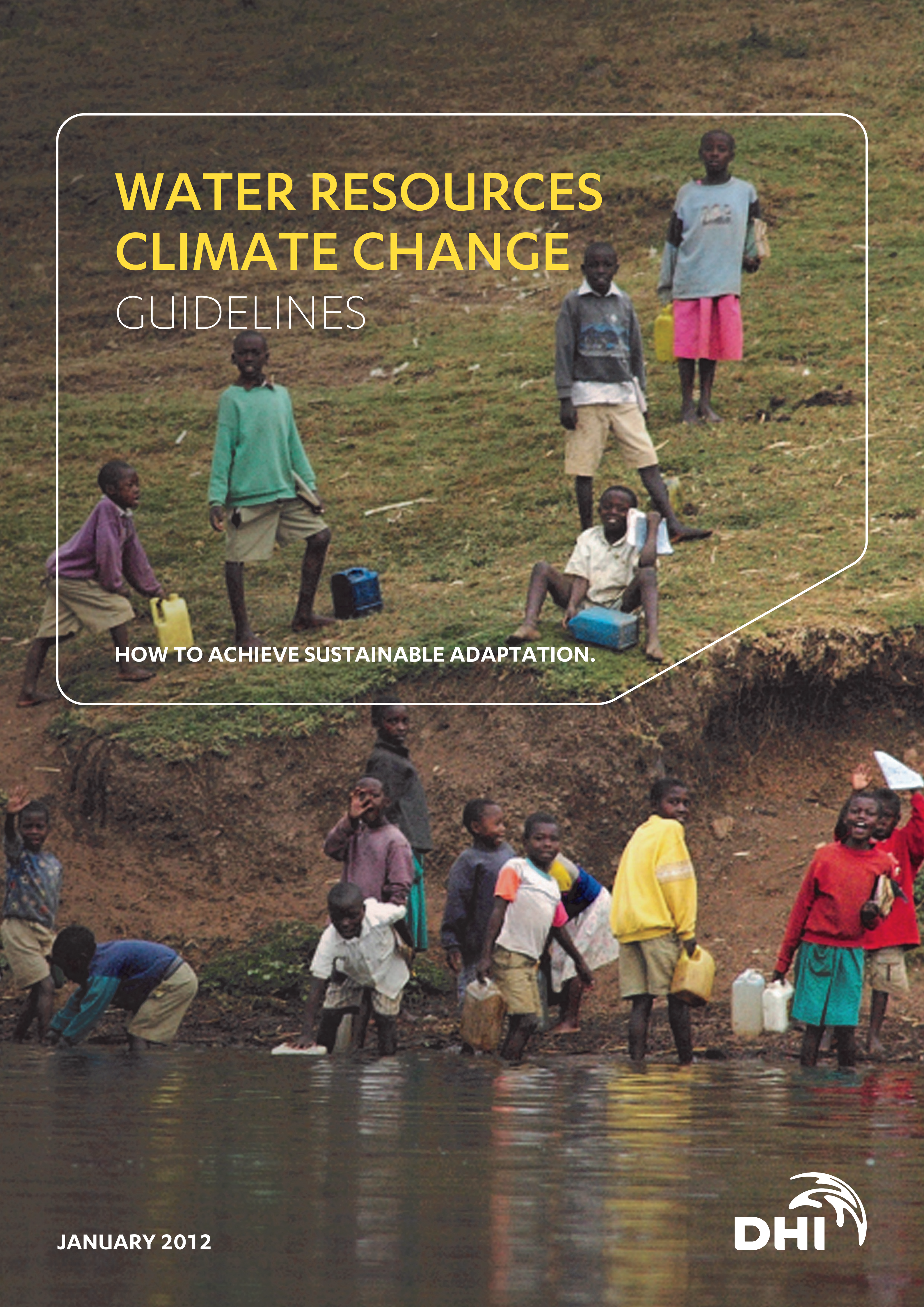


WATER RESOURCES CLIMATE CHANGE

GUIDELINES

HOW TO ACHIEVE SUSTAINABLE ADAPTATION.

JANUARY 2012

DHI

Authors

Anita May Asadullah (ana@dhigroup.com)

Michael Butts (mib@dhigroup.com)

Paul Glennie (pgl@dhigroup.com)

Palle Lindgaard-Jørgensen (plj@dhigroup.com)

Henrik Madsen (hem@dhigroup.com)

Niels Riegels (ndr@dhigroup.com)

This is an evolving field and these guidelines will be updated periodically. The next version of these guidelines is already being worked on. For all queries, suggestions and corrections please email one of the authors above.

For further information go to http://climatechange.dhigroup.com/

Acknowledgements

The authors are extremely grateful to the following for their reviews and inputs:

Peter Koefoed Bjørnsen, Anders Christian Erichsen, Lars-Göran Gustafsson, Finn Hansen, Flemming Hansen, Roar Jensen, Stefan Kaden, Kenneth Kjær-Jensen, Jørgen Krosgaard, Ole Mark, Bertram Monninkhoff, Sebastian Sklorz, Erik Mårtensson, Jennifer Oakley, Andrew Pott, Lone Rieskov, Terry van Kalken

Disclaimer

Table of contents

Table of contents

Introduction

How to read this guide

Who should read this guide?

This practical guide is primarily written for water resources engineers, hydrologists, managers, and planners. Although not written explicitly for policy makers, advisors within government, water resources commissions and basin organizations may also find it useful to get an oversight of strategies, methodologies and tools available for incorporating climate change impacts into water resources management.

Aims

The aim is to provide practical guidance on how to incorporate climate change when dealing with existing challenges in water resources management. Starting from a water resources management perspective, it provides an introduction to the key issues, practical guidance on how to consider climate change, and links to further information at each step.

The impact of climate change on water resources management is a complex issue and the volume of knowledge in this field continues to grow rapidly. Initially, much of the literature focussed on developing climate projections. Subsequently, these projections have been applied to numerous studies using many different methodologies to assess the impact of climate change on many sectors including water resources. Most recently, recognising the potential impact on water resources, efforts have focussed on developing appropriate adaptation measures and incorporating climate change into long-term planning cycles.

This document is not meant as a complete guide to the field of climate change in water resource management. Nor is it a substitute for expertise and experience dealing with climate change. It should, however, provide the reader with an overview of the methodologies, tools and strategies available for impact assessment or adaptation to climate change, and what is involved in implementing them.

Scope

Why did we write this guide?

Nearly all the methodologies available for assessing the potential impacts of climate change on water resources are based on using climate model data and water resources modelling. Similarly, if such an assessment indicates that the water resource, water infrastructure or ecosystem of interest is vulnerable to climate change then evaluations of alternative measures to adapt to climate change often rely on model simulations of these alternatives. DHI is well-known in the field of hydroinformatics for both the development and application of water resources modelling tools and decision support systems. This guide supports the effective application of these water resources tools in the context of climate change.

Which water resources issues are addressed?

The scope of this document should be broad enough to be relevant for a wide range of water resources issues across many of the related sectors, whilst still providing enough relevant practical guidance.

The types of projects that these guidelines are relevant to include, but are not limited to, the following:

- Flood management

How to read this guide

- Integrated water resources management
- Ecosystem conservation and restoration
- Infrastructure design and management.

The framework, methodologies and tools for analysis contained in this document can be applied to these and many other types of projects.

Where?

Illustrative examples are provided throughout and more detailed case studies given at the end. This guide is, however, designed to be broad enough to apply to most locations throughout the world. It provides guidance on how to approach specific projects and use global, regional, and local information.

At what scale?

As water resources management ranges from highly localised issues like flood protection to catchment, national and even transnational water allocation, the framework provided in this guide should be applicable to projects of all scales. Guidelines are tailored to provide options depending on the economic, human, and technical resources available.

Structure

There is no need to read this guide from cover to cover to get the information you want. You can just jump into the section you are most interested in or go to the main work flow diagram and navigate from there. The document is structured around the progression shown in Figure 1 and the corresponding seven chapters at the top of the page.

If your goal is to carry out an impact study to determine the effect of climate change on a specific water resource issue, then read chapters 1-> 3-> 4 . Within each chapter a quick overview of the key messages and important information can be found in the "60-second Summary" boxes. Links within the text allow you to jump to other relevant parts of the document or to external websites.

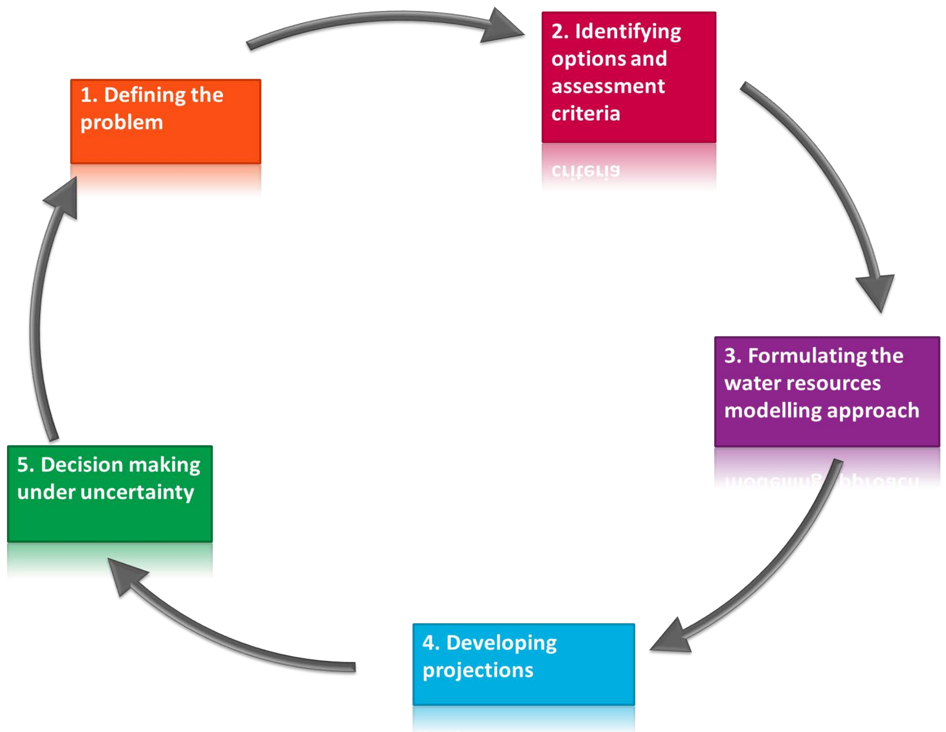


Figure 1. The document is structured around this workflow. The details of this structure as a table of contents is given at the end of this section.

