generally much larger than that of competing technologies. Figure 7.2.b

The cost-effectiveness of hydropower development, as well as the fact that it generates clean energy, merits consideration of its use; in spite of the fact that it is acknowledged that dams, in general, impact rivers. Such impacts should be mitigated to ensure full and effective use of clean energy.

In what follows it is demonstrated that run-of-river facilities will be more sensitive to the anticipated effects of climate change than reservoir storage projects.

(a)



(b)

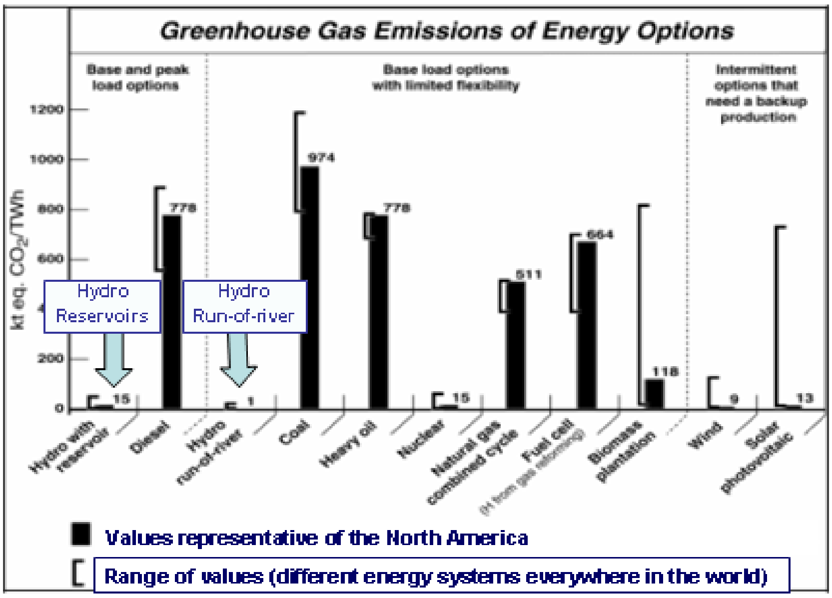


Figure 7-2. (a) Energy payback ratio – Comparison among different power source options
(b) GHG emissions – Comparison among power generation options (IHA, 2003)

7.3 CLIMATE CHANGE IMPACTS ON STREAMFLOW

When considering the impact of climate change on the reliability of water and power supply it is necessary to identify the most important hydrologic factors. An in-depth study of the characteristics of carryover reservoir storage found that the two hydrologic parameters mostly affecting the reliability of yield are the mean annual river flow and its coefficient of variation [2] (McMahon *et al.* 2007).

Although the anticipated changes in mean annual riverflow provide some indication of how water and power supply might be globally impacted, it does not provide an indication of how the reliability

[2] Coefficient of variation of annual river flow equals the standard deviation of annual river flow divided by the mean annual river flow.

of supply will be affected. The answer to this question can only be addressed if it is known how the coefficient of variation of annual river flow might change. In this regard, general agreement appears to exist between climate scientists that the hydrologic variability (represented by the annual coefficient of variation of riverflow) will increase as climate change proceeds. Although some indication exists of how the mean flow in rivers might change (Figure 7.3), no defensible quantification of the magnitude of increases in hydrologic variability due to the effects of climate change exists.

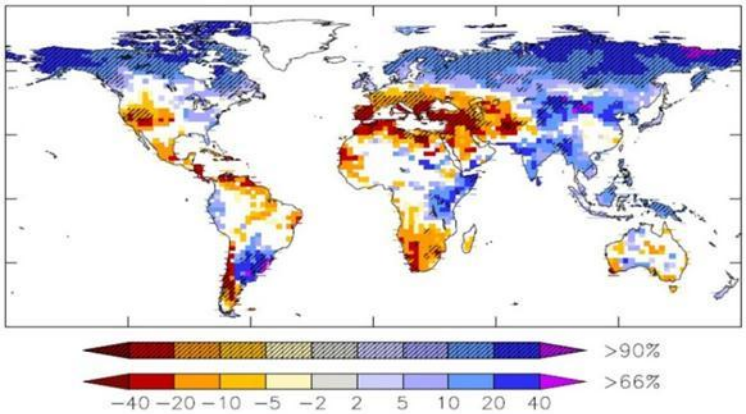


Figure 7-3. Anticipated change in mean annual river flow (after Bates et al. 2008).

7.4 IMPACT OF CLIMATE CHANGE ON RELIABILITY OF SUPPLY

The sensitivity of supply reliability to climate change is first illustrated without the use of storage. Thereafter the value of storage as a means of providing robust infrastructure is demonstrated.

7.4.1 Run-of-river

Water Supply

The reliability of water supply in rivers is quantified with duration curves. McMahon et al. (2007) found that the Gamma distribution reasonably represents the probability of occurrence of the vast majority of annual flow volumes in rivers, worldwide. For the Gamma probability distribution the dimensionless amount of water α flowing in a river at probability p can be expressed as,

$$\alpha = 1 + C_v \cdot z_{p\_g} \quad (1)$$

and (McMahon et al. 2007),

$$z_{p\_g} = \frac{2}{\gamma}\left[\left\{1 + \frac{6}{\gamma}\left(z_p - \frac{\gamma}{6}\right)\right\}^3 - 1\right] \quad (2)$$

Where $\propto = Q/\bar{Q}$ and z_{p_g} = standardized deviate of the Gamma distribution; z_p = standardized deviate of the Normal distribution (see Table 7.1 for selected values); C_v = annual coefficient of variation of flow (standard deviation divided by the mean flow) ; γ = skewness of the data.

The sensitivity of duration curves to the effects of climate change can be satisfactorily demonstrated by making use of Equations (1) and (2). The sensitivity of the reliability of supply for a low coefficient of variation (0.2) and for a high coefficient of variation (0.8) are shown in Figure 7.4. The figure shows that the reliability of supply is very sensitive to the coefficient of variation of annual streamflow in the absence of a dam providing carryover storage.

Hydropower

An indication of how run-of-river hydropower generation may, on average, be affected by climate change is determined by multiplying the annual flow associated with a selected reliability (from equations (1) and (2)) and the head *H* at the plant, i.e.

$$P = \eta \cdot \rho \cdot g \cdot \alpha \cdot \bar{Q} \cdot H \qquad (3)$$

Where η = plant efficiency (-); g = acceleration due to gravity (m/s^2); ρ = volumic mass of water (kg/m^3).

It is concluded that the reliability of both power and water supply from run-of-river facilities is sensitive to increases in hydrologic variability.

z_p	p
-2.33	1%
-1.64	5%
-1.28	10%
-0.84	20%

Table 7.1. Relationship between the standardized deviate of the Normal distribution and probability of failure p

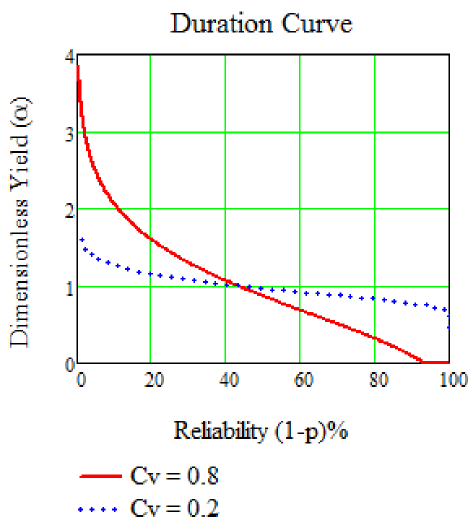


Figure 7-4. Duration curves for varying coefficient of variation (Annandale 2013)

7.4.2 Carryover storage

Water supply

The reliability of water supply can be increased by providing reservoir storage. The sensitivity of the reliability of water supply when using storage can be confidently determined by making use of the Gould-Dincer equation. McMahon et al. (2007) demonstrated that the equation provides defensible estimates of reliable yield when compared to conventional methods requiring more extensive analysis. The Gould-Dincer equation is expressed as,

$$\alpha = 1 - \frac{z_{p\_g}^2 \cdot C_v^2}{4 \cdot \tau} \tag{4}$$

Where, α = dimensionless yield, i.e. yield divided by the mean annual flow; z_{p_g} = standardized deviate of the Gamma distribution; τ = dimensionless storage, i.e. the reservoir storage volume divided by the mean annual flow in the river.

The sensitivity of storage to climate change can be illustrated by using Equation (4) to prepare a storage-yield-reliability graph (Figure 7.5), which shows for 99% supply reliability the relationship between dimensionless yield and the coefficient of variation of annual streamflow for varying reservoir volumes; ranging from 0.25 times the mean annual flow (MAF) to three times the MAF. The graph also contains a thick curve demarcating two storage domains, i.e. run-of-river and carryover storage domains. The sensitivity of yield to climate change in the region demarcated "run-of-river" is determined with the use of Equation (1). In that region storage does not protect against the carryover effects of climate change resulting from increased inter-annual hydrologic variability (Annandale 2013). In the carry-over region it is noted that small reservoir storage volumes are much more sensitive to the effects of climate change than larger reservoir volumes.

It is concluded from the storage-yield-reliability graph that large reservoir volumes represent robust infrastructure. An assessment of the relative robustness of alternative reservoir designs can be determined by comparing the change in yield for selected increases in hydrologic variability associated with climate change.

Hydropower

By making use of the Gould-Dincer method, Xie *et al.* (2012) developed a rapid assessment equation for storage hydropower facilities. Based on that analysis the average amount of energy that is annually generated is expressed as:

$$E = \eta \cdot \rho \cdot g \cdot \left(\overline{Q} - \frac{z_{p\_g}^2}{4S_{\text{ar1}}} \cdot C_v^{\,2} \cdot \overline{Q}^2 \right) \cdot \left(\frac{a \cdot S_{\text{ar2}}^b}{1+b} + c \right) \cdot T \tag{5}$$

Where S_{ar1} = total storage above dead storage elevation; S_{ar2} = active storage used for power generation; T = 1 year; a, b, c = coefficients describing the elevation-storage relationship.

Five operating rules for Three Gorges Dam were used by Xie *et al.* (2012) to demonstrate the usefulness of Equation (5). This equation can be used as a rapid assessment equation to assess the impact of anticipated climate change on energy production. Such an estimate has been made for Three Gorges Dam by assuming a 25% increase in hydrologic variability and no change in mean annual flow. Figure 7.6 shows estimated energy production for the current coefficient of variation (Cv = 0.107) and for an increase of 25% in the coefficient of variation of the Yangtze River (Cv = 0.134). The results indicate that the energy production, at 95% reliability, will decrease by about 10%.

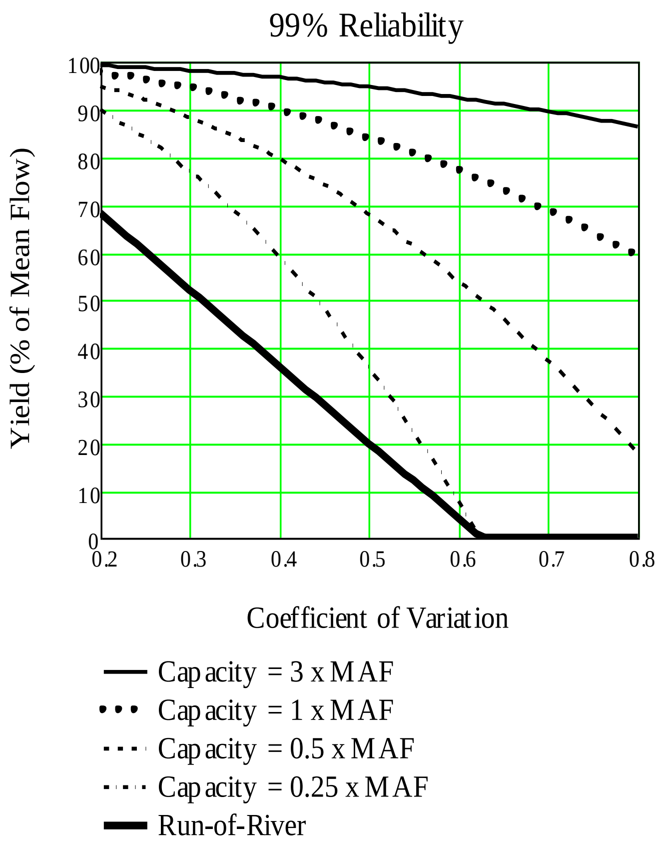


Figure 7-5. Storage-Yield-Reliability relationships for varying hydrologic variability (i.e. coefficient of variation) and 99% reliability (Annandale 2013)

This example illustrates how hydropower generation can be very sensitive to hydrological variability.

7.5 ROBUST INFRASTRUCTURE

The conclusion made from the analysis of climate change effects in the foregoing sections indicate that run-of-river facilities reliability should generally be more sensitive to the effects of climate change than storage facilities, in particular carryover storage facilities. The principal impacts of climate change affecting water and power supply reliability are changes in the mean annual flow in rivers and its coefficient of variation, both uncertain parameters.

The way to deal with this uncertainty is to design robust infrastructure. In the case of water supply and hydropower, robust infrastructure is characterized by infrastructure with the least sensitivity to climate change, i.e. the least sensitivity of changes in the reliability of power and water supply. The least sensitivity is obtained through maximizing reservoir storage (Figure 7.7).