How to read this guide

Highlights

You will find a practical flow chart aimed at guiding you through the various steps of each section of a climate change study, at the beginning of each chapter

The document is linked and underlined words in blue have hyperlinks present

to take you to further information on the subject.

In each section...

60-second summary...

60-second summary boxes for readers requiring a quick overview can be found in each section in lime green.

Practical guidelines to working with climate change projects in grey boxes.

Working with...

Illustrative examples

Illustrations of how the information has been applied to real projects are reported in orange boxes.

Information regarding uncertainty and the importance of it in the project results in green boxes

Uncertainty

DHI tools which can be used in the assessment of climate change impacts are listed throughout the document. Further information on the tools is provided at the end of the document.

How can DHI tools help?

How to read this guide

Climate Change FAQs

What is climate?

Despite the attention climate change receives there is still no universally accepted definition. A widely used definition is the average weather over a 30-year period. Alternative definitions include: the statistical properties of observed weather at a location at a given time of year or; the ensemble of all possible weather states given the conditions external to the climate system (Stone and Knutti 2011). A good introduction can be found in*: Modelling the Impact of Climate Change on Water Resources* (Fung et al. 2010).

What is the difference between weather and climate?

This can be summarised by the phrase, "Climate is what you expect, weather is what you get" (Stone and Knutti 2011). Weather describes the individual events observed and climate is a more general description of the character of all the different weather events of a place.

What is meant by climate change?

The climate system is dynamic and always changing. However, Climate Change is a term that is now used to refer to the accelerated changes within the climate system resulting from anthropogenic alterations of atmospheric composition. The shift in the global energy balance caused by increasing concentrations of greenhouse gases leads to different patterns of climate across the globe. Changes do not necessarily occur linearly over time nor do they occur uniformly across the globe.

What are current global projections?

[Projections from the 4th Assessment Report (AR4)] will be updated in 2014 by the 5th Assessment Report (AR5). Current predictions from AR4 include:

Air surface temperatures rising by between 1.1 and 6.4° C in the 21st century, especially over land and in high northern latitudes.

Snow cover and permafrost areas are expected to **contract**.

More **Frequent heat waves and heavy rainfall events** are expected.

Future tropical **cyclones are expected to** become more intense.

Extra-tropical storm tracks will move polewards, changing the current broad patterns of rainfall, wind and temperature.

Rainfall patterns will change with likely increases in high latitudes very likely and decreases in subtropical land regions.

Warming will add carbon to the atmosphere but the magnitude of this feedback is uncertain.

In general **sea levels will rise** but the magnitude of the rise is very uncertain. AR4 estimates report model-based changes between 18-59cm by 2100 but state there can be no best estimate or upper bound due to the large uncertainties surrounding ice flow dynamics, feedback systems, Greenland and Antarctica ice

60-second summary...

- Climate describes long term range of expected weather. Climate is what we expect and weather is what happens. No single weather event in isolation can inform us about climate.
- Climate change refers to accelerated warming from a changed composition of the atmosphere and the ensuing changes in distributions of heat, moisture and momentum around the globe.
- Climate change projections include, higher temperatures, heavier rainfall events, changes of patters of rainfall across the globe, sea level rise, more intense cyclones. Though there is much uncertainty about the magnitude of the changes.

Climate Change FAQs

sheet mass balance and thermal expansion of the oceans. These uncertainties would all lead to sea levels rising quicker than model estimates.

For impacts on floods and droughts see sections 2.3 & 2.4.

Can a single rainfall event tell us anything about climate change?

A single weather event describes only weather and not climate. Even if an event is particularly extreme, a single event cannot be evidence of climate change. Increased occurrence of events or sustained changes may reflect a shift in climate but by definition no single event can tell you about climate.

Can global warming be true even if we had a cold winter?

Global warming refers to the overall increase in the net incoming radiation to the planet as a whole (as a result of the changed composition of the atmosphere). This incoming energy is redistributed around the planet by the atmosphere and oceans, which drive the climate system and the patterns of heat and moisture. A cold winter in one part of the world is not contradictory with average global warming.

Why are we planning for climate change? Shouldn't we focus our efforts on trying to stop it?

Previous anthropogenic interventions mean we are already committed to a changed climate system and there is no way of avoiding accelerated changes in temperature, rainfall and sea levels. Thus, in addition to trying to limit the scale of change by reducing emissions we should be considering how to manage climate risks where appropriate.

If climate change isn't going to happen for a long time, why plan for it now?

Climate change is not just a thing of the future. Whilst short-term changes may be less extreme than projected changes by 2100, change is already occurring and risks over the next 50 years (which may be the design lifetime of infrastructure) may be significantly different to today's risks. This is why flexible adaptation to climate change risks is so important, and is one of the main reasons for writing these guidelines.

What climate change signals can be seen?

There is strong evidence of climate warming in recent decades from observations of increases in global mean air and ocean temperatures, melting of snow and ice, and rising sea levels. Although no globally consistent change in precipitation is observable, there is substantial evidence of zonal changes, such as the decline of average precipitation in the Northern Hemisphere sub-tropics that has occurred since the 1970s. Increases in the frequency of heavy precipitation events have been observed in Europe and North America, and increases in the frequency and severity of droughts have been observed over much of the Northern Hemisphere. Attribution studies (e.g. Zhang et al. 2007) suggest that these changes exceed what can be explained by the natural variability of the climate system.

But if governments act and emissions are reduced, all this planning will be for nothing?

It is highly unlikely that there will be a drastic cut in global emissions to pre-industrialised levels. However, even if greenhouse gas concentrations were to be stabilised,

"Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks" IPCC AR4 (Meehl et al 2007).

For more information see: Climate Change 2007: Working Group I: The Physical Science Basis

Summary climate change guidelines

How to read this guide
Climate change FAQs
Summary climate change guidelines
Guidelines as a work flow

Climate change guidelines

The recommended steps for undertaking a climate change study are listed below.

START ->

1. Define the problem. If it is an impact study go straight to step 3

Define the nature and severity of problems caused by climate change and the objectives and priorities of the study.

2. Identify options and assessment criteria

Identify a short list of options (e.g. infrastructure or management plans) which could be implemented to address the challenges outlined in step 1 and to decide on the criteria for assessing each option to select a preferred option or combination of options.

3. Formulate the water resources modelling approach

Decide how the impacts of climate change will be modelled to allow the necessary indicators to be calculated which are used to prioritise options.

4. Develop projections

Develop projections of future climate which can be used in water resource models to assess the impacts of the change and the performance of different infrastructure or management options.

5. Decide on a preferred option or strategy, in light of the uncertainties

Make decisions about whether any of the options meet your objectives and decide on a preferred option or set of options or decide to continue investigating other options (step 2) or even to reframe the question (step 1). Decide whether it is possible and necessary to reduce uncertainties (step 3 and step 4).

END -> Implement and monitor preferred option(s)

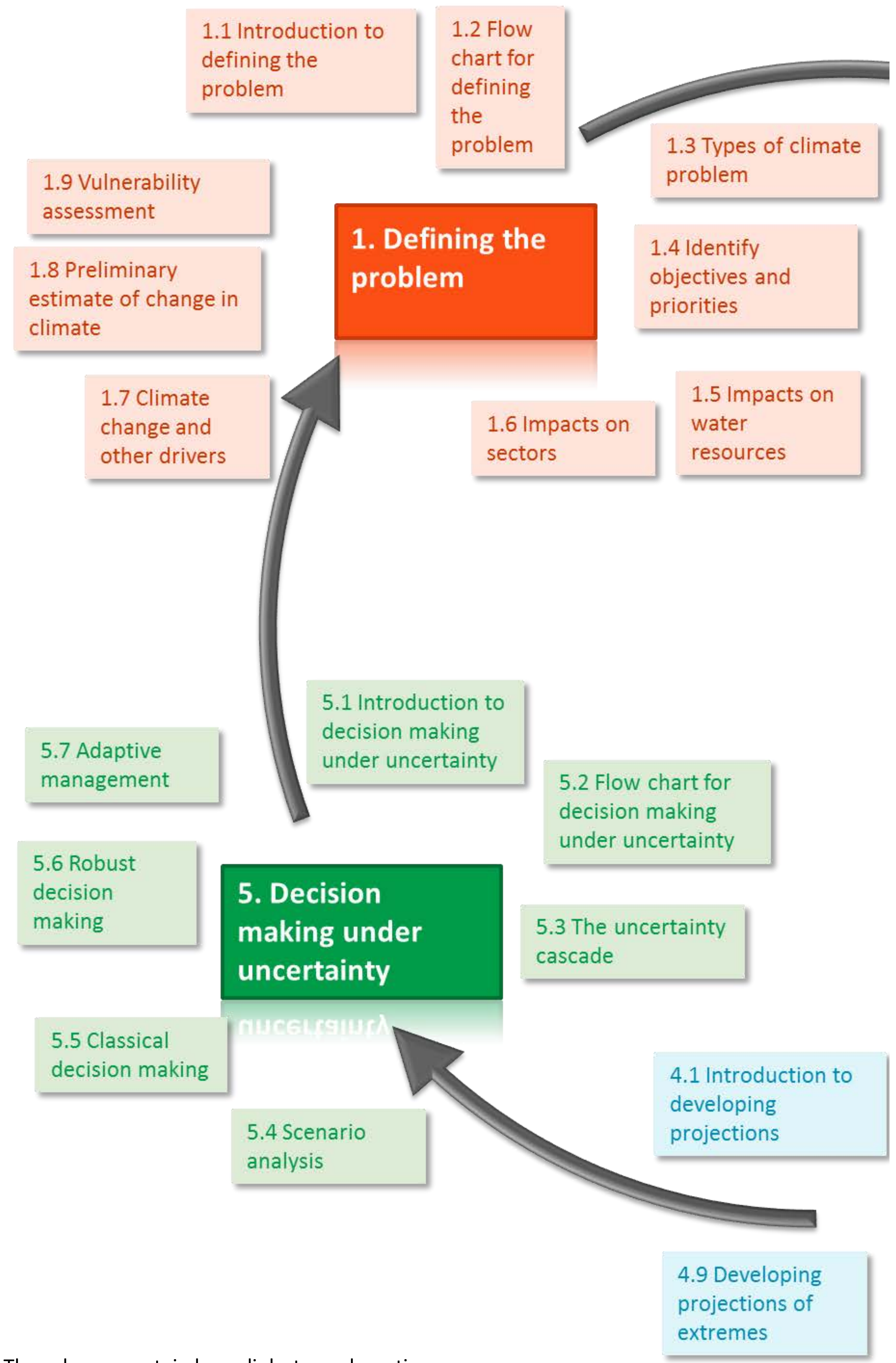
Summary climate change guidelines

A chapter is dedicated to each of these steps (chapters 1-5) up to the implementation and monitoring stage.

A more detailed workflow for each stage is presented at the beginning of each chapter

The guidelines can be visualised as a cyclical process as depicted on the following page.

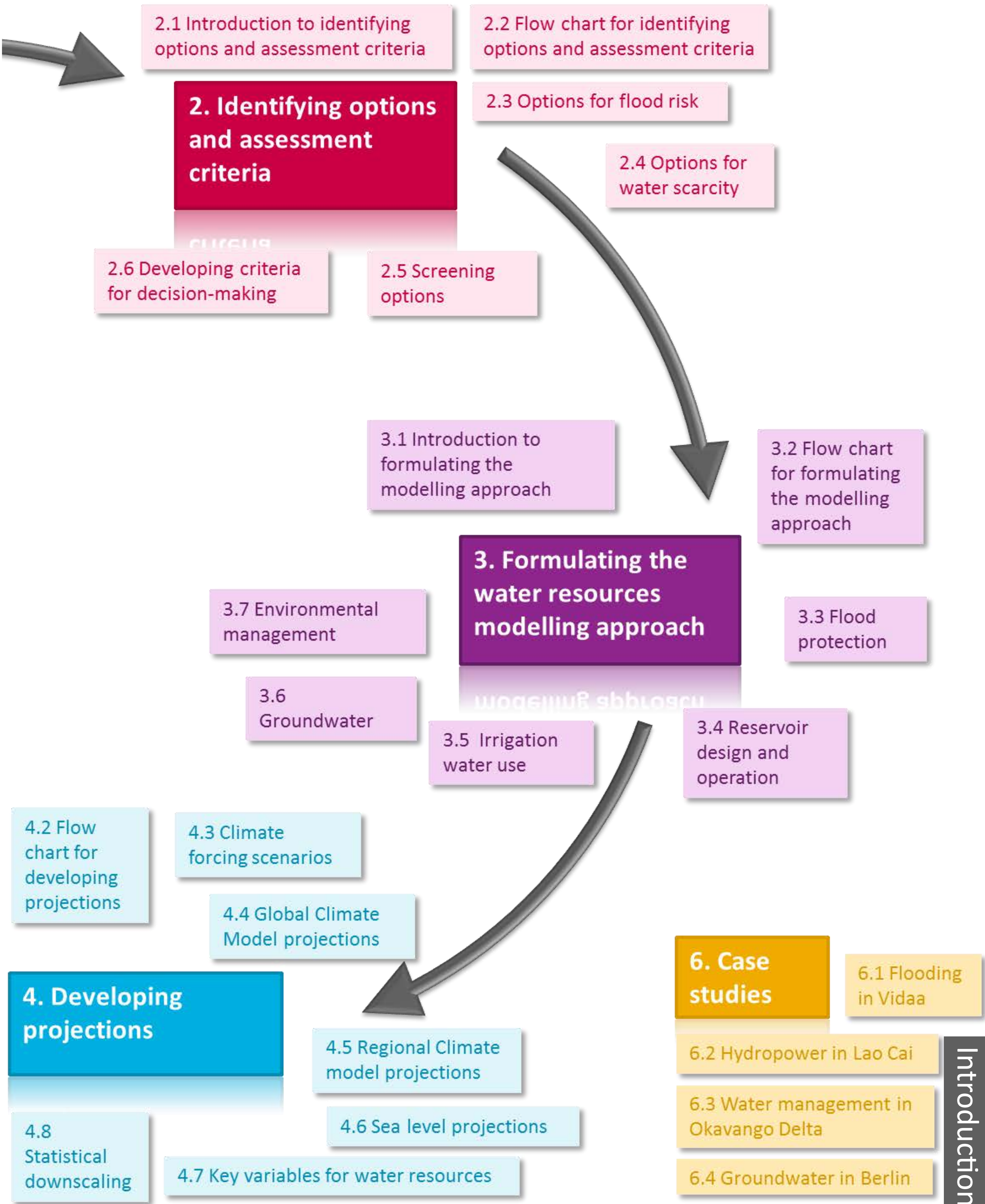
Guidelines as a work flow



These boxes contain hyperlinks to each section.

Introduction

Guidelines as a work flow



1. Defining the problem

1.1 Introduction to defining the problem

Why is it important to define the problem clearly?

Because of the potential complexity of climate change studies, it is important to define the problem clearly at the outset so that resources can be used efficiently. The level of effort needed to investigate climate impacts will vary depending on the objectives of the project. An initial assessment of climate impacts is helpful at this stage to estimate the significance of climate change to the system of interest. In addition, it is important to define the objectives of the project or study and the principles that will guide decision making.

Which steps are recommended in the problem definition phase?

The steps outlined below are recommended in the problem definition phase of the project or study. Each section of this chapter describes one of the following steps in detail.

1) Determine whether the problem is one of climate impact assessment, climate adaptation, or general water resources planning and management. Most climate-related projects or studies will fall into one of these three categories. Grouping a project within a category will help identify the extent to which climate change should be investigated and whether some components of the project cycle can be reduced in scope or eliminated.

2) Define the objectives of the study or project and the principles that will guide decision-making. This step will be useful when formulating decision-making criteria, which will in turn guide the development of the assessment approach. Attitudes towards risk should be defined in this step. It is also important at this stage to define the time horizon for the analysis.

3) Gather information about potential climate change impacts on the system of interest. In this step, existing information about potential climate change impacts is gathered.

4) Identify climate variables associated with climate change impacts. In this step, the variables associated with potential impacts are identified. This information will be important in formulating the assessment approach.

5) Identify other drivers besides those related to climate change that may affect the system of interest. It may be that other drivers such as population growth and economic development goals are as important (or more important) to the system of interest than climate change. These drivers should be identified and compared to climate change in terms of potential impacts.

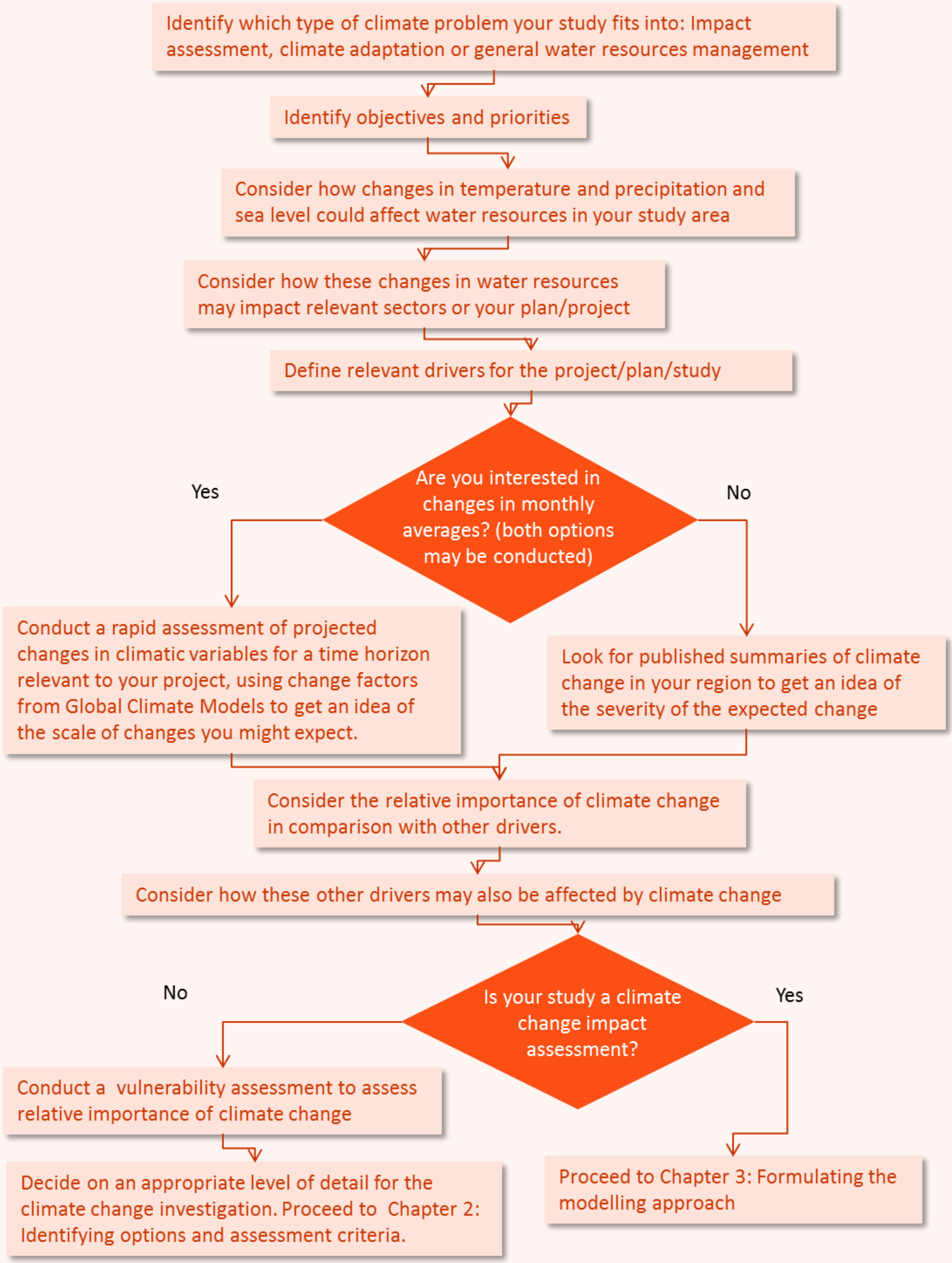
6) Develop a preliminary assessment of potential climate change impacts. In this step, an initial assessment of the extent to which the values of variables identified during step 4 may change is performed.