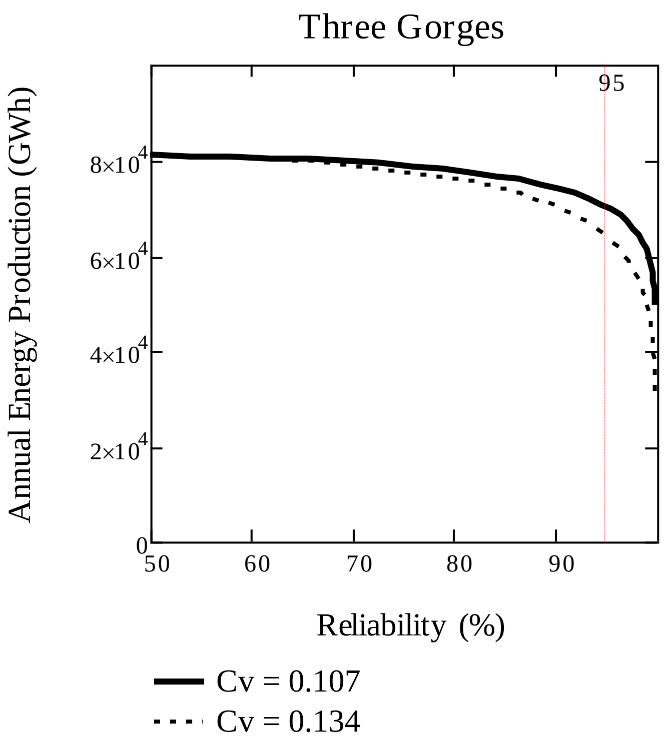


Figure 7-6. Potential impact of climate change on energy production at Three Gorges Dam

7.6 GLOBAL STORAGE – CURRENT TRENDS

The importance of reservoir storage to maximize the reliability of water supply and hydropower generation has been illustrated in the previous sections. It is therefore deemed prudent to review current trends in reservoir storage space worldwide.

Figure 7.8 shows the current trend of adding reservoir storage worldwide. Its rate reduced while the world population continues to grow. Additionally, it is estimated that about 1% of reservoir storage space is lost every year due to the effects of reservoir sedimentation (White 2003). Figure 7.9 illustrates the trends in net reservoir storage space, accounting for reservoir sedimentation. The negative trend in per capita reservoir storage space indicates that current conditions are similar to what they were in 1965 (Figure 7.9). More reservoir storage space is required to mitigate for the effects of climate change, reservoir sedimentation and global population growth.

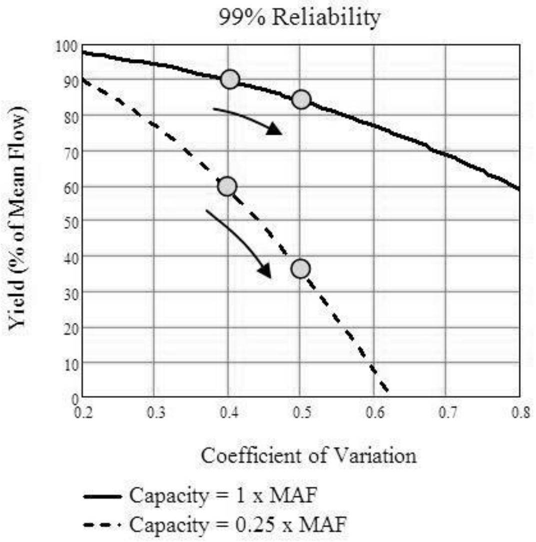


Figure 7-7. Relationship between water yield at 99% reliability for two reservoir volumes and varying coefficients of variation; illustrating the concept of robustness

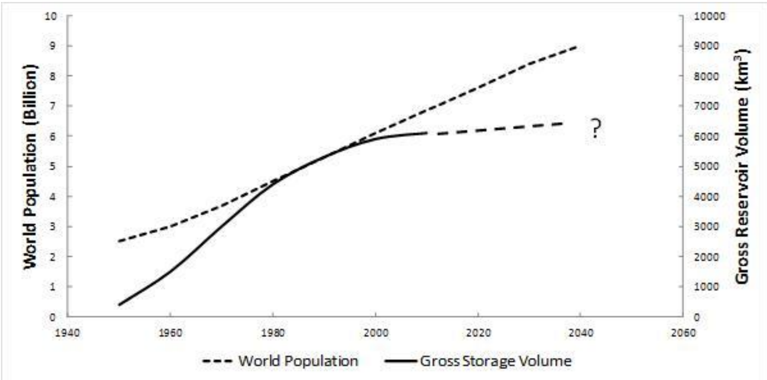


Figure 7-8. Trends in world population growth and gross reservoir volume

Current activity in dam construction and the loss of reservoir storage space due to reservoir sedimentation indicate a reducing trend; the amount of reservoir storage space continues to decrease globally. Such a trend is undesirable because analysis indicates that more reservoir storage space will be required to mitigate the impacts of climate change on water supply and hydropower generation reliability. The need for additional reservoir storage space is further emphasized by a growing world population.

Special attention is required to ensure that water supply needs and hydropower generation can be reliably satisfied for both current and future generations. This will entail assessing the sensitivity of existing infrastructure to the anticipated effects of climate change. Rapid assessment of the effects of climate change is made possible through the techniques presented in this chapter. The design and construction of new infrastructure providing the required amount of reservoir storage, is desirable. Such infrastructure should be designed in a robust manner, as indicated in this chapter.

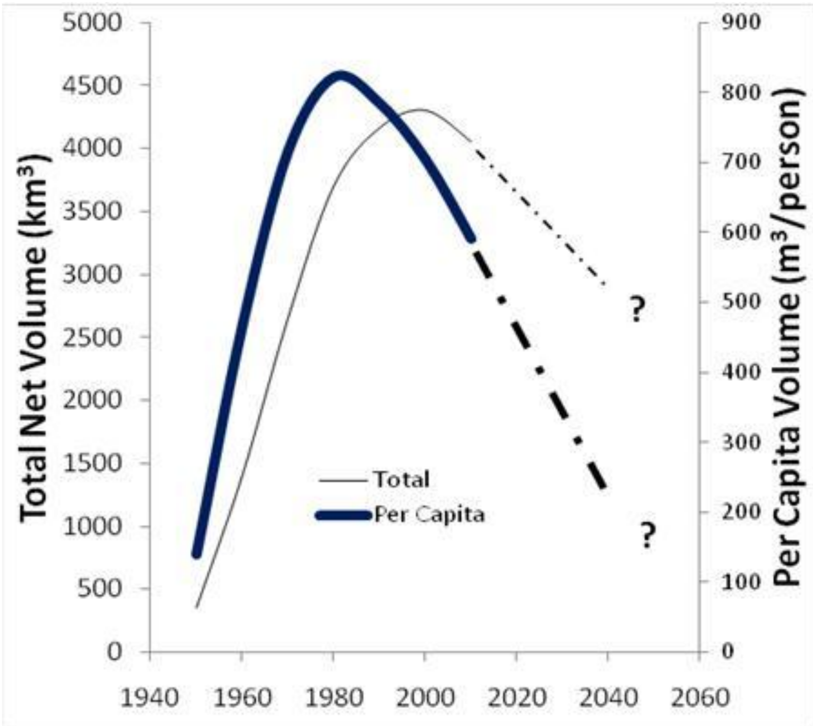


Figure 7-9. Net total and per capita global reservoir storage space (Annandale, 2013)

8. GREENHOUSE GAS EMISSIONS ASSOCIATED TO RESERVOIRS AND WATER RESOURCES

8.1 INTRODUCTION

The previous chapter underlines the growing needs for water storage, the benefits of reservoirs in terms of sustainable management of water resources and despite the fact they may have impacts on rivers, hydropower is considered as a clean energy. Figure 7-2.b demonstrates that globally hydro is the best energy option in terms of Greenhouse Gas (GHG) emissions and the only renewable energy that can support the intermittence related to the renewable energies

Since the early 90's, there is a growing concern regarding GHG emissions (carbon dioxide CO_2, methane CH_4 and nitrous oxide N_2O) from reservoirs (Rudd et al., 1993; Duchemin et al., 2002; Tremblay et al., 2005; Giles, 2006; Gunkel, 2009). In fact, GHG concentrations and emissions measured from surface water indicate the potential for large emissions of CO_2 or CH_4 from tropical (Rosa et al., 2004; Abril et al., 2005) as well as temperate reservoirs (Del Sontro et al., 2010); in comparison, the GHG emissions from cold boreal waters are generally small (Tremblay et al. 2005; Demarty et al, 2011). However, very few studies rigorously document GHG emissions from reservoirs at a global level and fewer still deal with the net impact of reservoir creation on watershed GHG emissions (Teodoru et al., 2012). There are currently no models that can accurately predict long term GHG emissions from a new reservoir without exhaustive field measurements over several years before and after impoundment. We present why, at this time, it is important to account for the potential GHG emissions when designing a new reservoir, how to conduct measurements and why each project must be considered as unique.

The following sections present (1) the processes related to GHG emissions from reservoirs and how reservoirs can impact climate change, (2) the state of knowledge in the field of GHG measurement and (3) the impact of future climate change on GHG emissions from reservoirs.

8.2 WHY AND HOW DO RESERVOIRS EMIT GHG ?

8.2.1 CO_2 and CH_4 emissions

Terrestrial and aquatic ecosystems constitute carbon stocks made up of the lithosphere, the biosphere, soils, surface waters, groundwater and sediments. Energy and matter transfers occur between these compartments and to the atmosphere via physical (wind, runoff, photo-oxidation), chemical (acidification) and biological (respiration, photosynthesis) processes. Ecosystems can be classified according to their capacity to capture or to emit carbon from/to the atmosphere. In general, terrestrial ecosystems are fixing atmospheric carbon and are considered as carbon sinks (forests, peatlands; Blais et al., 2005; Roehm and Roulet, 2003), whereas aquatic ecosystems (lakes, rivers, peatland pools and estuaries) which generally represent a transition zone between terrestrial ecosystems and the ocean and are considered a carbon sources (Cay and Wang, 1998; Abril an Borges, 2005; Cole, et al, 2008; Pelletier et al, 2014) to the atmosphere (Figure 8.1).

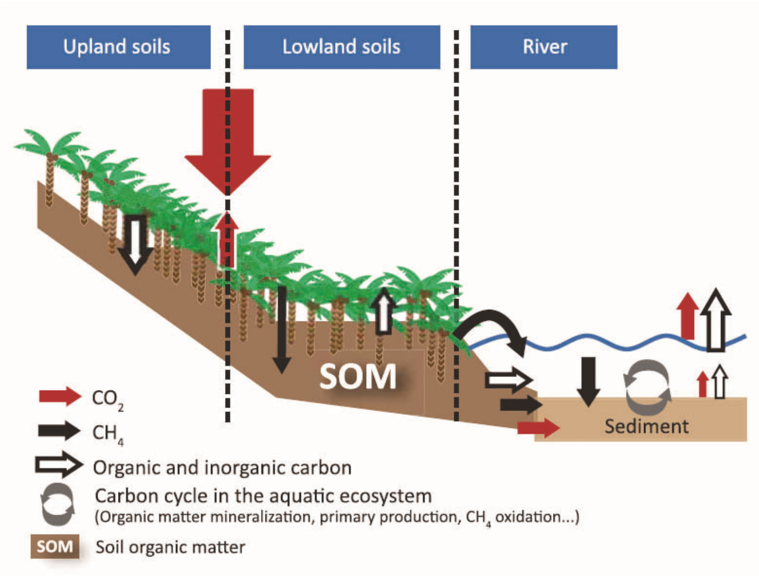


Figure 8-1 Carbone dioxide and methane emissions from a natural catchment (UNESCO/IHA 2010)

In terms of the carbon cycle, the processes occurring in natural aquatic ecosystems or reservoirs are the same (Figure 8.2, Tremblay et al. 2005, Teodoru et al. 2012). Briefly, primary producers provide organic matter (OM) to the ecosystem performing photosynthesis (CO_2 capture) in the euphotic zone (water column where light is available). In turn, a fraction of the OM is degraded by aerobic or anaerobic respiration (with or without oxygen) in the water column and the sediments. Some of the compounds produced during the degradation of OM or oxidation at the oxic-anoxic interface are used as nutrients by primary producers for photosynthesis. The CO_2 produced during OM degradation diffuses upward. The less degradable fraction of the OM settles to the bottom and is buried in the sediment where it may remain for very long period of time. This is the case for tree decomposition in boreal cold water that may take about 1000 years. Methane production (*methanogenesis*) occurs mostly (if not only) in the sediments, when all oxidants of the OM are consumed by bacteria. Methane diffuses upward, from the anoxic sediment to the water column, where it can be oxidized into CO_2 (*Aerobic Methane Oxidation* (AMO)). AMO takes place at the surface of the sediment, in the water column or in the vegetated shallow waters of the waterbody depending on oxygen availability (Wetzel, 2001). AMO lessens GHG emissions in CO_2 equivalent, since CH_4 has a higher global warming potential than CO_2 (more than 20 times greater; IPCC, 2013).

The presence of a thermal stratification in an aquatic ecosystem is an important property affecting gas diffusion to the surface. The density of water is regulated by its temperature among other parameters (salinity, ...); hence, colder water is denser than warmer water, with 4ºC water being the "heaviest". Lakes and reservoirs deeper than 5 to 7 meters can become stratified with well-defined layers: the epilimnion is the warmer surface layer presenting the highest light intensity and biological productivity, the metalimnion is the intermediate layer, the decrease in temperature creates a physical barrier between both upward and downward layers of different densities and the hypolimnion is the cooler bottom layer often depleted in oxygen due to OM decomposition (Wetzel, 2001). The water column of aquatic ecosystems can be well mixed or stratified (year round or seasonally). This stratification has a strong influence on the temporal variations of GHG emissions. Some aquatic ecosystems are stratified most of the year and de-stratify under certain circumstances related to meteorological and hydrological situations. The GHG accumulated below the thermocline during stratified periods are emitted during a very short period of time at the beginning of the de-stratification (known as the turnover). In colder regions, GHG can also accumulate under the ice and be released during the spring thaw period (Demarty et al, 2011).