7) Perform an assessment of the extent to which the system of interest may be vulnerable to climate change. In this step, the impacts of the changes identified in step 6 are estimated.

It may be necessary to re-visit these steps later in the project cycle as new information emerges from more detailed analyses.

For more information: The UK Climate Impacts Programme (Willows,2003) technical report "Climate adaptation: Risk, uncertainty, and decision-making" provides additional information about defining the problem in a climate change study or project. This report and other useful materials can be accessed at http://www.ukcip.org.uk.

1.2 Flow chart for defining the problem



1.3 Types of climate problems

Why is it important to define the problem type?

One of the most important decisions to be made at the outset of a climate change study or project is the level of effort associated with estimating climate change impacts. Defining the type of problem can help with identifying an appropriate level of detail. In addition, some studies will not require all of the steps described in these guidelines. Defining the problem type at the beginning can help with deciding which steps to leave out.

How are the different types of climate change problems defined?

Climate change adaptation assessments

Climate change adaptation assessments are those in which the primary driver of the project is climate change. Climate change adaptation assessments are motivated by the perceived need to address unaccounted for risks associated with present or future levels of climate variability or climate extremes. An example of a climate adaptation assessment is a project to improve flood defences in response to risks posed by climate change. Climate adaptation assessments are usually associated with sectors such as flood control where climate variability and extremes have required management in the past, but the additional risks posed by climate change may not have been accounted for.

Climate change impact assessments

Climate change impact assessments refer to those in which the *impacts* of climate change are assessed on already existing or designed infrastructure or water resources plans. An example is an assessment of whether existing or planned flood defence infrastructure or plans will be sufficient under expected climate change impacts. This is a common form of project.

General water resources planning and management

These are situations in which the project is not motivated directly by climate change but where climate change may be an important factor affecting a project's outcome. Examples include the development of a new water-supply system for an urban area or the construction of a hydropower facility. In these situations, it is important to develop a preliminary estimate of the extent to which climate change may impact project outcomes, as this affects the extent to which resources should be committed to further investigation of climate impacts (sections 1.8 & 1.9). Although climate change will have an impact on almost any water resources planning or management issue, the impact may not be significant relative to other drivers in water resources management.

How can this information be used to simplify the analysis?

Climate change adaptation assessments are likely to require the most resources and most of the steps in this guideline are likely to be required. For climate change impact assessments, the sections of the project cycle related to identifying and assessing options and decision making under uncertainty can be left out. For general water resources planning and management, a detailed analysis of climate change impacts may not be necessary, depending on the relative importance of other drivers.

60-second summary...

- Climate change studies or projects can be grouped into three categories: climate change adaptation assessments, climate change impact assessments, and general water resources planning and management.
- Climate change adaptation assessments are those in which the primary driver is to formulate strategies that address risks associated with climate change. These projects will generally require a detailed assessment of climate change impacts.
- The purpose of climate change impact assessments is to evaluate risks posed by climate on existing projects. These projects do not initially require the development of methods for assessing and comparing options.
- General water resources management is not motivated directly by climate change but may be impacted by it. The level of effort dedicated to projecting climate change impacts will depend on the perceived importance of climate change in relation to other drivers.

1.4 Identifying objectives and priorities

What considerations apply to the identification of objectives and priorities in a climate change context?

Some considerations are important when identifying objectives and priorities in a climate change context. These include determining attitudes towards risk and uncertainty and defining a time horizon.

What is the difference between risk and uncertainty?

To address the issue of determining attitudes towards risk and uncertainty, it is important to provide precise definitions of terms. This discussion uses definitions provided by the UK Climate Impacts Programme (Willows, 2003). The *risk* associated with an event is defined as the product of the probability and the consequence of the event. The term *uncertainty* describes a state of limited knowledge in which it is impossible to describe either an existing state or future outcome precisely. Using the example of flooding, the risk of a certain level of flood occurring is defined by the probability that the flood will occur and the expected magnitude of damages caused by the flood. Because the probability of occurrence and expected damages of a certain flood level can never be known exactly, there is uncertainty associated with any estimate of flood risk. The uncertainty associated with a risk estimate usually decreases as more is known about the probability and expected consequences of the event.

Why is it important to determine attitudes towards risk and uncertainty?

Some consideration of attitudes towards risk and uncertainty will help guide assessment and decision-making processes. In the most simple formulation, attitudes towards risk can be characterized as either risk-averse or risk-neutral. A risk-neutral decision-maker will seek to maximize the expected utility of a decision, where expected utility can be defined quantitatively as the sum of the products of the probabilities of each outcome associated with a particular decision, times the utilities of the outcomes. A risk-neutral approach may be appropriate when the probabilities and consequences of different outcomes are well-known. If considerable uncertainty exists about probabilities and consequences, then a risk-averse approach may be more appropriate. Risk aversion can take on different forms in a climate change context. Because of the uncertainty associated with climate change, a risk-averse decision-maker may want to base decision-making on a worst-case climate change scenario so that undesirable consequences of climate change can be avoided as far as possible. On the other hand, uncertainty also means that it is possible to over-invest if climate change impacts turn out to be less significant than expected; a reluctance to over-invest is therefore also a legitimate risk-averse position. A third approach to risk, called the no-regret approach, may also be useful in the climate change context. In this approach, the decision-maker is averse to taking actions that may result in regrets or missed opportunities later on. Guidelines for decision-making given different risk approaches are provided in the section on decision-making under uncertainty (section 5).

Why is it important to define a time horizon?

As will be explained in the section on developing projections (section 4), all projections of climate change are based on scenarios of future emissions that are inherently uncertain. However, future emissions may not have significant impacts on climate at shorter time scales, so consideration of different emissions scenarios may be unnecessary. In addition, climate impacts on variability and extremes (i.e., changes in flood and drought frequencies) are harder to detect than changes in averages and may be impossible to separate from the natural variability of the climate system at shorter time scales. Projects with a time horizon of less than 20 years may not justify the use of detailed climate projections.

60-second summary...

- Risk and uncertainty have different meanings. The risk associated with an event is defined as the product of the probability and the consequence of the event. Uncertainty describes a state of limited knowledge in which it is impossible to describe either an existing state or future outcome precisely.
- A risk-neutral decision maker seeks to maximize the utility of a decision. A risk-neutral approach may be appropriate when the probabilities and consequences of different outcomes are well known.
- A risk-averse decision maker prefers a more certain outcome with a lower expected utility to a less certain outcome with a higher expected utility. A risk averse approach may be appropriate when considerable uncertainty exists about probabilities and consequences of events.
- For decision time scales of less than 20 years, it is unlikely that future emissions will have a significant impact on climate. It is also difficult to quantify climate impacts on variability and extremes at shorter time scales.

1.5 Impacts on water resources

Climate change may have significant impacts on water resources. These include impacts on precipitation, snow and ice, sea level, evapotranspiration, soil moisture, runoff and river discharge, and water quality. The potential impacts presented here summarize information presented in the fourth IPCC assessment, Working Group II report (2007). Some trends observed in the recent historical record are also presented, although it is not always clear that these trends are the result of increasing greenhouse gas concentrations.

Patterns of large-scale variability: A number of features of the large-scale climate system have direct influence on the hydrologic cycle. These features are characterized by patterns of variability that are apparent at inter-annual or decadal time scales. These patterns of variability are responsible for long-term variability observed in hydrological flow data. The most significant mode of interannual variability in the global climate system is the El Nino Southern Oscillation (ENSO), which is associated with an east-west shift in tropical Pacific precipitation. ENSO is also associated with wave-like disturbances to the atmospheric circulation outside the tropics that have major regional impacts. Outside the tropics, variability of the atmospheric circulation on longer time-scales is dominated by variations in the strength and location of the jet streams and associated storm tracks. There is some evidence from climate model projections that sea-level pressures will increase over the subtropics and mid-latitudes, causing storm tracks to move polewards. These shifts are also visible in the recent historical record. It is not yet possible to make conclusive projections about changes to ENSO variability. Monsoon precipitation events are expected to become more intense in some areas.

Snow and ice: Climate warming is projected to increase rates at which snow cover and glaciers melt. Although snowfall is projected to increase in some regions, it appears unlikely that precipitation increases will compensate for increases in melting. In areas with seasonal snow cover, the snow accumulation season is projected to begin later and the melting season is projected to start earlier. Satellite observations of snow cover in the Northern Hemisphere over 1966-2005 show decreases in every month except November and December. Considerable mass loss has occurred on the majority of glaciers and ice caps worldwide, with increasing rates in the past two decades.

Sea level: Although not all of the drivers of sea-level rise are well understood, it is expected that a combination of thermal expansion and ice-caps and glacial melting will cause rates of sea level rise in the 21st century to exceed rates observed since 1961. The average rate of sea level rise was 1.8 ± 0.5 mm/year for 1961-2003 and 3.1 ± 0.7 mm/year for 1993-2003. Impacts on water resources include increased risk of coastal flooding and salinity intrusion.

Mean precipitation: Climate model projections suggest that mean precipitation will increase in areas of regional tropical precipitation maxima (e.g., monsoon regimes) and at high latitudes, with decreases possible in mid-latitudes and sub-tropical regions (Figure 1.5.1). The historical record indicates that precipitation has declined in the region from 10°N to 30°N since 1970, although evidence is inconclusive as to whether this is the result of increasing greenhouse gas concentrations.

Extreme precipitation and drought: Evidence from climate models also suggests that heavy precipitation events will become more frequent, and that the likelihood of summer drought conditions will increase in mid-latitude regions. Widespread increases in heavy precipitation events have been observed in the recent historical record, even in areas where mean precipitation has decreased. However, rainfall statistics

60-second summary...

- Climate change will impact water resources through changes to precipitation, temperature, and potential evapotranspiration, as well as changes to global circulation patterns that impact long-term climate variability.
- Some impacts with the highest degree of certainty include increased temperatures, increased snow and glacier melting rates, and that seasonal runoff patterns will shift in areas with winter snow as more precipitation falls as rain and snow melts earlier in the year.

1.5 Impacts on water resources

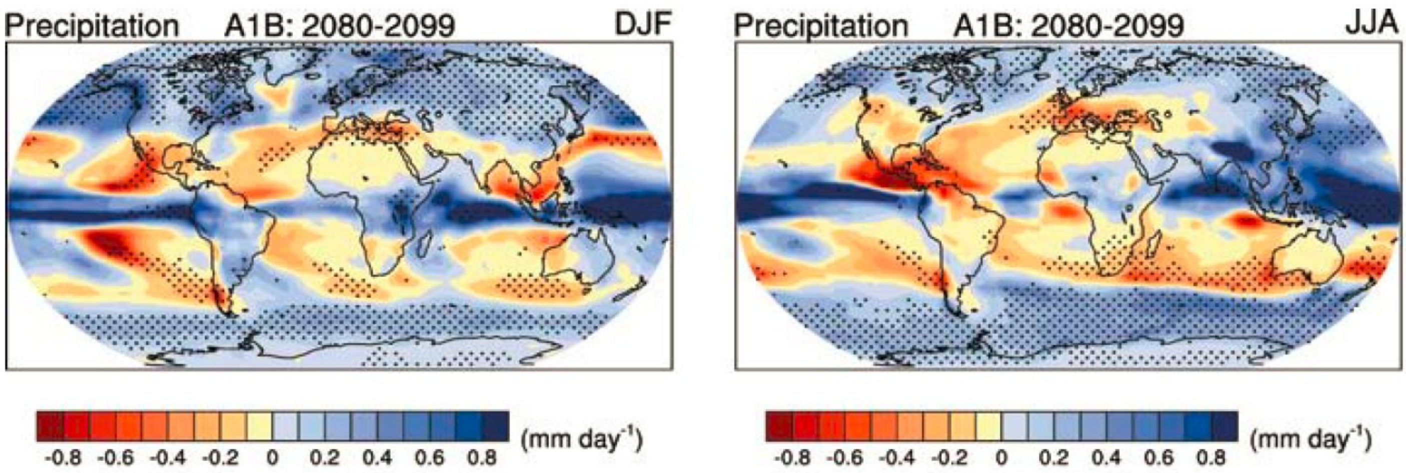


Figure 1.5.1 Projected changes in mean precipitation for December-January-February (left) and June-July-August (right). Projections are averages of 15 simulations associated with the fourth IPCC report (2007). Changes are presented for the SRES A1B scenario and represent projected changes from 1980-1999 to 2080-2099.

are affected by interannual to decadal-scale variations and only a few regions have sufficiently long records to analyse trends reliably. Statistically significant increases in the frequency of heavy precipitation have been observed in Europe and North America.

Evapotranspiration: Potential evapotranspiration is expected to increase in almost all regions of the world. This is because the water-holding capacity of the atmosphere increases with higher temperatures, while relative humidity is not expected to increase significantly. Carbon dioxide enrichment of the atmosphere has the potential to reduce transpiration from plants because the stomata of leaves, through which transpiration takes place, would have to open less to take up the same amount of CO_2. However, if rising CO_2 concentrations lead to increased plant growth, transpiration may increase as a result of increased leaf area. No conclusive findings are available regarding historical evapotranspiration trends.

Soil moisture: Changes in soil moisture are a function of changes in the volume and timing of precipitation and evapotranspiration. Projections of changes in soil moisture are generally consistent with projected precipitation changes. However, soil moisture decreases may occur in high latitudes, despite precipitation increases, because of declining snow cover. Little information is available about long-term trends for historical soil moisture.

Runoff and river discharge: The extent to which climate change may alter river flows depends on changes in the volume and timing of precipitation and on whether precipitation falls as snow or rain. Changes in evapotranspiration may also have impacts on river flows. There is considerable uncertainty about how climate change might affect annual runoff, although climate models suggest that changes may be similar to projected precipitation changes. There is more certainty that climate change will impact the seasonality of river flows in regions where winter precipitation currently falls as snow. Warmer temperatures are projected to lead to decreased spring flows because of reduced or earlier snowmelt, with increased winter flows. These projections are supported by trends in the recent historical record and changes in extremes.

Groundwater: Climate change affects groundwater recharge rates and depths of groundwater tables, though relatively little research has been done on this. As many groundwater reservoirs discharge into and are recharged from surface water, climate change impacts on surface water flows are expected to impact groundwater. Increased precipitation variability, particularly changes in mean precipitation and seasonal changes, may affect recharge rates. Variability may also affect recharge if high-intensity events exceed soil moisture frequencies more often.

Water quality: Rising temperatures are likely to lower water quality in lakes through increased thermal stability and altered mixing patterns. More intense rainfall may also lead to an increase in turbidity in lakes and reservoirs due to soil erosion. In semi-arid and arid areas, climate change is likely to increase salinization of shallow groundwater due to increased evapotranspiration. Due to expected reduced run-off, surface water quality is also expected to decline as concentrations of contaminants increase.

1.6 Impacts on sectors

Climate change impacts on water resources may affect ecosystems; agriculture, land use, and forestry; human health; water supply and sanitation; settlements and intrastructure; and other sectors of the economy including insurance, tourism, industry, and transportation. The following survey summarizes information on sectoral impacts presented in the [fourth IPCC assessment report from 2007](#) as well the opinions of DHI staff.

Freshwater ecosystems: Generally, surface water quality is dependent on nutrient inputs, particularly N and P. Climate change will likely affect water quality through changes in nutrient input both directly and indirectly: indirectly through e.g. changes in the type of cultivated crops, cultivation practises and use of fertilizer; and directly through the predicted changes in precipitation that directly affects the runoff regime.

Furthermore, changes in temperature will work as a stress factor for some ecosystems and may affect the nutrient dynamics through complex ecosystem processes. These two factors: Changes in nutrient loadings and temperature may accelerate the degradation processes of natural habitats.

Increased temperature may change the autotroph and heterotroph balance in the water bodies and especially in lakes and reservoirs. This may lead to changed balance between CO2 consumption and CO2 production and give negative feedback increasing climate changes. It may also accelerate the production of other greenhouse gasses such as methane.

Other important areas that will be impacted are the transition zones between land and surface waters – areas like wetlands and riparian zones. These areas are important with respect to nutrient turnover and are will be affected by both temperature increases and hydrological changes.

Other water quality issues that may be affected by climate change include type and amount of dissolved and adsorbed pesticides and their breakdown products as a result of changes in types of cultivated crops together with a general increase in temperature favouring new types of pests.

Forests, savannahs, and grasslands: If climate change increases drought frequencies, wildfires may increase in size and frequency. Increasing drought frequencies may also induce stress in trees, leaving them more susceptible to fires, pests, and disease. There is evidence that grassland and savannah productivity is highly sensitive to precipitation variability, and that rainfall variability may have greater impacts on productivity than rainfall amount.

Agriculture and livestock: Water plays a crucial role in food production. More than 80% of agriculture is rain-fed, dependent on precipitation to meet evapotranspiration demand and maintain soil moisture. In areas where precipitation is already limited by climate, agricultural production is vulnerable to climate change (figure 1.6.1). Although irrigated land represents only 18% of total agricultural land, the contribution of irrigated land to total agricultural production is much greater, and irrigated agriculture could also be vulnerable to climate change if surface water and groundwater supplies are diminished.

There is some evidence that increasing CO_2 concentrations may reduce crop water use through increased leaf-level water use efficiency. However, these efficiency gains may be offset by increased evaporative demand under higher temperatures. There is also uncertainty about how the combined impacts of elevated CO_2 concentration and increasing temperatures

60-second summary...

- Climate change impacts on water resources may affect ecosystems, agriculture, human health, water supply, human, settlements and infrastructure.
- Many of the potentially severe impacts are related to projected changes in climate variability and increases in flood and drought frequencies.
- Significant impacts are possible in arid and semi-arid regions, which may become drier in the future.
- In catchments where snowmelt is a significant part of the water balance, seasonal runoff patterns may change as snow melts earlier in the season and more precipitation falls as rain instead of snow.

1.6 Impacts on sectors

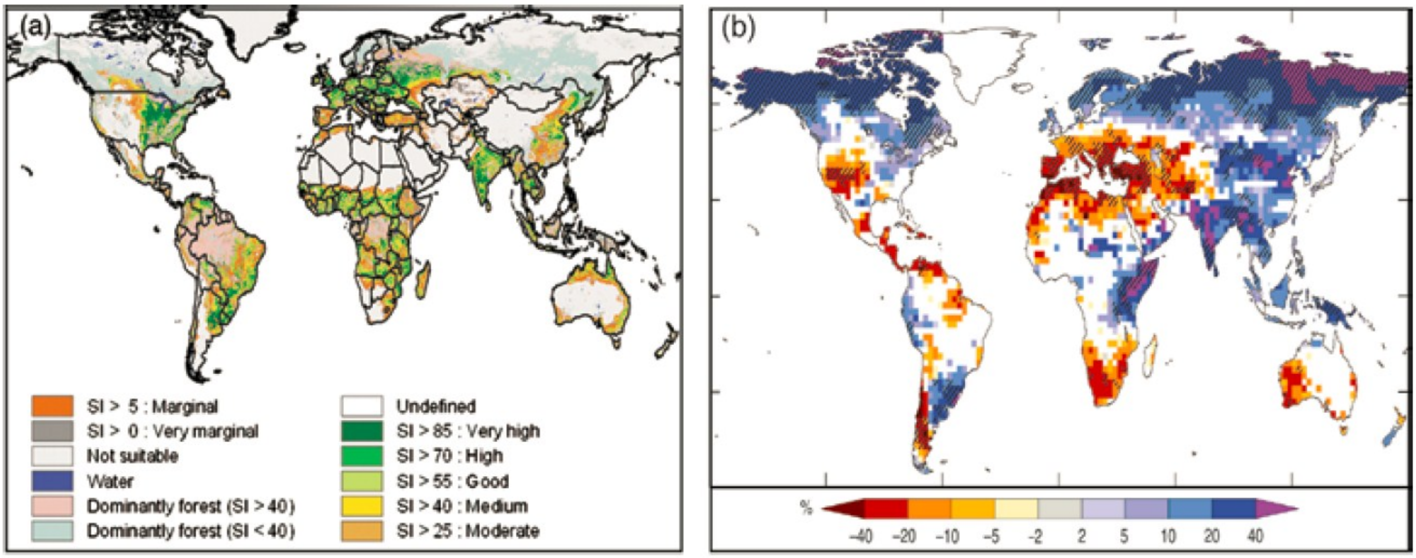


Figure 1.6.1 Suitability indices for rain-fed agriculture (left) and projected changes in runoff (right). The crop suitability index (SI) is based on Fischer et al. (2002). Projected changes in runoff are estimates of changes between 1980-1999 and 2090-2099. Projections represent the mean of an ensemble of climate models associated with the fourth IPCC assessment report (2007).

might affect crop yields.