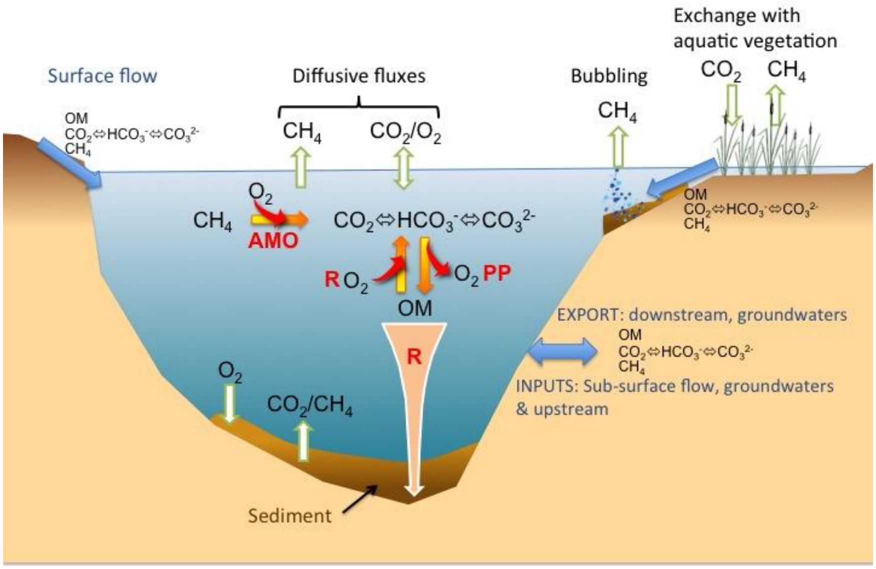


Figure 8-2. Carbon cycle in the waterscape (From Harby *et al.,* 2012).

Gas exchange between aquatic ecosystems and the atmosphere occurs through three different pathways: (1) diffusion from or to the aquatic ecosystems through the air-water interface, (2) bubbling fluxes (or ebullition) corresponding to the direct transfer of methane (very little concentrations of CO2 and N2O due to higher solubility) from the sediment to the atmosphere with little interaction with AMO and (3) in vegetated littoral zones where CH4 can diffuse from the sediments/soils to the atmosphere through the root system and the plant tissues.

The creation of a reservoir represents a perturbation of the carbon cycle at the watershed scale, implying a shift from terrestrial ecosystems towards more aquatic processes favoring organic matter degradation and thus carbon emissions to the atmosphere (Tadonléké et al., 2005). GHG production in reservoirs is fuelled by the flooded organic matter the first few years after flooding. However inputs from the watershed may maintain GHG emission over longer period of time when anoxic conditions are prevailing (Tremblay et al. 2005). The flooding of large quantities of organic matter induces a release of dissolve organic carbon in the water column, enhancing bacterial respiration and therefore CO_2 emissions. In parallel, after flooding, soils become sediments, which are sites of CO_2 and CH_4 production as long as the labile OM is available. In many cases, reservoir sedimentation is 2 to 3 times higher than their natural counterparts (Teodoru et al. 2012). To account for GHG emissions related to reservoir creation, diffusion, bubbling and downstream emissions as well as sedimentation have to be considered (Figure 8.3). Downstream dam emissions are those observed below generating stations. They include degassing (refers to GHG diffusive emissions associated with turbulent waters at turbine and spillway discharges), bubbling and diffusive fluxes (Abril et al., 2005).

According to the available studies on young and old reservoirs worldwide, the magnitude of CO_2 emissions is related to the reservoirs age and latitude (Barros et al., 2011). Typically, the largest amount of GHG emissions takes place during the first 10 years after flooding for boreal (Tremblay et al, 2005; Marchand et al., 2012; figure 8.4a) as well as for tropical reservoirs (Abril et al., 2005; Demarty and Bastien, 2011; Figure 8.4b). For boreal reservoir, after the first 10 years, emissions are similar to those from natural aquatic systems in the same general area.

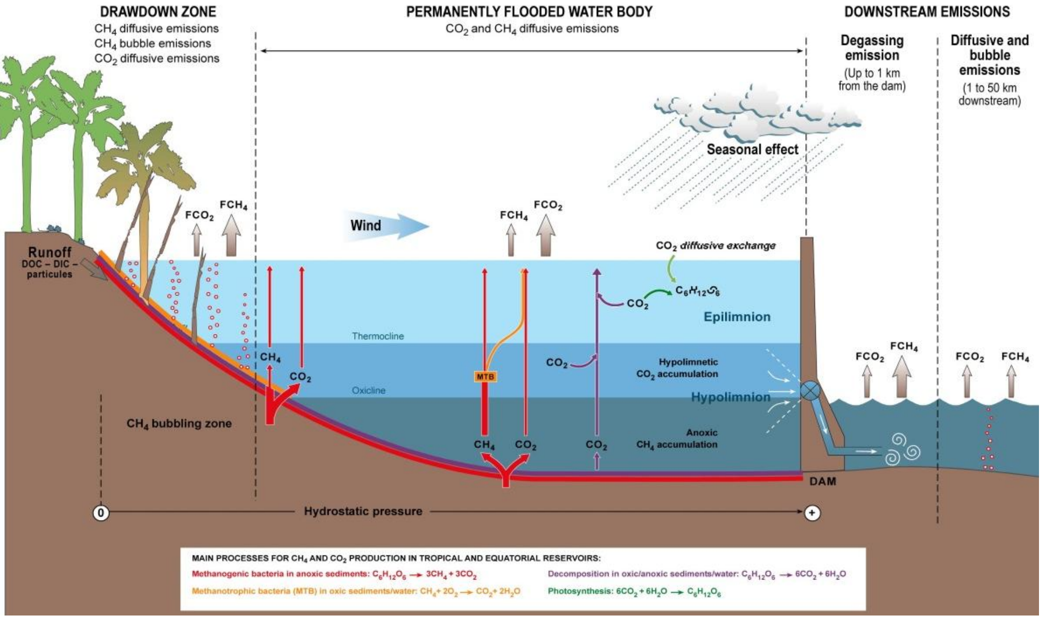


Figure 8-3. Main processes leading to GHG emissions from reservoirs
(from Demarty and Bastien, 2011)

8.2.2 N_2O emissions

N_2O is an intermediate by-product of two microbiological processes, nitrification (in presence of oxygen) and denitrification (in absence of oxygen), which occur mainly at the sediment water interface but could also take place in organic matter rich water column. Regarding N_2O generated from flooding, the evidence so far indicates that N_2O is not a major issue: although N_2O has a global warming potential (GWP) 298 times greater than CO_2 (IPCC, 2013), the fluxes are likely negligible in the overall GHG budget as measured in boreal, alpine and tropical reservoirs (Huttunen et al., 2002; Tremblay et al., 2009; Dos Santos et al., 2006; Diem et al, 2012).

N_2O emissions occur through diffusion at the air-water interface and degassing at turbine and spillways, as for CO_2 and CH_4.

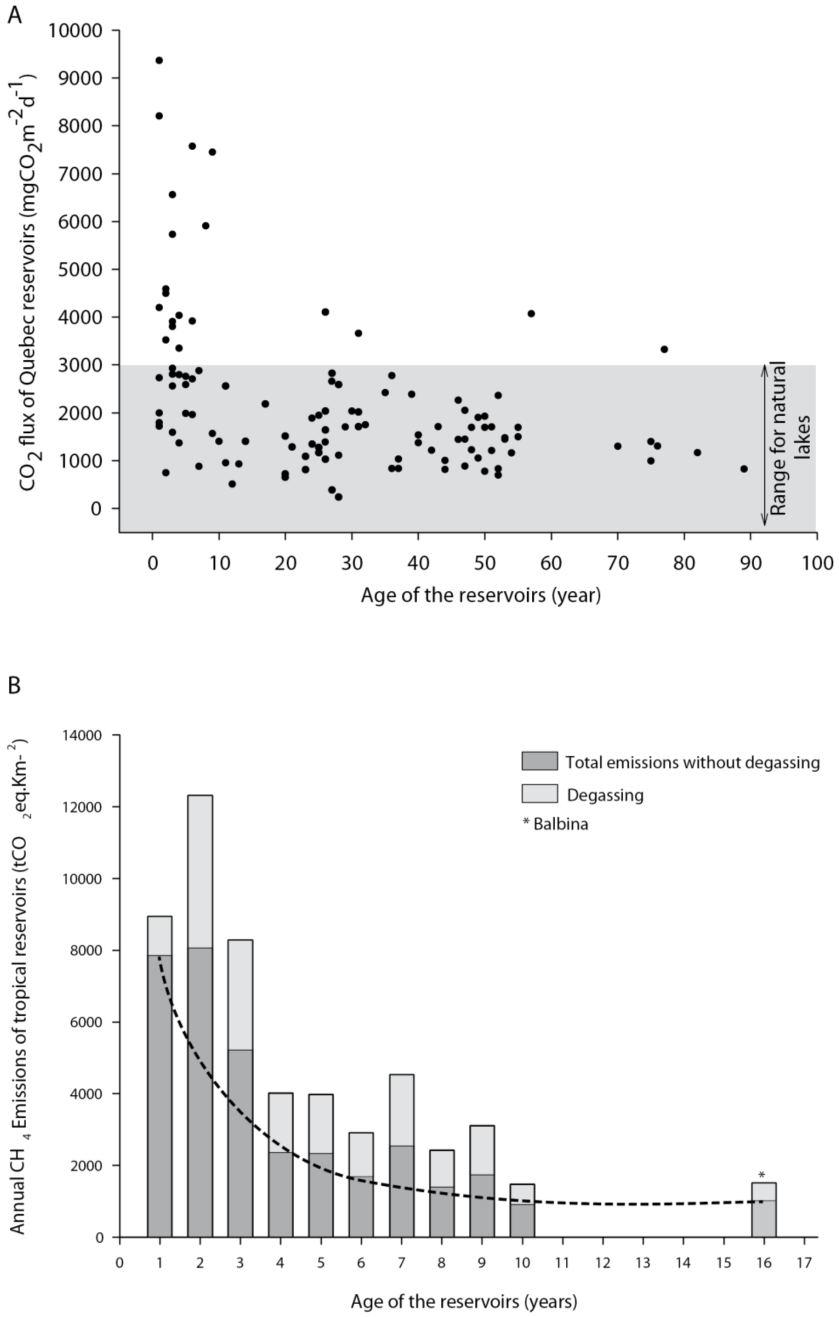


Figure 8-4.

A - Evolution of gross summer CO_2 diffusive emissions per square metre per day with reservoir age in Quebec, Canada. (from Marchand et al., 2012).

ATTENTION : units for graph (A) are : mg CO_2 / m^2 / day (for summer season)

B - Annual CH_4 emissions per square kilometer for two tropical reservoirs (Petit Saut, French Guiana and Balbina, Brazil) as a function of age. Dotted line represents the decreasing trend (from Demarty & Bastien, 2011-b)

ATTENTION : units for graph (B) are : tons CO_2 eq. / km^2 / year – different from graph (B) units

8.3 IMPACT OF RESERVOIRS ON CLIMATE CHANGE

Accumulated knowledge since the 90's demonstrates that all kinds of reservoirs are susceptible to emitting GHG, at least for the first few years after their creation. So, one question is, are there bad vs. good reservoirs in terms of GHG emissions?

First of all, only few studies characterises the net emissions of reservoirs and the global impact of flooding on climate change cannot be evaluated accordingly. Studies conducted in the Amazon forest area have shown that some tropical reservoirs (Balbina, Tucurui) can emit GHG in larger proportions than would a thermal power plant (Demarty and Bastien, 2011). Oppositely, the long term follow-up of the boreal reservoir Eastmain-1 in Québec, Canada, demonstrated that, despite high GHG emissions following impoundment, this type of reservoir had no impact in terms of emissions at the watershed scale considering the life-time of the project (100 years). Some other tropical reservoirs have been shown to capture CO_2 due to their high concentrations of primary producers (Rosa et al., 2004; Chanudet et al., 2011). This looks positive in terms of GHG emissions, but in a wider environmental perspective, large primary producer populations are often related to accelerated eutrophication of reservoirs due to human activities, algal blooms (possibly toxic, Deblois et al., 2008) and water column/sediment anoxia, which may lead to the creation of CH_4. It finally appears that a few general conclusions can be made. GHG emission driving factors such as reservoir surface area and landscape, OM content of the flooded ecosystems, human activities in the watershed, power plant design and operation are affecting reservoir GHG emissions. Processes are the same all over the world, the amplitude and duration of the emissions generally varying depending on the latitude and water temperature (Marotta et al., 2009; Barros et al., 2011). The following points should therefore be considered for future reservoirs to avoid high emission projects:

- Favour smaller reservoir surface/water volume ratio and consequently short residence time and less OM flooded;
- When measuring GHG emissions, all pathways should be taken into account (diffusion, ebullition, degassing) and a particular attention should be towards measuring methane and determining net GHG emissions (Teodoru et al. 2012, UNESCO/IHA, 201, Tremblay et al. 2005);
- GHG emissions should be considered right from the conception phase. If the water intake to the power turbines is located near the surface of the reservoir or through flexible gates drawing water mostly from the surface of the reservoir, the risk of downstream degassing of methane is much lower. If water to the turbines is fed from the oxygen-depleted water closer to the bottom of the reservoir (hypolimnion), dissolved methane may be entrained with the water and degassed downstream of the power plant. The use of bottom gates for releasing water or flushing the reservoir may also increase the risk of downstream methane emissions for the same reason. Hydro operations ensuring that water stays inside the reservoir for short periods of time will reduce the risk for emitting GHG (Harby et al., 2012);
- Human activities should be considered. In fact anthropogenic activities in the reservoir watershed lead to nutrients and OM inputs that can drastically increase GHG (and H_2S) emissions in creating anoxic conditions in the water column and the sediments (Del Sontro et al., 2010). Up until now, total suspended sediment inputs were considered in the projects design to account for reservoir filling and to eventually plan maintenance dredging. The OM contained in this sediment charge must now be considered as a potential large source of GHG emission; water treatment plants could be settled upstream of the reservoirs to avoid these emissions.

8.4 MEASUREMENT OF GHG EMISSIONS FROM RESERVOIRS

The international consensus regarding the goal of GHG emission measurements is to estimate the net impact of reservoir creation at the watershed scale (Figure 8.5). Net emissions are calculated in subtracting emissions before from emissions after the flooding. The watershed is chosen as the surface unit to circumscribe the impact study, since reservoirs are affected by processes occurring in the surrounding terrestrial and aquatic components.

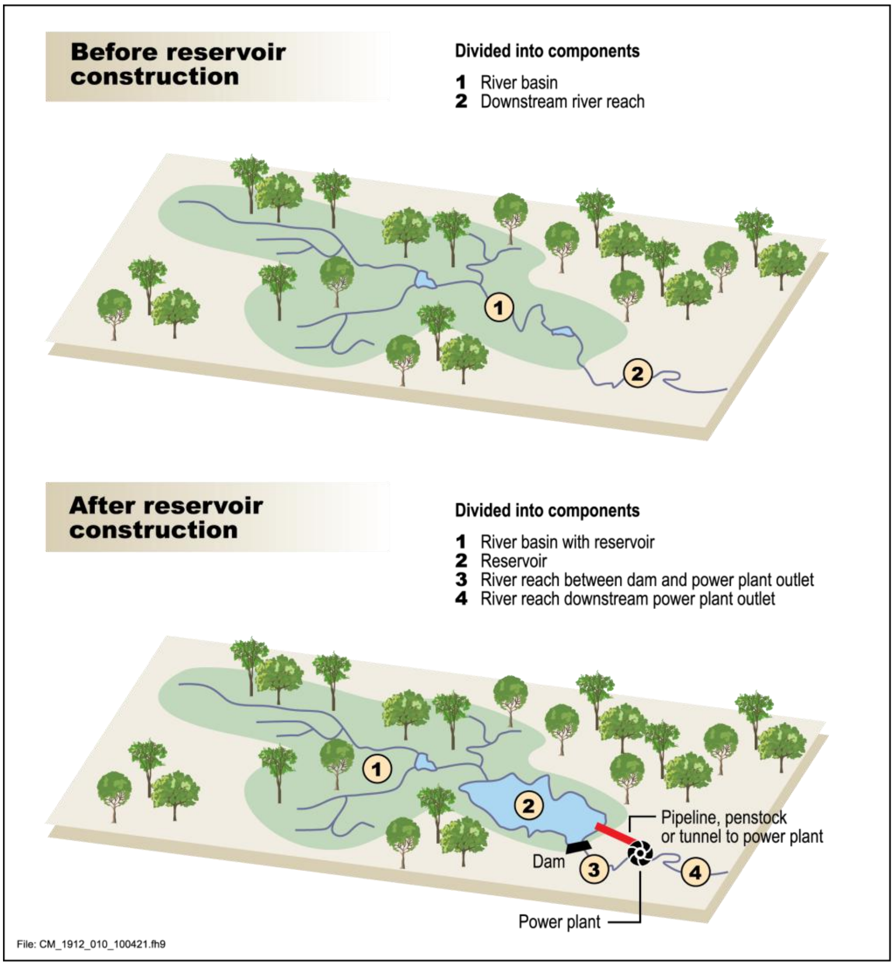


Figure 8-5. Boundaries for reservoir projects (form UNESCO/IHA, 2010)

Terrestrial and aquatic emissions can be measured by various methods, using in situ or ex situ sensors. Punctual measurements can be done during field campaigns (several sampling stations) and time series can be obtained through automated systems installed in generating stations (Demarty et al., 2009). To limit uncertainties linked to some of these methods and to assure the reproducibility and comparison of the results, a comity of international experts published a GHG measurement guidelines report for freshwater reservoirs under the aegis of the International Hydropower Association (UNESCO/IHA, 2010). These methods have recently been used in Laos (Deshmukh et al., 2014; Chanudet et al., 2011), China (Zhao et al., 2015), Australia (Bastien and Demarty, 2013), Malaysia (unpublished data), Cameroun (2014-2020, Demarty pers. comm) and Canada (Marchand et al., 2012; Venkiteswaran et al., 2013; Pelletier et al., 2014).

At this time, it is now possible to model long term GHG emissions from reservoirs from regular water quality follow-up and in situ emission measurements. This exercise has been done by Delmas et al. (2005), then by Descloux et al. (2014) and Chanudet et al. (2015) using a 3D numerical model. Teodoru et al. (2012) extrapolated empirical trends over the projected life span (100 years) of their studied reservoir (see also UNESCO/IHA, 2010 about this method).

8.5 IMPACT OF FUTURE CLIMATE CHANGE ON GHG EMISSIONS FROM RESERVOIRS

Previous chapters introduce the impact of climate change on precipitation and runoff, erosion and sediment transport, flow regime and residence time, etc. All these parameters influence watersheds carbon and nutrient dynamics and therefore may affect GHG emissions for both reservoirs and natural aquatics ecosystems. Table 1 gives some examples of the anticipated increase or decrease in gross GHG emissions from reservoirs for different scenario related to climate change impacts at the watershed scale. When considering net reservoir GHG emissions, these changes could be smaller as natural ecosystems (aquatic and terrestrial) will also be affected by climate change.

At the watershed scale	In the reservoir	GHG emission increase	GHG emission decrease
Increase in erosion	Increase sediment transport and OM concentration	X (increase in OM availability)	
Increase in precipitation	Decrease in residence time		X (decrease in OM availability)
Increase in air temperature - Drought	increase in water column temperature	X (CO_2)	
	Shallower water column	X (CH_4 bubbling)	X (CH_4 oxidation in CO_2)
Wind storms, cyclones	Water column mixing	X (release of gases accumulated in the hypolimnion)	X (turnover may reduce water anoxia)

Table 8-1. Examples of impact of events related to climate change on reservoirs GHG emissions

These previsions are made according to the state of the science. But additional exhaustive studies on GHG emissions from reservoirs are necessary world-around to better understand the mechanisms involved and anticipate the impact of climate change on these processes.

9. ADAPTATION STRATEGY. CASE STUDIES

9.1 ADAPTATION PRINCIPLES

From around the world, lessons are emerging for adapting both practice and policy in water resources management under climate change. How these lessons will be integrated locally are likely to be different. Some thoughts for discussion are included in the following.

The best assumption about climate change is: in the future, it will be different from what we think now. Living with extremes may become the norm for some regions, totally departing from convention. In some regions the weather systems are becoming more extreme and less predictable on both ends, that means more time spent in drought/ extreme drought, more flood events and less time spent under conditions that are currently thought to be “normal”. Traditional engineering approaches, which tend to be prescriptive in nature and well-suited for highly predictable events, are not necessarily suitable for the unpredictable nature of climate change (eg experiences with unprecedented drought in the Murray-Darling Basin and extreme flooding at sites across Australia). As the impacts of climate change unfold, we are beginning to see the limits that the past approaches to river management are imposing on our future. New engineering approaches are required.

There is growing recognition for innovative water policy reform and institutional capacity, particularly where drought and other water scarcity related problems are a concern. However, the impacts due to climate change and adaptation opportunities will vary and differ significantly from one region to another one. Important differentiating factors include:

- Hydrological and water resources system characteristics
- Climate change: is the region drying, extremely variable climate or wetting?
- Infrastructure: does substantial infrastructure already exist or is it a region to be developed? (this could be in the form of dams and reservoirs, but also infrastructure for governance, communications, etc.)
- Living standards: are the communities in the region developing to improve their standard of living or is it already developed and accustomed to a higher supply of water/standard of living?
- Cultural/ indigenous values and practices
- Environmental water - water needs for environmental functions (under modified and enhanced climatic conditions)

In the past, dams and reservoirs have featured prominently in adapting to the impacts of climate change. However, under circumstances of water scarcity due to changes in climate, for example, it is expected that there will be an increasing focus on resolving complex basin-scale issues for which a combination of technical and institutional skills are required.

Clearly, there is no less demand for the technical expertise of the engineer. It is critical. But the very nature of this technical expertise and how it is adopted by others outside the engineering profession is changing in the face of climate change. Technical solutions are only one facet of several that are emerging. Not surprising, the role of engineers is expanding and so is their sphere of influence. Rather than focus solely on solutions for infrastructure at specific locations, the scope of the challenge has expanded to the scale of large river basins with complex river management systems serving multiple purposes or groupings of smaller basins. Examples of adaptations are set out in the EU Water Framework Directive, Australia’s Water Act, and other equivalent integrated water resource planning and management initiatives.

In the past, there was a focus on designing critical infrastructure for securing supplies of water for human consumption and economic development. Given the challenges of climate change, river managers are now being expected to deliver multiple objectives in combination, including:

1. risk mitigation – including flood and drought impact mitigation
2. human health objectives - services focused on water supply, waste water treatment and sanitation
3. economic development objectives – services focused on infrastructure, hydroelectricity and irrigation
4. water quality protection – pollution reduction of rivers directly as well as the receiving waters to which rivers discharge
5. ecological protection and enhancement – protecting and/or restoring wetlands, rivers, flood plains and riverine environments
6. tourism & recreation
7. navigation – ensuring suitable conditions and arrangements for the function of the "river highways"

River managers face significant challenges in achieving these objectives in light of climate change, going well beyond the classic civil engineer's role. In some arid and semi-arid parts of the world, for example, engineers are designing environmental works and measures to secure sufficient water to sustain the natural environment and healthy river systems on a broad river basin scale. Particularly for arid to semi-arid regions (characterized by drying and highly variable climates), the notion of *sustainable limits* to human/ economic *water consumption* is challenging commonly held views on social and economic *development and growth*. As a consequence, engineers are critical in building the new knowledge base and making adaptations at the scale of the river basin/ river systems. This practical expertise complements scientific research on climate change impacts to and vulnerability of rivers and ecosystems, material (such as carbon and salt) cycles, and planning for flood control, water use and environmental conservation, and other efforts.

As climate change gains visibility, it is becoming a fundamental task of engineers to provide accurate and credible information that is easy to digest by experts in other fields as well as by the public to gain appreciation for technical and practical considerations. This is a challenging task given the complexity of the issues. It is also challenging because science is also exploring new frontiers. The best available science is only a guide; its interpretation does not irrefutably lead to any one best answer, a solution. Because of the high degree of variation in geo-physical, social and political context in which the management and planning of river systems occurs across the globe, adaptation will necessarily vary to suit the local context.

We can also observe that as understanding grows and views change around water resources management under climate change, so does what we manage for. Taking again arid and semi-arid regions as a point of reference, in some locations floods, for example, can be expected to increase in intensity and or frequency, including in developed areas. In Australia, recent flooding due to extreme rainfall events is demonstrating that floodwater storage and conveyance options may be limited. In some circumstances, the view of *complete containment* of floodwater has become no longer as significant as whether floodwater can be managed to be "passed safely" along the whole watercourse. In light of this, views around flood management are gradually shifting. Occasionally it can be observed that consideration is being given to decisions that avoid unsustainable development on floodplains, in favour of decisions that allow the connection of wetlands which provide natural flood protection features (such as retention basins), provide ecosystem services and support productive agriculture. This shift in management focus may also be reinforced in some locations where the question is raised whether flooding may be more important for soil moisture and groundwater recharge than rainfall events. This is not intended to diminish the critical role of infrastructure in water storage and delivery in an increasingly thirsty world, energy production, food production and flood protection; nor does it ignore improvements associated with the construction, operations or maintenance of critical infrastructure that will provide carbon emissions reductions.

In the past, engineers worked to define and solve quite site specific problems, commonly on their own. Today, due to the complex nature of the deliverables, multiple objectives and the decision making setting, this is no longer achievable. Engineers are being asked to work alongside decision makers, politicians, natural resource scientists, social scientists, economists and the greater community. Adaptation options are to be assessed by a wide range of collaborators. Collaboration is a simple concept, yet it is not easy to achieve. Without collaboration, policies and actions are likely to be uncoordinated or poorly targeted at the basin or river system scale, possibly creating inefficiencies that may exacerbate some risks that are potentially costly. Furthermore, what is best, or "best practice", is likely to be relevant only to a specific purpose and circumstance (ie there is no "universal" best practice). More importantly, when water availability is limited, views on social and economic development and growth are likely to be challenged. Therefore, public involvement and support early in the decision making process around water resources management will also pave the way for constructive decision-making about adaptation priorities and the development of options and strategies.

It is recognized that adaptation priorities will differ from country to country, region to region and over time. Whatever the priorities are, the need to deal with climate change will drive how water is managed. Climate change alters system relationships - hydrological, ecological, economic and societal. Managing for climate change requires adaptability to water quantity, water quality and variability, and includes measures to deal with unprecedented environmental conditions and unprecedented economic and societal pressures, as well as measures to facilitate social adjustment in the region.

Managing a stationary system is different from managing a system undergoing change, characterized by uncertainty in predicting the future changes in climate and their impacts, changing circumstances and experience, and potential ecological thresholds & tipping points. *Adaptive management* is an approach that involves learning from management actions, and using that learning to improve management (Holling, 1978). It is "learning to manage by managing to learn" (Bormann *et al*, 1993). An adaptive management process recognizes uncertainties inherent in our understanding of river system processes, impacts of water management options and future changes and threats. Community priorities, perceptions and expectations are also dynamic. This means that water resources management needs to be flexible and able to evolve. Adaptive management is an ongoing inquiry into the nature of the river system and the assumptions underpinning this inquiry.

Adaptive management assumes that although science and technical experts may recognize problems, they may not necessarily fix them. Issues involving resources and the environment are complex, involving interactions whose understanding involves many disciplines. The judgment of scientists and technical experts is often constrained by their training in their respective disciplines, and unlikely to include human motivation and responses as part of the system to be studied and managed. Any single discipline is unlikely to be able to singlehandedly address effectively hard choices about which environmental assets will be given water when water is limited; societal adjustment (compounding existing adjustment pressures); disputes and inaction (against a backdrop of the pre-existing issues such as, for example, the over-allocation of water for human uses in water limited regions).