There is evidence that warming in high-latitude regions would benefit crop yields. However, warming in areas that are seasonally dry would probably have a negative impact on yields. If the frequency of extreme rainfall events increases, crop yields could be reduced because of excessive soil moisture, inundation, and soil erosion.

In regions with irrigated agriculture, climate change may have impacts due to changes in the spatial and temporal distribution of streamflow. In catchments where snowmelt is a significant contributor to the water balance, early snowmelt may cause earlier spring flooding with a reduced peak, and lead to a summer irrigation water shortage.

Many of the world's rangelands are located in semi-arid areas that are vulnerable to water deficits. Increased climate variability and drought frequencies may lead to livestock losses. There is some evidence that mild warming may increase grassland productivity in high latitude regions.

Human health: Increases in flood and drought frequencies and reductions in mean precipitation have the potential to impact human health. If flood frequencies increase, human health may be impacted by sewage contamination during flood events. If drought frequencies increase, water quality in rivers may suffer because of reduced dilution of pollutant concentration, with potential health impacts. In areas with limited access to improved water supplies, such as in sub-Saharan Africa, long-term declines in water availability may make it more difficult to extend improved water supplies.

Water supply and sanitation: Climate change could have substantial impacts on water services. This impacts could include: reductions in water availability in glacier-fed basins; surface water quality impacts from temperature rises; salinization of coastal aquifers from sea-level rise; changes in seasonal water availability from shifts in precipitation patterns; complications to reservoir operations arising from increases in intra- and inter-annual variability; salinization of groundwater as a result of increased evapotranspiration; and more frequent floods and droughts.

Settlements and infrastructure: Changes in water availability, water quality, precipitation characteristics, and the likelihood and magnitude of flood events may have significant impacts on human settlements and infrastructure. The locations most at risk of water supply problems include small islands, arid and semi-arid developing countries, regions supplied by rivers fed by glacial melt and/or seasonal snowmelt, and countries with a high proportion of coastal wetlands and coastal cities. Increased flood frequencies may have impacts on transportation infrastructure including localized street flooding; flooding of subway systems; and flood and landslide-related damages to bridges, roads, and railways. Climate change could also have impacts on hydropower production and cooling water availability for thermal power plants.

1.7 Climate change and other drivers

Can we consider water resources management and climate change in isolation?

Many of the impacts of climate change will be felt through water resources (IPCC 2007). However, the challenges faced in water resources management and the options for adapting to climate change must be considered within a broader context across a range of sectors. For example, climate mitigation policy, land use management, food and energy supply, and water resources are all linked and have impacts on each other (Waughray 2011).

What are the main drivers in water resources management, and is climate change one of them?

Drivers which affect water resources can be broadly cate-

Table 1.7.1: Drivers affecting water resources

Drivers	General impacts	Trends in drivers	Impacts of climate change on driver
Demographic: population dynamics (growth, age distributions, urbanization and migration).	More people and at higher concentrations increase water demand, and the potential for pollution.	Still rapid population increase in developing regions. In 2009, over half of the world's population became urban.	Increased water scarcity, flooding, and sea level rise may alter and accelerate migration patterns.
Economic: growth	Both local and more far-reaching impacts. Increasing global trade in goods and services can relieve water stress in some areas but aggravate it in others through 'virtual water', particularly through agricultural products.	Rapid economic development in some regions, including populous regions.	Climate variability and extreme events can have significant negative impacts on economic growth.
Social: poverty, education, value systems, and lifestyle and consumption patterns.	Complex combination of +ve & -ve impacts. Poverty, education and value systems affect perceptions and attitudes towards the environment. Changes in lifestyle and consumption patterns are one of the principle drivers of change.	Increases in education and awareness offset by increases in consumption patterns globally.	Complex. Climate change likely to exacerbate poverty, but impacts may lead to greater education and awareness.
Technological innovation:	Can have both +ve & -ve impacts, sometimes simultaneously.	One of the most unpredictable drivers. Can create rapid and unexpected changes, both in pressures and solutions.	Climate change will be a major driver of technological innovation and transfer, brought about by the need to mitigate and adapt to climate change.
Policies, law, finance	Effective policy and legal frameworks are an essential ingredient to reducing pressures on water resources, but policies from other sectors may have negative impacts on water resources if not adequately integrated.	Generally improving, including better integration across sectors, though progress is slow in some cases.	Policies for mitigating and adapting to climate change may also have impacts on water resources. Climate change can stress political systems by transferring resources from other areas to tackle climate change.
Climate change	Will primarily affect water resources availability, as well as quality (section 1.5) and extremes (see also IPCC sec. 3.5).	Expected to accelerate in coming decades.	-

1.7 Climate change and other drivers

Uncertainty in future society

Uncertainties in the nature of future society such as demographics, politics, socioeconomic and technical developments will not only affect the future trajectories in emissions of greenhouse gases which drive climate change but also the ways in which climate change will be managed and how it will impact society. Furthermore, these uncertainties in societal change will have direct impacts on water resources, irrespective of the impacts of climate change.

gorized as shown in table 1.7.1, though these drivers are closely linked (table primarily adapted from WWAP 2009).

As well as being a driver in its own right, climate change is also expected to impact other drivers as shown in table 1.7.1.

Which drivers are the most relevant for me?

Drivers are generally closely related and cannot be considered in isolation. The relative importance of drivers depends very much on local context, though the international context should also be considered. Generally, the main drivers for water use are population and economic development, as well as changes in diet, with climate change often exacerbating problems. There is also a trend towards prioritization of domestic and industrial supply over agricultural supply, whilst trying to accommodate environmental demands in some places.

The dominant non-climate-change-related drivers of future irrigation water use are: the extent of irrigated area, crop type, cropping intensity and irrigation water-use efficiency (IPCC 2008).

How does climate change compare to other drivers?

Overall, it is important to consider climate change together with other drivers, as well the impact on other drivers, depending on how detailed the analysis needs to be. Model studies show that in some areas land-use change will have relatively low impact compared to climate change (e.g. Rhine basin, south-east Michigan, Pennsylvania and central Ethiopia), whereas in others land-use change and climate change are expected to have similar impacts to water availability (e.g. south-east Australia, southern India) (IPCC 2007e). A global study compared the relative impacts of climate change and population and economic development on the ratio between demand and availability compared to contemporary conditions (Vörösmarty et al 2000, figure 1.7.1). It showed that globally, population and economic growth are likely to have a more widespread impact than climate change only, but that impacts

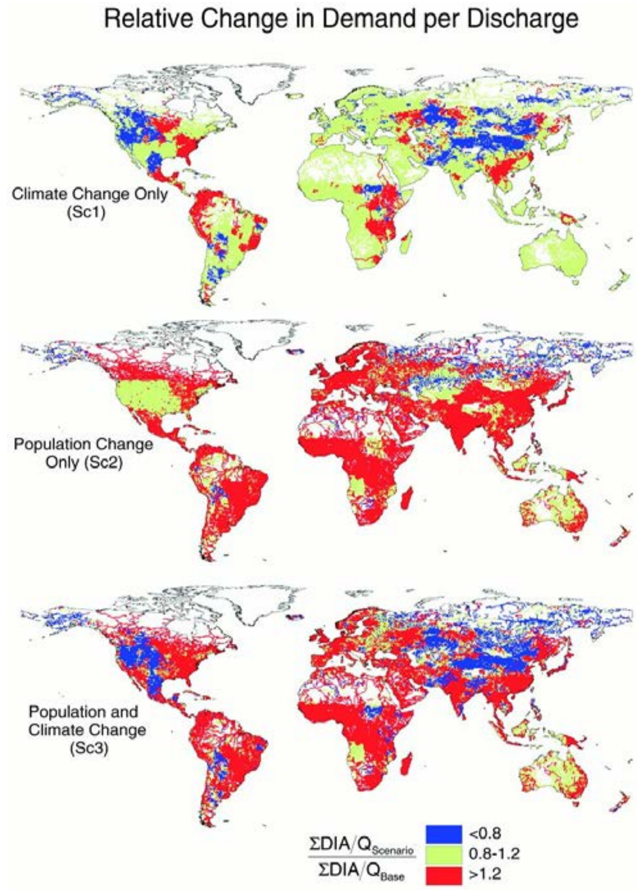


Figure 1.7.1: Relative change in demand per discharge compared to contemporary conditions. Blue areas show a reduction of more than 20%, red shows an increase of more than 20%. Source: Vörösmarty et al 2000

in some places will be very different when climate change is taken into account. This figure is used for illustrative purposes and should not replace more local and recent assessments.

For more information on how to do an initial screening of drivers and how to compare the impacts of climate change with the impacts of these drivers, see section 1.9.

60-second summary...

- Climate change is just one of a range of drivers, including population growth and migration, and economic development.
- Climate change has an impact on most drivers, often accelerating their impacts.
- The relative 'importance' of climate change compared to other drivers, and the impacts of climate change on other drivers, depends on the local situation.

1.8 Preliminary estimate of change in climate

1.1 Introduction to defining the problem
1.2 Flow chart for defining the problem
1.3 Types of climate problem
1.4 Identify objectives and
1.5 Impacts on water resources
1.6 Impacts on sectors
1.7 Climate change & other drivers
1.8 Preliminary estimate of change
1.9 Vulnerability assessment
Climate change challenges

Which climate variables could be considered in a preliminary assessment?

Climate variables that could be included in a preliminary assessment of change can be grouped into the following categories: primary, synoptic, compound, and proxy climate variables. Primary variables are direct outputs from climate models like precipitation and temperature. Synoptic variables are also direct outputs from climate models but are associated with larger spatial scales. Compound variables are functions of combinations of primary variables. Proxy variables are dependent on combinations of primary variables, compound variables, and other factors that are not directly linked to the climate system. A list of variables by type is presented in Table 1.8.1. Synoptic-scale climate variables are simulated more reliably by climate models, but are more difficult to relate to water resources impacts. Proxy variables may require the use of impact models such as rainfall-runoff and soil water balance models in order to characterize climate change impacts.