Adaptive management recognizes that actions and decisions are only effective to the degree they take uncertainty into account, consider a variety of plausible strategies; are robust to uncertainties, informative, reversible. It will act before scientific consensus is achieved. And it will question claims of sustainability that may lead to complacency and degradation.

The successful implementation of an adaptive management strategy recognises the uncertainties in outcomes at any stage along the process. It is for this reason that a "No Regrets" approach to adaption is recommended. Such an approach is illustrated in Figure 9.1 below. The "No Regrets" approach involves undertaking some form of intervention or action to reduce a current or perceived future risk, and at the completion of that intervention modeling future possible outcomes, and monitoring system performance.

If the future outcomes are unacceptable or monitoring indicates an unacceptable outcome, then further interventions can be assessed and implemented. In most systems as various interventions are progressively implemented, the degree of confidence in future outcome increases and uncertainty decreases as indicated in the Figure. This staged approach is often the most flexible and efficient method of addressing complex issues and each intervention or action is undertaken within the best available confidence limits, on a true "No Regrets" approach.

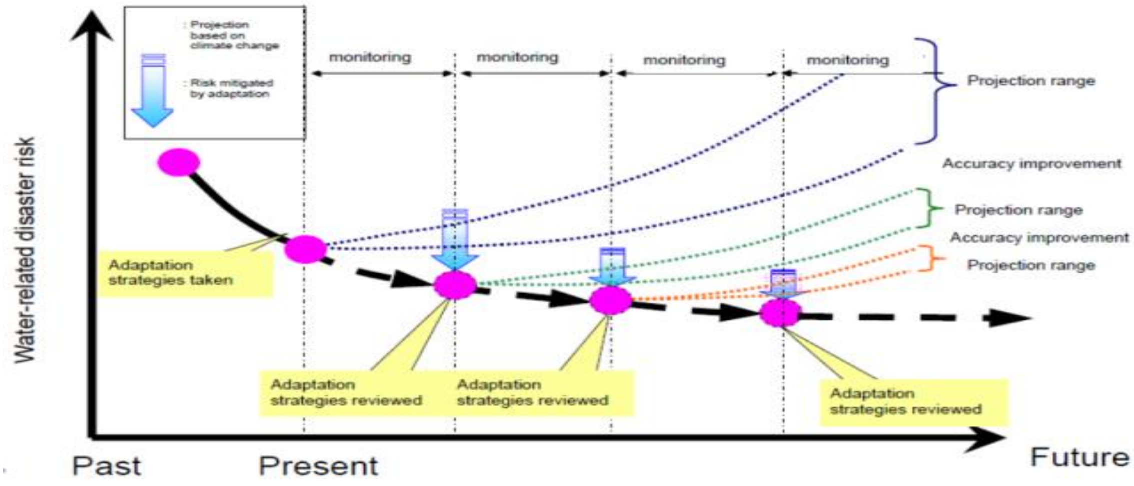


Figure 9-1 – No Regrets Approach to Adaptive Management

Despite the diverse range of experiences across the globe, several reoccurring themes can be identified that may serve as guiding principles which are summarised as follows:-

Principles

1. Projected Impacts of climate change in water resources and floods and droughts are uncertain, and cannot provide exact information of the rate of future changes to decision-makers, but they can offer very useful general information, and they could serve as preliminary and initial assessment
2. Water availability and water quality are cornerstones of social and economic development, and environmental sustainability
3. In the expanded context of the water resources system, dams and reservoirs become an integral part of a multifaceted adaptation strategy, not the single focus
4. Collaboration across multiple disciplines, interests and stakeholders is necessary to provide coordinated and well targeted water resources management
5. Adaptation to climate change will take more than a technological fix
6. The best *plan* for adaptation includes a commitment to commence its implementation
7. Public involvement, engagement and, ideally, support early in the decision making process will also pave the way for constructive decision-making about adaptation priorities and the development of options and strategies
8. Planned (and coordinated) adaptive management aims to replace ad hoc responses with long-term (policy) arrangements, which may include interim contingency measures
   (This is particularly critical in the case of managing water supplies in times of extreme and prolonged drought.)

9. Human consumption practices that undermine the environment are, as such, unsustainable, in particular for arid and semi-arid regions where more frequent drought events are probable in the future due to climate change
10. The safest flood preparedness allows floods to "pass safely" rather than aiming for complete containment as complete containment may not be achievable with climate change
11. Water must be of suitable quality for its intended purpose.

9.2 STRUCTURAL OR FUNCTIONAL ADAPTATION MEASURES

The principles outlined above clearly demonstrate that successful adaptation must be a combination of structural and functional changes combined with a high degree of collaboration across the different disciplines. This is essential to ensure that all stakeholders and interested parties will have 'buy in' to the preferred solution. When taking due account of the wide diversity of likely climate change impacts it is no longer appropriate to consider the 'technical fix', such as building a new dam, increasing the reservoir capacity or providing a larger spillway as the only way forward. This approach has been valid for a number of years, but the changes arising from climate change and the levels of uncertainty that are associated with the problem, means that a combination of structural improvements and operational changes is even more important in order to provide the flexibility in solution selection that the problems demand.

9.2.1 Structural Adaptation Measures

Structural adaptation measures will incorporate physical modifications to existing projects or the construction of new infrastructure in order to alleviate the impacts of climate change. In some cases these measures will be introduced to maintain the functionality, safety and effectiveness of the works and to satisfy the original design criteria in the light of predicted climate change impacts. However in other cases, it is likely that the structural changes will not only mitigate negative impacts arising from climate change, but even result in improved performance.

Even though incorporating physical characteristics into new projects to cater for possible future impacts of climate change might be economically difficult to justify, it would still need to be considered particularly if the project would otherwise have an unacceptable level of risk of not performing to expectation. A practical example of this would be the addition of upstream storage capacity or water flow diversion to compensate for increased variability of flows, or to contribute to the reduction of peak or low inflows.

The following is a list of potential structural measures that could be applied in anticipation of – or progressive adaptation to – climate change:

- Change the number and type of water control gates both for flood management and water release requirements;
- Increase in the capacity of the spillway works and/or the provision of emergency spillways;
- Add controllable gates to free overflow spillways in order to provide greater regulation of flood peaks;
- Modify the dimension of canals or tunnels that are for water transfer;
- Create new upstream storage reservoirs and re-consider the multi-purpose potential of new reservoir projects;
- Modify the active storage capacity of reservoirs by increasing the height of the storage dam and/or raising the sill level of the overflow works;
- Increase the amount of freeboard above top water level in order to accommodate predicted increases in flood rise and wave surcharge values;

- Replace or reinforce upstream slope protection such as rip-rap to provide satisfactory erosion protection under increased dynamic loading from waves.

These structural modifications will be applicable to dam and reservoir projects of all kinds and most water resources managers and engineers will be very familiar with this kind of physical intervention, including the likely costs, the technical challenges and the benefits that can be realised. However the uncertainties associated with climate change driven projects will inevitably add a further degree of uncertainty to all of these aspects. One thing that is certain is that in the future there will be an increased need to modify, adapt and to change. To meet these challenges structural interventions including the design of new dams will need to be planned and executed in such a way that, if needed, additional spillways or other physical components could be introduced into the project at a later date.

9.2.2 Functional Adaptation Measures

In contrast with the physical changes to the works, the functional or non-structural instruments are modifications to operating policies. They can of course be applied alone, without making any modification to the structural configuration and dimensions of the project, although in other cases an optimal balance of structural and non-structural adaptations may frequently be the most appropriate way of meeting the needs of climate change. The following constitutes a list of functional actions that could be applied:-

- Developing or improving hydrological forecasting tools including the development and application of appropriate measures to deal with extreme hydrological events;
- Developing of improved technologies to evaluate the performance of projects and to identify ways of operating them under modified climatic conditions;
- Bringing changes to operating rules such as revised reservoir level limits in order to provide an increased flood storage buffer;
- Modification to the functional requirements of specific components of the project;
- Modification to the price of power, energy or water. This could have an impact upon the extraction of water for irrigation, industrial, and other consumptive activities;
- Better coordination of the operation of the project with other water uses in the watershed;
- Improvement to technologies that are used to coordinate the interaction of various hydro projects as well as the global operation of complexes involving several watersheds;
- Modification to rules that have an influence upon recreation, irrigation, water supply and industrial water abstraction;
- Improvements to the communication and decision-making process used by various stakeholders;
- Carrying out studies directed at identifying the impacts of climate change upon the various users of water within a watershed;
- Creation of regulatory bodies that are mandated to develop and apply improved operating strategies;
- Promotion of educational efforts that are targeted with informing citizens of the impact of climate change, with the hope of finding adaptive measures that would compensate for the impacts and reduce negative impact on dams and reservoirs;
- Development of improved approaches to assure appropriate cooperation between various users of water within a watershed;
- Modification to legal agreements between various governments, stake holders and other identities that have an impact upon the operation of the watershed;

- Improvement of mathematical models to evaluate the impact of climate changes;
- Restricting the development of land within the zones susceptible to flooding;
- Modification of engineering design practices so that non-structural adaptation can be considered as an integral part of the design process which must be considered in conjunction with proposals for structural change.

9.3 REGIONAL CASE STUDIES OF ADAPTATION TO CLIMATE IMPACT

To illustrate the diversity of climate change issues and to show how the problems are already being addressed, a number of recent and current case studies have been selected. These cover different climatic situations around the world ranging from the arid regions of south-east Australia and west Texas in the USA, to the temperate climate of Japan, tropical Guyana and the alpine region of France. In various parts of the world the impacts of climate change are significantly different and as a consequence the problems that are encountered are also different.

The adaptation measures that need to be applied also reflect this diversity both in terms of the types of water projects that are impacted and the solutions that are being proposed in order to mitigate the impacts. In particular the combination of structural and non-structural change is a feature of several of the case studies.

Details of the case studies are included in Appendix A and summarised in the following sections.

9.3.1 Case Study A – Murray Darling Basin Plan (Australia)

The Murray Darling Basin in south-east Australia is a vast area that covers over 1 million km^2. It incorporates a number of major infrastructure projects that are designed to utilise and manage the water resources of the basin. These include the Snowy Mountains hydropower project and other numerous dams, weirs and river control structures that regulate the supply to thousands of kilometres of irrigation canals. The basin comprises more than 77,000 km of rivers and 25,000 wetland areas including complex ecosystems with several endangered species of birds and animals.

Climate change studies indicate that the future climate across the basin will become even more variable, as well as hotter and drier but with the likelihood of more extreme flood events. There was a very severe drought between 2000 and 2011 where the inflows into the basin were 40% below the long term average values. This had crippling impacts on the environment, the health of the rivers, the water availability for agricultural production and upon the community at large.

Faced with these problems the Australian Government has embarked upon a far reaching plan to understand the potential problems of future water scarcity and to tackle these problems with a basin wide strategy. In this context the climate model projections indicate a reduction of 10% in the average surface water availability by 2030, and with increased variability between the northern and southern parts of the basin. There are numerous aspects to the plan that will entail both structural and functional adaptations, but the central core of the strategy is an integrated approach to the restoration of sustainable water extractions and river health.

A project of this scale has incorporated an extensive community consultation to evaluate the many competing interests on the complex river system and to understand how the demands might be impacted in the future. The plan that has been developed presents an adaptive management programme which uses a combination of engineering improvements, operational adjustments, re-acquisition of water property rights and on-going monitoring. The delivery of the plan has commenced in 2012 with completion scheduled for 2019, and the budget allocation for implementation is USD 12 billion.

9.3.2 Case Study B – Conservancy Adaptation Project (Guyana)

The populated coastal area of Guyana is situated at up to 2m below the mean sea level. This means that any water which accumulates along the coastal strip can only be discharged during the small drainage windows at low tide, or by pumping. As a result of climate change the rate of future sea level rise is estimated to be around 1cm per year. As a consequence the durations of the available drainage windows are decreasing.

Extreme rainfall events are also becoming more common. In 2005 a rainfall event with a return period of approximately 1 in 5,000 years caused severe flooding and left the whole populated coastline inundated. During this event, the East Demerara Water Conservancy (EDWC) dam, which retains a large shallow reservoir inland of the coastal strip, was overtopped and suffered localised slip failures, but did not breach. The Government of Guyana recognised that had the dam breached, the results would have been catastrophic for the populated areas downstream. In response to this near disaster a new project was commenced to mitigate the effects of climate change and to prevent a recurrence of flooding. The project is funded by the Special Climate Change Fund of the World Bank.

Once again the project is a combination of structural and non-structural adaptation with an overall objective of reducing the country's vulnerability to catastrophic flooding. The main features are:-

- Strengthening of the Government's understanding of the EDWC system and the coastal plain drainage regimes through hydraulic modelling that is based on topographic information gathered by LiDAR and the installation of an extensive network of hydrologic instrumentation.
- Increasing the drainage relief capacity of the EDWC by the excavation of new drainage channels.
- Increasing the drainage relief capacity of the coastal plain drainage regimes by the implementation of key interventions and recommendation of further works.
- Design and construction of rehabilitation works to strengthen the 60km long EDWC dam and its associated structures.
- Strengthening of the Government's capacity to identify key interventions and to carry out effective maintenance through a hands-on training and technology transfer programme.

9.3.3 Case Study C – Les Bois Hydropower Project (France)

This hydropower project in eastern France was constructed in the 1970s and uses water that comes from the 'Mer de Glace' glacier melt process. Unfortunately the glacier front retreat has accelerated in the last decade due to climate change and the intake structure will be exposed and become ineffective in the next few years. As a result the functionality of the hydropower plant would be severely impacted with a significant reduction in generation capability. The melting of the glacier and the retreat process has been modelled by the French glaciology research laboratory using a combination of different greenhouse gas emission scenarios to develop a glacier response model.

The model was then used to evaluate a number of modification options which were aimed at ensuring the future operation of the plant in a secure, effective and durable manner. To provide future robustness to the remedial works the options were based upon the most pessimistic glacier retreat predictions.

Three options were examined and in this case study all three of the options were based primarily on structural intervention. The three alternatives involved the construction and reinforcement of protection works to the existing intake structure, the displacement of the structure in a downstream direction which would have involved a loss of energy production, or the re-location of the intake in the upstream direction. The latter was the most costly solution but it offered the greatest security of future operations and was selected as the preferred option. The construction of these new works began in 2007 and the project was completed in 2011 at an overall cost of approximately USD 21 million.

9.3.4 Case Study D – Kumano River Project (Japan)

This is an example of operational adaptation of an existing project and does not involve structural change. In Japan the owners of utility storage reservoirs for hydropower or water supply purposes are not legally obliged to contribute to flood control. In this respect the normal requirement is very limited and involves only the provision of vacant storage capacity to compensate for the effects of reduction of river channel storage and any increase in flood propagation velocity. These requirements apply solely when the flood is occurring and the target reservoir water level for this operation is referred to as the "discharge preparation water level".

The Kumano river basin in western Japan is regularly subjected to severe typhoons and has a long history of suffering flood damage. However there is no dam on the river that is specifically designed for flood control. Climate change modelling indicates the likely occurrence of more frequent and more severe typhoons. In 2011 Typhoon Talas struck a wide area of western Japan which brought record-breaking rainfall and flooding to the Kumano river basin. The flood damage was so serious that the Electric Power Development Co. Ltd. (J-Power), as the owner of two large storage reservoirs on the river (Ikehara dam and Kazeya dam), decided to voluntarily promote participation and cooperation in flood control. Moreover it was established that this could be achieved through operational changes alone, and that remedial works or physical modifications to the dams and reservoirs would not be needed.

The adaptation project that was implemented has involved a modified operating regime whereby an "interim target water level" that is lower than the specified ‘discharge preparation water level’ has been introduced in order to increase the flood storage volume that is available. Drawdown to achieve the interim target water level is performed by generation discharge only. In order to determine the criteria to begin the drawdown, it is necessary to accurately predict the total average rainfall in the catchment that will occur over the next 2 to 3 day period.

By combining the numerical meteorological predictions of the Japan Meteorological Agency with the statistical relationship between the observed typhoon courses, the total average rainfall in the catchment and the magnitude of flood discharges, it has been possible to determine updated criteria that are used in the application of new operating regimes for both reservoirs. These have been implemented since the middle of 2012 and the net result that has been achieved is an increased resilience against extreme floods, with no significant loss of power generation.

9.3.5 Case Study E – Colorado River Municipal Water District (USA)

The Colorado River Municipal Water District supplies water to about 400,000 people in west Texas, USA and relies on three surface reservoirs which were constructed between 1952 and 1990. Driven by an increase in demand and diminishing supplies due to ongoing drought conditions, the surface water supplies have been augmented by the installation of 21 new groundwater wells and associated infrastructure.

9.3.6 Case Study F – Hydrological Stability Enhancement Project of Existing Dams (Korea)

The Republic of Korea has been affected by the impacts of climate change significantly over the past one hundred years, including an estimated average temperature rise of 1.7^{O} C which is 2.3 times higher than the global average. Climate modelling indicates that Korea will experience great fluctuations in water resource availability and rainfall intensity in the future, and in a country where approximately two thirds of annual rainfall occurs over three month period the intensity of rainfall events is also predicted to increase.

Recent studies have shown that estimates of PMPs have increased by as much as 300% in some catchments and as a result 23 out of 27 major dams studies are to be remediated to provide security against extreme flood events. The remedial works program has a budget of USD 2.2 billion and commenced in 2003.

In addition to flood capacity, the changed rainfall patterns and storm intensities are also likely to have a detrimental effect on water quality due to high sediment loads in runoff into reservoirs. This in turn has the potential to impact on hydropower facilities, fisheries, drinking water quality and tourism. A number of mitigation measures are being undertaken both in the catchments and in the reservoirs of five dams to minimise the potential impacts of increased inflow turbidity, at an estimated cost of an additional USD 1 billion.

10. ICOLD RECOMMENDATIONS

Previous chapters of this bulletin have considered the current state of knowledge, facts and uncertainties around climate change, its impacts on our water resource systems and on dams and reservoirs.

There is little doubt that a changing climate will have profound impact on the distribution and availability of water resources both as concerns average conditions and its variability. Therefore the prospect of climate change has become a key issue for the operation, management and planning dams and reservoirs.

There are several different methods and approaches available to dam and reservoir owners to analyse potential impacts of climate change on their water resources systems, and it is important that a range of climate change scenarios are modelled to assist in future planning and management of dams including temperature, precipitation and water resource availability and variability.

The best way to deal with these uncertainties is to plan, design and construct robust infrastructure, which is characterized as having the least sensitivity to climate change effects. A number of examples have been presented which show approaches which have been used to deal with the uncertainties and impacts of climate change on dams and reservoirs. An adaptive “no regrets” approach is recommended for dealing with the prospect and impacts of climate change on water resource availability and variability and consequently on the management of dams and reservoirs.

ICOLD summarizes hereafter a list of general recommendations, which can have their translation in terms of practical action for dam developers described in the “technical” chapters presented earlier in this bulletin (chapters 3 to 9), some having to be defined and precised on a case-by-case basis.

Recommendations

The recommendations address three broad themes: a systems approach, adaptive management and collaboration.

Recommendation 1: Adopt a whole-of-system approach

Possible actions to:

a) take into account the appropriate multiple needs / objectives at the river basin scale

- *Define the critical challenges and characteristic of working at the scale of the river system/ basin*
- *Develop priorities and criteria at the river system/ basin-scale*
- *Identify issues that cross the water policy, governance and river basin management spheres*
- *Identify requirements for technical and/ or institutional capacity building*
- *Recognise that in order for river managers to address the new challenges presented by climate change at the scale of the river system/ basin, roles and responsibilities of the civil engineer will also need to adapt*

Comments

Multiple needs / objectives at the river basin scale **with regard to:**

- o risk mitigation (to human and environmental health)
- o human use, includes water for individuals as well as communities/ cultural heritage

- human economic development (for both human and environmental aspects), includes water for agriculture, tourism & recreation, and navigation
- water quality protection
- ecological protection and enhancement
- hydro-electric energy production
- other (in some countries water is needed to cool nuclear power stations)

How we look at things influences how we manage/ what we manage for - be open to re-think things

- Rather than focus on solutions for individual infrastructure at specific locations, the scope of the challenge has expanded to the scale of large river basins with complex river management systems serving multiple purposes or objectives or groupings of smaller basins
- under circumstances of water scarcity, it is expected that there will be an increasing focus on resolving complex basin-scale issues, for which a combination of technical and institutional skills are required
- adaptation and expertise in water delivery and river basin management will be important for building international cooperation and overseas relationships as a basis for diplomatic, foreign aid and development work
- adaptation will also become important for business development and strengthening economic ties between countries

b) establish what is really at risk in your water resources system, using risk-based approaches (see chapter 3)

c) establish priorities in water usages and needs, and ensure that sufficient water for the environment is secured to sustain natural environments and healthy river systems through extremely dry periods

- *Establish priorities, indicators, monitoring and evaluation regimes*
- *Environmental works and measures*
- *Sustainable levels of water taken for human purposes*

d) ensure that sufficient water of adequate quality is secured for critical human needs for dependent communities to get them through extremely dry periods

- *Water sharing and reserve policies*
- *Water quality standards*
- *Disaster action plan*

Recommendation 2: Apply an adaptive management process

Possible actions to:

e) *Identify expertise / information gaps in understanding*

- *initiate a workshop together with other relevant agencies to identify comparative strengths (and weaknesses) in knowledge and understanding*
- *identify areas/ groups of people where capacity in this can be built (upon) in, for example, the water policy, governance and river basin management sectors*

- *share expertise internationally, including targeted partnership, aid and development efforts*

Comments

- *plan proactively for advances in knowledge, rather than taking a "wait and see" approach*
- *continually assess assumptions and their relevance*

f) *share* methods and approaches that are being adopted to adapt to climate change in the water sectors

- *consider multiple likely climate change scenarios that cover the range of potential evolution ; do not only rely on one single climate change scenario to avoid misleading conclusions (too pessimistic or too optimistic)*
- *Consider establishing a secondment/exchange / twinning program with other basin organisations and related institutions*
- *Actively participate in (international) comparisons and cooperative evaluations*

Comments

- Develop and share appropriate methods and approaches (deterministic, probabilistic) to :
  - (i) assess climate risk on your water resources system, and
  - (ii) adapt to climate change in the water sectors

  (see chapter 5)
- Share/ assess the methods and approaches being adopted to adapt to climate change in the water sectors, particularly around the comprehensive assessment of potential impacts, risks and adaptation options
- Explore possibilities for international collaboration around how river commissions might work together on developing more systematic and structured approaches to "comparing notes" and transferring lessons learnt and best practice models based on adopting a cooperative program of rigorous performance evaluation

g) establish an integrated basin management organization with an aim to develop/ transfer best practices in river basin management

- *Establish an interagency coordinating group to oversee visiting experts and "intelligence" on water and river basin management*
- *Engage actively with multidisciplinary water research and promote (international) exchanges in higher education and other research initiatives*
- *Keep aware of progress in initiatives around the world in delivering, such as MDBA Basin Plan, the Water Framework Directive and the EU experiences of basin scale planning and implementation.*
- *Preserve sufficient annual allocation for natural resources (lakes, ponds, rivers), through appropriate management*

Comments

- open to all with an interest in transferring best practice in river basin management
- provide support for an independent party - eg a university – to host a workshop amongst suitable agencies to explore the potential interest in establishing an INBO (or equivalent)
- might be open to all other state, federal or local agencies and others with an interest in transferring best practice in RBM

- invite agencies to establish an interagency coordinating group with the defined purpose of ensuring that when there visiting experts and international delegations that the federal agencies are sufficiently coordinated and are capable of appropriately sharing in exposure to visiting experts and "intelligence" on water and river basin management
- explore the potential of working more closely and/or formalise a closer working relationship with a number of the university water centres that actively promoting international exchanges and promoting capacity building in multidisciplinary water research
- offer a small retainer to one of these water centres to provide to XXX regular half yearly updates on international water and basin initiatives
- stay broadly across progress in delivering X, Y, Z and consider how it can benefit these experiences of basin scale planning and implementation, giving particular attention to policy integration and interagency and community consultation

Recommendation 3: Collaborate with a wide range of disciplines, interest and stakeholders (including engineers alongside decision makers, politicians, natural resource scientists, social scientists, economists and the greater community) in the assessment of enduring and effective adaptation options

The practical experience of engineers together with scientific research on climate change impacts to and vulnerability of rivers and ecosystems is critical in making appropriate adaptations at the scale of the river basin/ river systems.

Possible actions to:

h) Identify and explain how dams and reservoirs can mitigate climate change impact in your watershed (see chapters 5 and 7)

i) Explain how – and how much - GHG emissions are linked to dams and reservoirs (see chapter 8)

j) Engage, involve the public and stakeholders actively and early on and ongoingly

- *Develop leadership and a commitment to public support early on*

k) Communicate clearly, concisely and simply

- *Commit to clear, concise and simple communication and education around science and technology, particularly, around assumptions and the role of dams and reservoirs in climate change risks and opportunities management.*

As regard to stakeholders engagement, Governments, Authorities, and Project developers would have a leading role in making sure that needs and expectations are considered at each development phase, and possibly early integrated in the basic functions of the dam/reservoir project. This would also comprise compensatory measures.

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12. ACKNOWLEDGEMENTS

12.1 CHAPTERS LEADING AUTHORS

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The Committee on Global Climate Change and Dams, Reservoirs and the Associated Water Resourses gratefully expresses special thanks and recognition to the following leading and contributing authors of technical chapters – see list of authors and co-authors in section 2.2.2.

12.2 ICOLD ENVIRONMENT COMMITTEE

The Committee on Global Climate Change and Dams, Reservoirs and the Associated Water Resourses thanks ICOLD's Environmental Committee for contributions to Chapter 8. In particular, our Technical Committee expresses special thanks to ICOLD TC on Environement chairman, M. Jean-Pierre Chabal, and to Mrs Maud Demarty, who provided an instrumental contribution for Chapter 8.

12.3 CONNECTIONS WITH OTHER REGIONAL OR INTERNATIONAL INITIATIVES

Although most of the information, given in this formally first bulletin of ICOLD dealing climate change issues, has been gathered thanks to the experience of the authors, they would however like to acknowledge the following other initiatives which are existing worldwide and to which reference is made when relevant in the present bulletin.

- IPCC Assessment report 5
    - Working Group I report : The physical science basis (released in 2013)
    - Working Group II report : Impacts, adaptation and vulnerability (released in 2014)
- IPCC Special Report on Renewable Energy (SRREN) – 2011
- IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) – 2012 – see reference [4.8]
- Ouranos consortium (Canada) – see http://www.ouranos.ca
- USBR WaterSMART : see http://www.usbr.gov/WaterSMART/
- World Bank initiative on Climate change and Africa strategy: "Enhancing the climate resilience of Africa's Infrastructure: the power and water sector" – R. Cervigni, R. Linden, J. Neuman, K. Strzepek editors (World Bank, United Nations and AFD, 2015)
- European CORDEX project : see www.cordex.org and following reference :

  Giorgi F, Jones C, Asrar GR. (2006). Addressing climate information needs at the regional level: the CORDEX framework. Bulletin World Meteo. Org. 58:175–183.
- European ENSEMBLES project : see www.ensembles-eu.org

- Observatoire du Sahara et du Sahel - see http://www.oss-online.org/
- Observatoire du Bassin du Niger – see http://www.abn.ne
- International Energy Agency : Hydropower agreement, Task 1: Managing the Carbon Balance in Freshwater Reservoirs – see : http://www.ieahydro.org/Current_Activities.html
- International Hydropower Association (IHA) : GHG measurement associated to reservoirs guidelines : http://www.hydropower.org/iha/development/ghg/guidelines.html

… and many others.