Which characteristics of climate variables should be considered in a preliminary assessment?

It is important to be clear about the statistical characteristics of variables under consideration and the different ways in which variables may change. Characteristics to consider in a preliminary assessment include magnitude and direction; the statistical basis of change; averaging or sampling period; and joint probabilities of events and variables. A list of important characteristics to consider is presented in Table 1.8.2.

Why is it important to think about characteristics of variables in a preliminary assessment?

Different characteristics of climate variables can convey different information about the nature of climate change. The impact of a change in magnitude

Table 1.8.1: Climate variables to consider in a preliminary assessment of change (adapted from Willows 2003)

Variable type	Variables to consider
Primary	Carbon dioxide, sea level, temperature, precipitation, wind, cloud cover, dry periods
Synoptic	Weather types, pressure, pressure gradients, storm tracks, ocean climatology
Compound	Humidity, evapotranspiration, storm surge levels
Proxy	Runoff, soil moisture

Table 1.8.2: Characteristics of climate variables (adapted from Willows 2003)

Characteristic	Examples	Notes
Magnitude and direction	Change, rate of change	Important to be clear about statistical basis of changes in magnitude (see next row)
Statistical basis of change	Average, cumulative value, measures of variability, measures of frequency and extremes	Changes in averages, variability and extremes can all impact water resources in different ways, so important to consider all potential changes.
Averaging or sampling period	Instantaneous, hourly or sub-hourly, daily, monthly, annual, decadal or longer	Different signals may be visible at different time scales. For example, an annual time scale will not provide information about changes in seasonal precipitation patterns.
Joint probability events and variables	Consecutive occurrences, coincident or joint occurrence with other variable(s)	An example could be the probability of joint occurrence of river flooding, sea level rise, and a storm surge in a coastal area.

1.8 Preliminary estimate of change in climate

of precipitation can have a different meaning depending on the statistical basis of the change. For example, although average precipitation may not be projected to change, variability may be projected to increase or decrease. Changes may also have different meanings depending on the averaging or sampling period associated with the change. To continue the example of precipitation, although precipitation may not be projected to change on an annual basis, there may be significant changes in the seasonal timing of precipitation that affect how water will be managed. It is also important to consider joint events, such as the joint impact from river flooding, sea level rise and storm surge in a coastal area.

How can I conduct a quick analysis?

Options for quick analyses are limited to looking at change factors from Global Climate Models (GCM)(section 4.4) and looking at published changes from previous studies, national climate change impact and adaptation plans or regional values in IPCC reports (table 1.8.3).

Change factors

A change factor is the difference in the mean monthly value between current climate, typically the period 1961-1990, and a given time period, expressed either as a relative or absolute change. Change factors describe the average change in monthly values and do not provide any information about changes in variability and extremes or any other characteristics of the variable and hence may be of limited use. Most often changes in precipitation are expressed as relative changes e.g. 1.08 denoting an 8% increase in rainfall. Temperature changes are often expressed as absolute values e.g. 2.3 pointing to 2.3°C increase in temperature.

Published values

To complement results from change factors or for studies which require information other than changes in monthly means, published values may be available for your region from the IPCC or local sources.

IPCC reports which can be found on the IPCC website often contain values for all regions of the globe though these must obviously be used with caution as your study site may not be representative of the region it lies within.

There may also be national or regional studies by national meteorological institutes or research organisations which may point to the direction or scale of the climate change projected.

For more information on climate change screening see Olhoff & Schaer 2010. Before proceeding with a full-blown assessment of climate change, it may be useful to conduct a rapid preliminary assessment of the projected changes for your study area.

60-second summary...

- Preliminary estimates of changes in climate variables are available from the IPCC (as change factors from GCMs, or special reports) and national meteorological institutes and research organizations.
- Changes in precipitation and temperature are most widely available, but other variables could be considered.
- It is important to consider the characteristics of the projected climate variables, as this affects how the changes can be interpreted.

Table 1.8.3: Examples of data available for preliminary assessment of changes in climate variables

Source of information	Variables available	Statistical basis of change	Averaging or sampling period
Change factors from global and regional climate model projections	Precipitation, temperature	Average monthly values	Average monthly values for a reference period (usually 1960-90) are compared to a future 30-year period.
IPCC special report on extremes (2011, 2012) http://ipcc-wg2.gov/SREX/	Precipitation, temperature, dry days, soil moisture.	Exceedance probability (daily), annual maxima.	Values over a 20 year reference period (1981-2000) are compared to two future periods, 2046-2065 and 2081-2100.

1.9 Vulnerability assessment

Vulnerability to climate change exists almost everywhere, but the level of vulnerability varies significantly depending on the extent of expected impacts and the capacity to adapt to change.

What is a vulnerability assessment?

A vulnerability assessment is a preliminary assessment of the extent to which the system of interest is vulnerable to changes to climate variables (Table 1.8.1). Because of the uncertainties associated with preliminary assessments of climate change, it will not be possible to develop a conclusive assessment of vulnerability at this stage. However, this exercise is useful for identifying priorities for further investigation.

What is the difference between sensitivity and vulnerability?

The term sensitivity refers to the extent to which a system would be affected by climate change. Vulnerability refers to the extent to which a system would be unable to cope with adverse impacts from climate change. Therefore, vulnerability is a function of both sensitivity and adaptive capacity.

What method is recommended for vulnerability assessment?

The [UK Climate Impacts Program technical report on decision-making under uncertainty](#) (Willows, 2003) outlines a checklist approach for vulnerability assessment. This approach is presented here. While the checklist approach is fairly simple, it provides a useful structure for ensuring that all potential impacts have been considered and for developing preliminary estimates of vulnerability.

How can vulnerability to changes in climate variables be assessed?

After a checklist of change estimates has been assembled, vulnerability to changes in climate variables should be assessed qualitatively. At this stage, the assessment should be based on expert judgment and the experiences of stakeholders. For each projected change in a climate variable, experts and stakeholders should provide qualitative assessments of the vulnerability of the system of interest to the change. They should also provide an assessment of their level of confidence in the link between the change in each climate variable and the impact on the system. This should not be a judgment about the level of certainty associated with climate change projections but rather about the link between climate change and system impacts. Other drivers that may affect the system of interest should also be identified in order to develop priorities for more detailed analyses. Relevant drivers for water resources systems are listed in [Table 1.7.1](#).

The checklist method for vulnerability assessment

1. Obtain information on projected changes in climate variable from the IPCC, global and regional climate models, and other published reports by meteorological institutes and research organizations.

2. Identify the characteristics of the variables and predicted changes, including the magnitude of change, the statistical basis of change, the averaging or sampling period, and any information about joint probabilities (Table 1.8.2).

3. Estimate the sensitivity of the project or system of interest to the projected changes. This is a qualitative assessment, done through consultation with experts and stakeholders.

4. Estimate the level of vulnerability of the project or system of interest. In other words, if the project or system is thought to be sensitive to projected climate changes, is there adaptive capacity to cope with these impacts? This should also be a qualitative assessment.

5.Estimate the level of confidence in the link between each projected change and the vulnerability of the project or system. This is not a judgment about the level of confidence in projected climate changes but rather about the link between climate change and system impacts.

2. Identifying options and assessment criteria

2.1 Introduction to identifying options and assessment criteria

This section is primarily relevant for climate change adaptation assessments, where the identification and comparison of options to adapt to climate change is required (section 1.3).

A flow chart is provided to guide the reader through the steps for identifying options and developing assessment criteria (section 2.2). It then provides an introduction to flood mitigation options (section 2.3) and water scarcity adaptation options (section 2.4). Section 2.5 describes how to undertake an initial screening of the long-list of options to identify which options require more detailed assessment. Section 2.6 discusses the development of criteria (indicators) for decision-making.

What is adaptation?

Adaptation in the context of climate change is the act of changing current practices to reduce the potential negative impacts from climate change, and should also consider impacts of other drivers (section 1.7). Adaptation options or measures are specific steps taken to reduce the impacts of climate change (examples are given below). Adaptation should inherently be robust to deal with multiple uncertainties.

What is adaptive water management?

Water resources management is a complex issue, with climate change being just one of many factors (Section 1.7). Adaptive water management addresses uncertainty and complexity by increasing the capacity to learn while managing. This is achieved through an iterative process of improving assessment techniques, management policies and adaptation options in response to monitoring outcomes (NeWater 2009). See section 5.7.

More information on adaptive water management can be found on the NeWater website.

Why is adaptation necessary?

Challenges posed by climate change can be categorized into management challenges and infrastructure design challenges. Both water resources management and design have only recently started to take climate change into account. Climate change is likely to exacerbate existing threats such as flooding and water scarcity, and is likely to add pressures on all sectors, including the environment (sections 1.5 & 1.6). Water infrastructure has been designed for 'current' climatic conditions and thus may be inadequately designed for future conditions. Selecting appropriate adaptation measures is critical to reduce vulnerability.

Many adaptation options are considered part of good water resources management and should respond to a number of drivers, not just climate change (section 1.7).