13. BRIEF GLOSSARY

Adaptive management – is the process of adapting to changes as they become known and understood.

AMO – Aerobic methane oxidation

AR4, AR5 – refer to 4th and 5th Assessment Report published by IPCC

CH_4 – Methane.

CMIP5 – Coupled model inter-comparison project phase 5 provides a standard experimental protocol for coordinated climate model experiments

CO_2 – Carbon dioxide.

Confidence level – per IPCC definition (see Box TS.1 of the Technical Summary of the AR5 (2013) for more details):

> Confidence levels, such as *high, medium*, and *low confidence*, are the part of the five qualifiers defined in the IPCC assessment reports.

ENSO – El Nino-Southern Oscillation is the Pacific Ocean temperature effect on the atmospheric circulation.

GCM – General Circulation Model(s). Sometimes, GCM also stands for Global Climate Model(s)

GHG – Greenhouse gas.

IPCC – Intergovernmental Panel on Climate Change, organized by the United Nations Environment Programme and World Meteorological Organization.

Likelihood statement - per IPCC definition (see Box TS.1 of the Technical Summary of the AR5 (2013) for more details):

> Likelihood levels are defined with quantitative probability in the IPCC assessment reports, such as: *likely* 66-100%, *very likely* 90-100%, and *virtually certain* 99-100% probability.

N_2O **-** Nitrous oxide.

No regrets approach – is the process of making adaptive management changes when needed, not before the situation is fully understood and not too late.

PMP – Probable maximum precipitation

PMF – Probable maximum flood

RCM – Regional climate models

RCP – Representative concentration pathways are greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report (AR5). They replace the family of SRES scenarios that was used in AR4.

Whole-of-the-system approach – is taking into account the appropriate multiple needs and of objectives at the river basin scale.

ICOLD authors also acknowledge following IPCC sources of additional glossaries:

http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_appendix.pdf

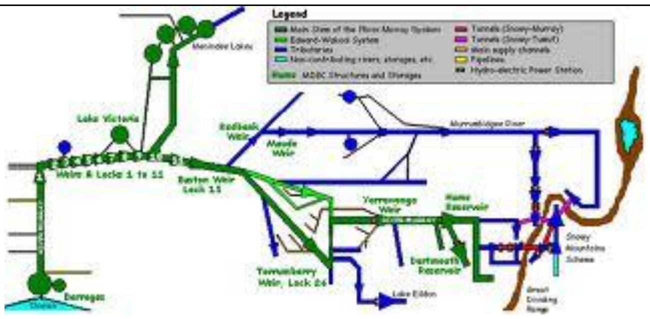
http://www.ipcc.ch/publications_and_data/publications_and_data_glossary.shtml#.UglGVo7GK6E

14. APPENDIX A – ICOLD CLIMATE CHANGE CASE STUDIES

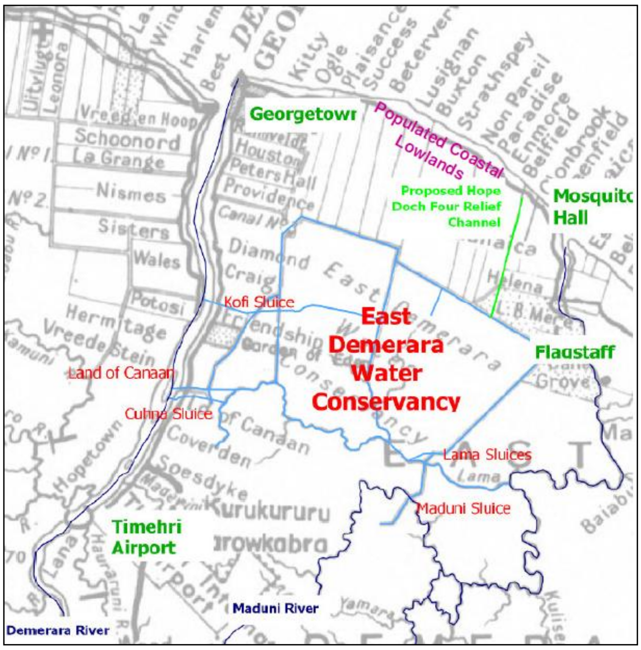
Project Case Study A

Project Name		**Murray Darling Basin Plan (Australia)**
Project Cost		Budget allocation approximately USD12 billion (2012)
Project Type		Integrated approach to restoration of sustainable water extractions and river health using adaptive management approaches including modification of operational practices and engineering works.
Date	Commencement	Community consultation phase commenced 2009; Delivery implementation commenced 2012.
	Completion	Target completion 2019
Location	Country	Australia
	Coordinates	35.2828° S, 149.1314° E
	Map	
Climate Change Scenario		Inflows into the Murray-Darling Basin are naturally extremely variable with history recording a number of short and long term droughts. Inflows to the basin over the twelve years of the recent "millennium drought" (2000 to 2011) were 40% below long term averages. Palaeo-climatic evidence suggests that worse droughts than this have occurred in the past. Climate change studies (eg the Southern Eastern Australia Climate Change Institute (www.seaci.org)) indicate the Basin climate is likely to become even more variable, as well as hotter and drier together with the likelihood of more extreme floods. Mid-range model projections are for a reduction of 10% in average surface water availability across the Basin by 2030, with significant variability also likely between the northern and southern basin.

Other Factors		The Murray Darling Basin covers approximately 1,059,000 km2 or 14% of the Australian landmass. It comprises over 77,000 km of rivers flowing through five states, more than 25,000 wetlands and is home to over two million people, rare and complex ecosystems, and several endangered species of birds and animals. It is a place of special indigenous significance and home to more than 30 Aboriginal nations whose connection with the land, water and environment extends over many thousands of years. The Basin is Australia’s most important agricultural region with an annual production value in excess of $10 billion, and the industry relies heavily on irrigation to supply one third of the national food supply and also supporting many important food export industries. It is a region of extreme economic, social, cultural, spiritual and environmental value.
Project Description	Background	The crippling impacts of the millennium drought across the Murray Darling Basin on the environment, agricultural production and communities together with an increased awareness of the impacts of climate change lead the Australian Government to review the overall management of water resources in the Murray-Darling Basin. Over the past two hundred years several major engineering projects including the Snowy Mountains Scheme, 14 large dams and weirs (including some of Australia’s largest dams) and thousands of kilometres of irrigation distribution systems have been developed and management of the river systems altered significantly from pre-existing conditions. The stresses evident from the drought and the future predictions of climate variability and extremes in inflows were the catalyst to reviewing current water management practices across the Basin.
	Issue	The Murray Darling Basin is a very complex river system with many competing interests, communities and environments. A solution to addressing long term climate change scenarios as well as addressing many of the decisions of the past required extensive scientific modelling, community engagement and political debate.
	Action	The Australian Government’s Murray-Darling Basin Authority was tasked with delivering a future management strategy for the Basin, known as the Murray-Darling Basin Plan. This Plan outlines and integrated future adaptive management program which uses a combination of engineering works, operational adjustments, re-acquisition of water property rights from individuals, community engagement and ongoing monitoring and review.

Figures/ Photographs	 Schematic Diagram of Murray-Darling River System  Hume Dam on the River Murray  Community consultation during development of the Plan
References	www.mdba.gov.au/basin-plan www.environment.gov.au/water/basin-plan/index.html www.seaci.org www.youtube.com/watch?v=Jbi3e4Ogx1c&feature=player_detailpage www.youtube.com/watch?feature=player_detailpage&v=Wumfo3AJ57c

Project Case Study B

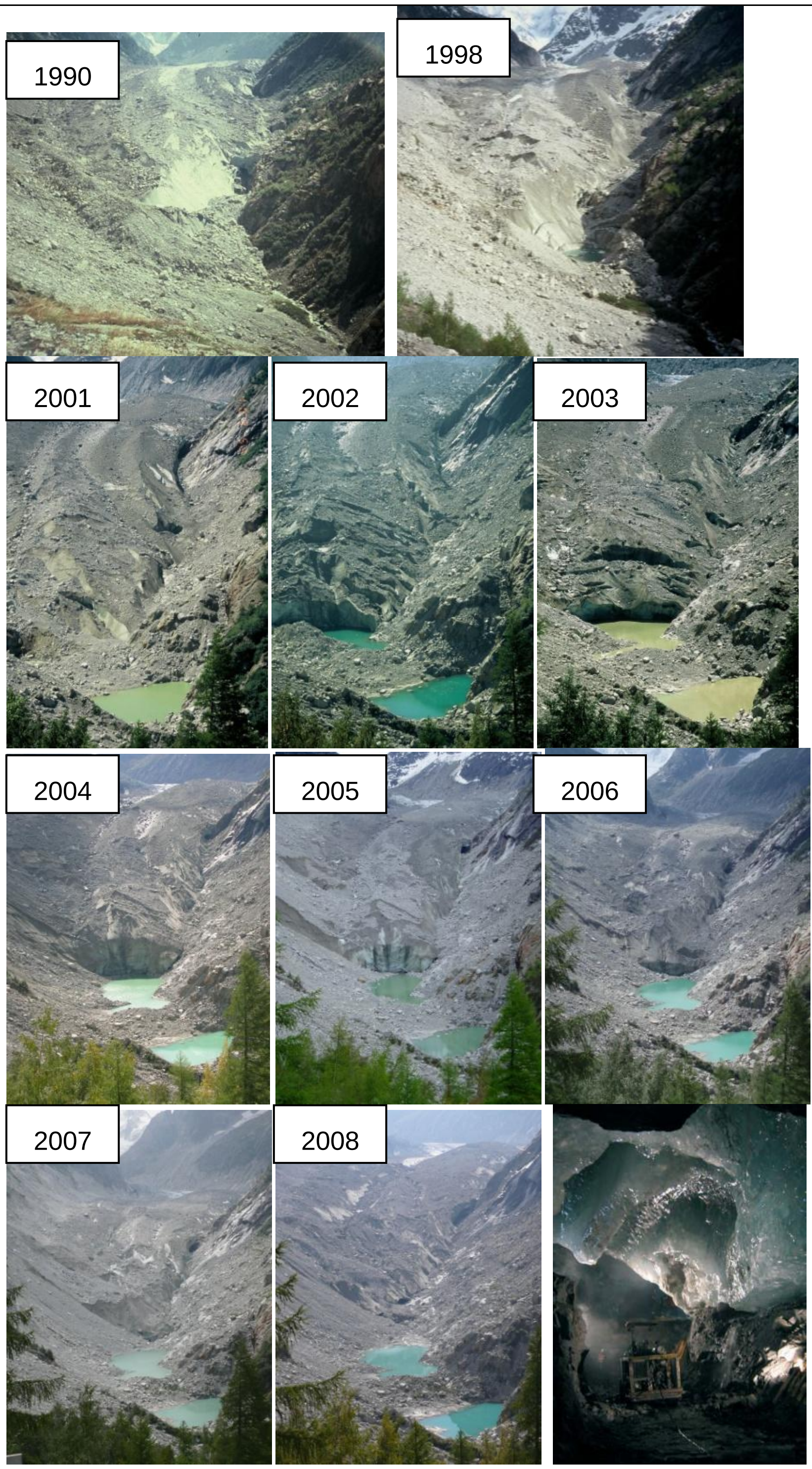
Project Name		**Guyana Conservancy Adaptation Project: Pre-Investment Studies (Guyana)**
Project Cost		USD 2.9M (2011)
Project Type		Adaptation
Date	Commencement	March 2011
	Completion	March 2013
Location	Country	Guyana, South America
	Coordinates	6.8000º N, 58.1667 º E
	Map	
Climate Change Scenario		The populated coastline of Guyana lies up to 2m below the mean sea level. This means that any water which accumulates along the coastal strip can only be discharged during the small drainage windows at low tide, or by pumping. The rate of sea level rise in this area is estimated at around 1cm per year, so that those drainage windows are decreasing. Added to that, extreme rainfall events appear to be getting more common in Guyana, and in 2005 a rainfall event which has been likened to the 1:5,000 year event left the whole populated coastline inundated, with water levels in people's home reaching chest height. It was three weeks before the flood waters could be discharged. During this event, the EDWC[3] Dam, which retains a large shallow reservoir inland of the coastal strip, was overtopped and

[3] East Demerara Water Conservancy

		suffered localised slip failures, but did not breach. The Government of Guyana recognised that had the dam breached, the results would have been catastrophic for the populated areas downstream. The increase in extreme rainfall has meant that the reservoir is now routinely operated above the stated Top Water Level, putting more pressure on the under-designed dam.
Other Factors		Guyana is a very poor country, and as such the Government have very little money to spend on maintenance, so the drainage systems and the EDWC Dam itself have been left to fall into disrepair.
Project Description	Background	This project is funded by the Global Environment Facility Special Climate Change Fund, and administered by the World Bank.
	Issue	The objective of this project is to: reduce the country's vulnerability to catastrophic flooding
	Action	The project aims to achieve that objective in the following ways: 1. Strengthening the Government of Guyana's understanding of the EDWC system and coastal plain drainage regimes by the production and use of hydraulic models, based on topographic information gathered by LiDAR and the installation of an extensive network of hydrologic instrumentation. 2. Increasing the drainage relief capacity of the EDWC by the excavation of new drainage channels, as designed through the use of the EDWC hydraulic model. 3. Increasing the drainage relief capacity of the coastal plain drainage regimes by the implementation of key interventions and recommendation of further works, as determined through the use of the hydraulic models. 4. Design of rehabilitation works to strengthen the 60km long EDWC dam and associated structures. 5. Strengthening the Government's capacity to identify key interventions and carry out effective maintenance through a hands-on training programme and technology transfer.
References		The project website is under construction. In the meantime details can be found at the following web addresses http://www.worldbank.org/projects/P103539/conservancy-adaptation-project?lang=en http://www.thegef.org/gef/project_detail?projID=3227

Project Case Study C

Project Name		**“Les Bois” hydropower plant (France) : glacier water intake structure displacement due to climate-induced glacier front retreat**
Project Cost		16 Millions Euros = approx. 21 millions USD
Project Type		Structural adaptation
Date	Commencement	2007
	Completion	2011
Location	Country	France (city : Chamonix, French Alps)
	Coordinates	GPS : lat. 45°56'08''N – long. 06°51'18''E
	Map	https://maps.google.fr/maps?q=les+bois+chamonix&hl=en&gbv=2&ie=UTF-8
Climate Change Scenario		Glacier front retreat progress has been projected by French glaciology research lab (LGGE) using a combination of different GHG emissions scenarios (A1, A2, B1, B2 families) and a glacier response model, that led to both pessimistic and optimistic scenarios for the next 20 years. Displacement of the intake structure has been based on the pessimistic scenario results
Other Factors		If no adaptation action has been taken, the existing intake structure underneath the glacier would have been becoming apparent in 2 or 3 years and progressively affected and fulfilled by landslide materials coming from the banks. Thus, efficiency if not entire operation would have been partially or totally lost.
Project Description	Background	Les Blois power plant is a 40 MW project owned by Electricité de France (EDF), constructed in the early 70s, and using water coming from “Mer de Glace” glacier melt process.
	Issue	Glacier front retreat has accelerated in the last decade (see pictures), such that the intake structure could become uncovered in the next 2 to 3 years.
	Action	3 options were considered to maintain plant operation in a durable manner : secure and reinforce protection of existing intake structure (risky) ; displace intake structure downstream (loss of power and energy) ; displace intake structure upstream (costly but ensuring performance of the project). This final option has been chosen.
Figures/ Photographs		Glacier front retreat for 1990-2008 (see progress of lakes formation at the glacier front while retreating) :

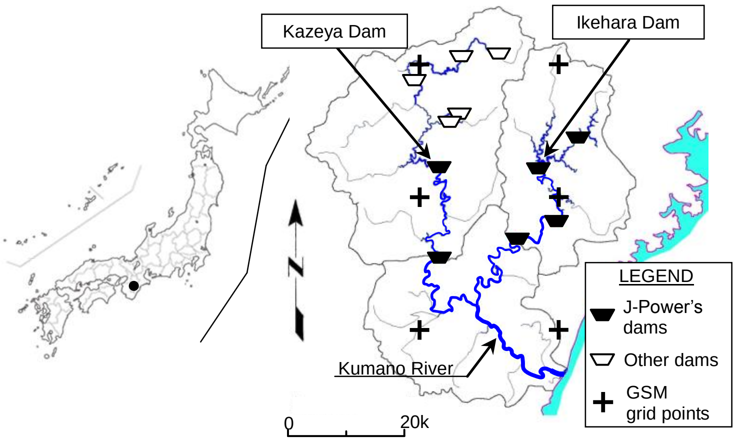



Excavation works for new intake structure


Works underneath glacier

References	An exceptional project : Les Bois power plant in Chamonix. In *Tunnels & Espace souterrain*, n°219 - Mai/Juin 2010, pp. 217-230. Centrale hydro-électrique des Bois en Haute-Savoie : travaux d’adaptation suite au recul de la Mer de Glace. In *Travaux*, n°875, Oct. 2010, pp. 63-69.

Project Case Study D

Project Name		**Reduction of flood discharge from two hydropower dams in Kumano river (Japan)**
Project Cost		Not opened (Reduction of power generation)
Project Type		Operational adaptation
Date	Commencement	June 1, 2012
	Completion	Not proposed (Continuous improvement based on actual operation)
Location	Country	Japan
	Coordinates	E135˚58′26″ & N34˚2 ′31″ (Ikehara dam) E135˚47′14″ & N34˚2 ′30″ (Kazeya dam)
	Map	
Climate Change Scenario		Not proposed. (In Japan, all operational / structural adaptation of dams is performed based on experience of abnormal rainfall or flood which actually took place, not based on projection of climate change.)
Other Factors		In Japan, water use dams are not legally obliged to contribute to flood control. Legal obligation of water use dams is to keep vacant capacity for cancellation of the effects of reduction of river channel storage and increase of flood propagation velocity, only when flood is occurring. The water level for this operation is called "discharge preparation water level".
Project Description	Background	Facing regular course of typhoons, the Kumano river basin has long been suffering from flood damage, but there is no flood control dam.
	Issue	Typhoon Talas, the 12th typhoon of 2011, which attacked wide area of western Japan, brought record-breaking rainfall and flood in Kumano river basin. Its flood damage was so serious that Electric Power Development Co. Ltd. (J-Power), as an owner of water use dams, decided to promote its cooperation with flood control voluntarily.
	Action	J-Power, which owns 2 large hydropower dams, Ikehara dam and Kazeya dam in Kumano river, had voluntarily been continuing cooperation with flood control since 1997 by setting "target water level" below discharge preparation water level. After Typhoon Talas, J-Power decided to set further lower "interim target water level" to enlarge the vacant capacity.

Drawdown toward interim target water level is performed by only generation discharge. In order to determine criteria to begin the drawdown, it is necessary to predict total average rainfall in the catchment in 2 or 3 days in the future in high accuracy. Combining the numerical meteorological prediction by Japan Meteorological Agency and the statistical relationship between the observed typhoon courses, total average rainfall in the catchment and magnitude of floods, the criteria were determined as shown in the following table.

Meteorological information		Criteria Stage 1 (Common to the 2 dams)	Criteria Stage 2 (Ikehara dam)
Typhoon information	Present centre location	To the north of 15°N and between120 ° E and 145°E	ditto
	Predicted course	Less than 300km from the 2 dams	ditto
Rainfall prediction by Global Spectral Model (GSM)	84-hours total rainfall based on the maximum value of the GPV at the 6 grid points located in the catchment	More than 200mm	More than 500mm

Figures/ Photographs

Dam features	Ikehara Dam (left)		Kazeya Dam (right)	
Completeion year	1964		1960	
Height (m)	111.0		101.0	
Effective Capacity (Mm^3)	220.1		89.0	
Maximum Water Usage (m^3/s)	342.0		60.0	
Available vacant capacity to reduce flood discharge	Water level (m+L.W.L)	Vacant capacity (Mm^3)	Water level (m+L.W.L)	Vacant capacity (Mm^3)
Normal water level	35.0	0.0	30.0	0.0
Discharge preparation water level (legal obligation)	32.8	18.0	26.0	17.0
Target water level (1997-2011)	29.0	48.0	24.0	24.0
Interim target water level (2012-)	Stage 1: 27.5	59.0	23.0	28.0
	Stage 2: 26.0	70.0		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2) Technical Committee on Dam Operation, "Interim Report Toward Improvement of Implementation of Dam Operation. May 2012", Electric Power Development Co. Ltd. (online), available from <http://www.jpower.co.jp/oshirase/pdf/oshirase120604-3.pdf>

Project Case Study E

<table>
<tr><td colspan="2">Project Name

Colorado River Municipal Water District - Ward County Water Supply Expansion Project (USA)</td><td>Description

The Colorado River Municipal Water District supplies municipal and industrial water in whole or in part to about 400,000 people in west Texas, USA. It relied upon 3 surface reservoirs and some emergency groundwater supplies. This project increased the groundwater availability during droughts.</td></tr>
<tr><td colspan="2">Project Cost</td><td>Total project cost USD and year

$130 million in 2012</td></tr>
<tr><td colspan="2">Project Type

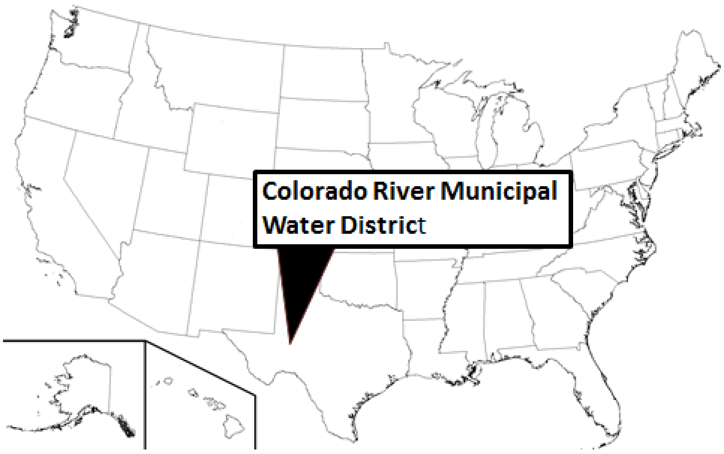
Developed groundwater</td><td>Operational/ structural/ adaptation

Developed groundwater wells to provide water when surface water was not available. There is limited recharge to the groundwater so it will only be used when surface water is not available.</td></tr>
<tr><td rowspan="2">Date

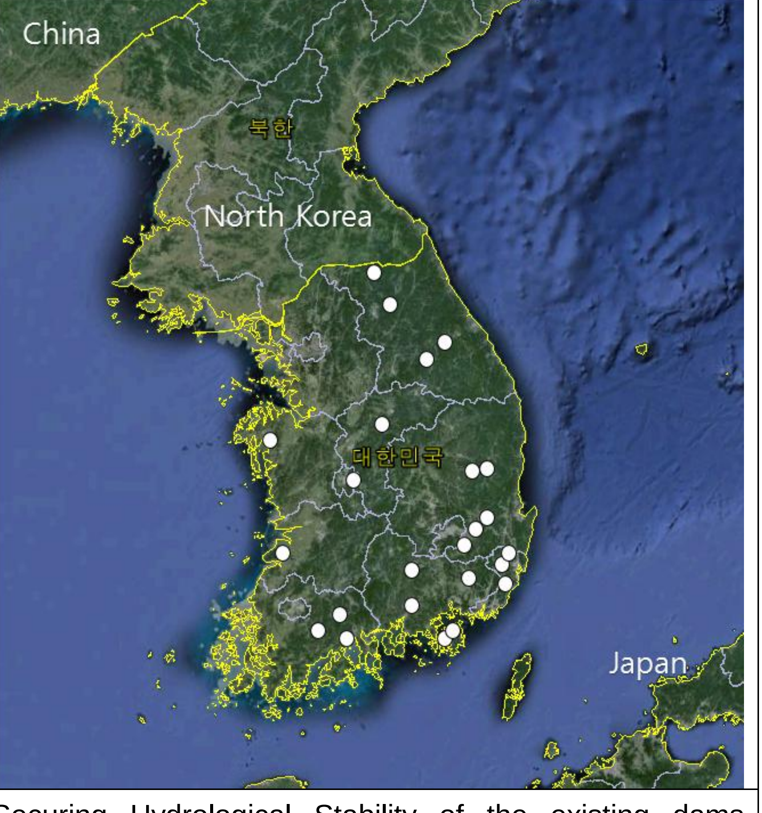
2012</td><td>Commencement</td><td>June, 2011</td></tr>
<tr><td>Completion</td><td>December, 2012</td></tr>
<tr><td rowspan="3">Location</td><td>Country</td><td>USA (Texas)</td></tr>
<tr><td>Coordinates</td><td>Longitude – 103,03,16.85

Latitude – 31,34,5.53</td></tr>
<tr><td>Map</td><td>Please attach map on next page</td></tr>
</table>

Climate Change Scenario		Colorado River Municipal Water District has developed a water supply system of 3 major water supply reservoirs. The first was placed into operation in the 1950’s, the last in the 1990’s. The region has no additional surface water to develop and has suffered a reacquiring since the 1990’s. The reliable supplies from the reservoirs has dropped nearly 50% since the 1990’s. The total storage volume dropped to as low as about 80,000 af (<10%) in 2012.
Other Factors		1. The region is experiencing rapid growth driven by new technology in oil recovery that is bringing new drilling in older oil fields. 2. The groundwater that is being used has limited recharge so it is only used when other surface water supplies are not available. 3. The District is currently soliciting proposals to find other groundwater supplies if the drought persists.
Project Description	Background	CRMWD has provided surface water to cities in west Texas since the early 1950’s. Lake JB Thomas was closed in 1952, EV Spence in 1969, and OH Ivie in 1990. With the exception of the early 1970’s the District has provided all of the water supply needs for the region through surface water.
	Issue	CRMWD’s three surface water supplies are nearly empty and have very little inflow to sustain the evaporation and water supply demands. In preparation of the surface water going dry, the project will provide enough ground water for health and safety of its customers.
	Action	CRMWD purchased a well field and the ground water rights, installed 21 new groundwater wells, 20 miles of well collection piping, 45 miles of 42/48-inch diameter transmission pipeline and four pump stations.

Figures/ Photographs	
References	none

Project Case Study F

Project Name		**Hydrological Stability Enhancement Project of the Existing Dams (Korea)**
Project Cost		2.2 billion USD
Project Type		Structural& adaptation
Date	Commencement	April, 2003
	Completion	Ongoing
Location	Country	Republic of Korea
	Coordinates	24 sites of the overall country Between 34°N and 38°N, 129°E and 132°E
	Map	
Climate Change Scenario		Securing Hydrological Stability of the existing dams against Probable Maximum Floods due to the Climate Change
Other Factors		Chronic economic damages due to increasing rainfall intensity
Project Description	Background	Re-estimation of the PMF showed that the increased rainfall may overtop the existing dams resulting in failure
	Issue	Some dams have been failed caused loss of lives and

		properties
	Action	Re-evaluation of the hydrological stability in all major dams in Korea was performed and various measures have been applied to each dams
Figures/ Photographs		 Example of the spillway expansion in Soyanggang dam. Two additional tunnels have been completed to cover the increased PMF
References		http://english.kwater.or.kr/