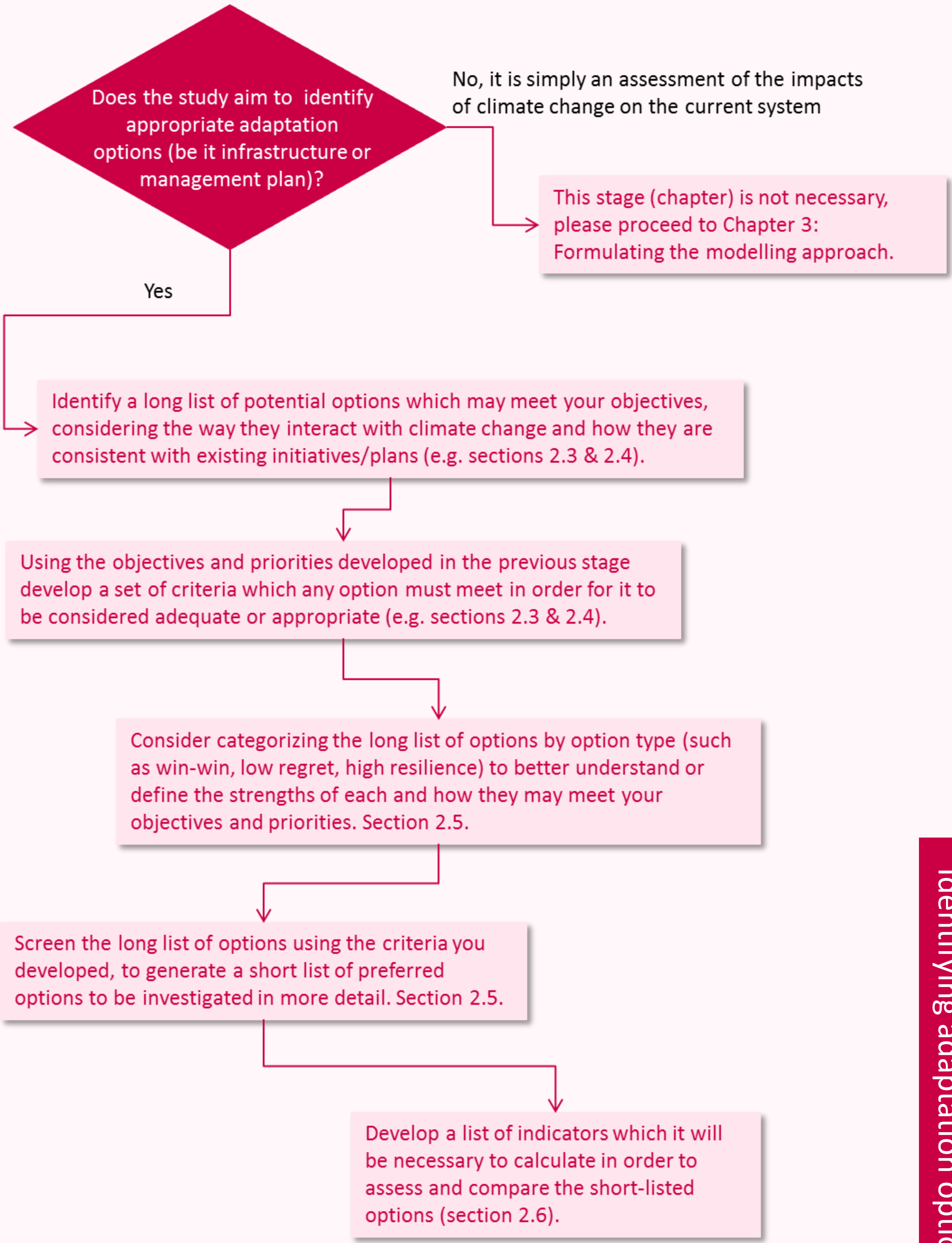
What adaptation options are available?

There are numerous adaptation options available, ranging from local to national to regional in scale, from sector-specific to cross-sectoral, including demand and supply management, 'softer' management options, and 'harder' infrastructure options. Examples of adaptation options are discussed in sections 2.3 and 2.4. However, a list of potential adaptation options would be almost endless. Therefore it is recommended that the reader refers to available literature relevant to their field of interest. For more information, see analysis by sector prepared for background paper to UNFCCC (2007). See also the TNA Guidebook series (UNEP-Risø 2011) on technologies for climate change adaptation within different sectors, and FAO (2008) for vulnerability and adaptability in agriculture.

60-second summary...

- Most adaptation options are already an integral part of current good practice in water resources management.
- Adaptation should be flexible and robust to deal with multiple uncertainties.

2.2 Flow chart for identifying options and assessment criteria



2.3 Options for flood risk

How is flood risk changing?

Flood risk is increasing with increases in flood damage as a result of increasing development and population. This can be exacerbated by changes in land use change upstream in a river system (eg. deforestation) and downstream (urbanisation) with less infiltration and more runoff. In many cases it appears that climate change will increase this risk. Climate model simulations indicate climate change will lead to increases in intensity and variability of rainfall as a result of increases in either the frequency of heavy precipitation or the total precipitation during heavy precipitation events. The complex relationship between rainfall and the processes generating runoff, their timing and the effects of land use change, make it difficult to make general statements about the impact of these changes on future changes in runoff and flooding. The vulnerability to changes in flooding needs to be evaluated for each case.

The most sustainable way to reduce this increased risk is to move people and assets out of the flood plain, construct flood protection structures for flood-prone areas or give the river room for flooding. Existing protection structures and systems are designed against a flood with a certain statistical return period and may fail more frequently under climate change.

Flood management is a well-established discipline and there are many potential flood protection measures. Traditionally these are split into structural and non-structural measures (Table 2.3.1); however, current flood protection practice often relies on integrating different types of measures. Simply raising embankment levels may move the flood problem further down the river and increase the risk of disastrous flooding. And even if the embankments levels are raised, there is always a chance that this level will be exceeded so the "residual" risk must be managed somehow.

What are the main flood mitigation options?

The list of potential flood protection measures and therefore flood adaptation measures is enormous; however, broadly speaking these can be categorised into:

1. Increasing natural retention and storage capacity or making room for water
2. Strengthening existing or construction of new protection structures
3. Building resilience
4. Forecasting, early warning, and preparedness.

1. Increasing natural retention and storage capacity or making room for water

Flood impacts at downstream locations can be reduced by increasing retention and storage capacity upstream by creating water retention areas. In rural areas this can be temporary storage in low-lying farmland, riparian wetlands, ditches and ponds or by river restoration. In urban areas, this can be recreational areas, sport fields, etc. where it is less costly and damaging to accept floodwaters. Polders and flood control reservoirs are widely used particularly in Europe and are often contained by dikes and/or dams. This can also be achieved by flood diversion channels that move water to other channels or storage areas.

Types of measures that make room for the river by increasing the discharge capacity of the floodplain include deepening of river meadows, displacement

Table 2.3.1: Examples of structural and non-structural flood adaptation measures

Structural	Non-structural
Dikes	Zoning controls
Polders	Regulation of construction on flood plains
Flood Diversion channels	Flood proofing
Real time monitoring networks	Flood forecasting
Control structure e.g. gates	Optimization of reservoir and structure operations
Pumps	Flood preparedness
Reservoirs	Public Educations
	Flood insurance

2.3 Options for flood risk

of the embankments further away from the river or removing natural or man-made obstacles.

The protection and/or restoration of 'natural infrastructure' (e.g. wetlands, dunes), can have significant positive impacts on flood mitigation, and may be considered as part of a suite of options (Smith and Barchiesi 2009).

2. Strengthening existing protection or construction of new protection structures

Existing protection structures such as dikes or embankments will continue to play an important role in flood protection, particularly in high risk, high value areas. In light of expected climate change the acceptable design criteria for such areas should be revisited to determine whether strengthening or raising of embankments is needed. The capacity of weirs and sluices might be increased to increase storage capacity. New protection structures should include climate change at the design stage. In all cases, the simplest approach is to develop a climate factor for design. Thus for embankments designed for a particular design flood, (e.g. the 100-year event), it may be estimated from climate projections that this design event will increase by 20% under climate change in 2050. Consequently future designs will be rated for a 20 percent higher discharge or planned so that they can be upgraded if needed. See section 4.9 for more information on how to develop projections of extremes for design purposes.

An alternative more cost-effective approach may be to include more flexibility in the design to allow staged upgrading of structures or combining these with measures that provide more room for the river.

3. Building resilience

Recognising that homes, industry, transport and other infrastructure can never be fully protected, there are measures that can be put in place that can minimise the damage and speed up the repair time, i.e. flood resilience. At a local level this can range from putting flood guards (flood proofing) on the main doors, to moving valuables upstairs during a flood. The number of such flood proofing options is enormous. Flood preparedness, for example, simply involves being aware of how to best be forewarned, how to act during a flood, developing community programs, etc. Flood preparedness and resilience can be encouraged by developing community programs or providing financial incentives. Proper planning can identify flood-prone areas and introducing regulations to discourage or minimize development in such flood prone areas.

4. Forecasting and early warning systems.

Flood forecasting and early warning has a number of advantages with respect to flood protection. Forecasts are used for initiating emergency contingency plans, operating of structures and flood protection reservoirs, or the evacuation of affected areas. Forecasting also permits more effective operation of water resource systems such as water supply reservoirs, cooling water supply, hydropower schemes, water transfers and diversions. Even when flood protection infrastructure is in place, flood forecasting can be used to manage the residual risk during the most extreme events.

Flood forecasting and warning represents a low-regret measure, as the costs are low when compared to the benefits and the costs are often low when compared to structural measures such as the construction of reservoirs or embankments. In addition, the environmental impact of implementing flood forecasting and warning systems is considerably less than many other flood control measures.

DHI has a number of tools and services available for modelling these four broad adaptation measures including MIKE FLOOD and MIKE 11 (see DHI Tools section).

60-second summary...

- Flooding is expected to increase in intensity and frequency in many regions.
- Flood mitigation options themselves are similar to those without the impacts of climate change, but the selection and design of options need to increase resilience under uncertainty.
- An effective adaptation strategy may include both structural and non-structural measures.

2.4 Options for water scarcity

How is climate change likely to affect water scarcity?

In the coming decades, total run-off is projected to increase by 10-40% at high latitudes and in some wet tropical areas (though with greater seasonal variability), and decrease by 10-30% in some dry regions (IPCC 2007c). Groundwater recharge is expected to decrease significantly in some already water-stressed arid and semi-arid areas (IPCC 2007c). It is not just the total quantity of available supply that is likely to reduce in some areas, but also the timing is likely to be altered. Water scarcity is not just a supply issue, but also a question of increasing demand. Water scarcity already affects several sectors (agriculture, domestic, industry, and environment), and climate change is likely to exacerbate existing problems (IPCC 2007c).

What are adaptation options for planning for water scarcity?

There is a large range of supply and demand side adaptation options for water scarcity (see table 2.4.1, as well as FAO 2008, UNFCCC 2007, and UNEP-Risø 2011), most of which are part of good practice water management. A mixture of options is usually required to boost resilience. Options can be sector-specific, but as measures taken for a particular sector are likely to benefit other sectors, benefits and costs should be shared between sectors. Part of the solution for addressing water scarcity is the development of efficient allocation systems, with users being allocated various priorities. MIKE Basin, coupled with DHI's Decision Support System (DSS) (see DHI Tools section), is an ideal tool for developing allocation strategies and trialing benefit-sharing options. The DSS includes an economic component that allows for an analysis of allocating water to highest-value users, as well as altering users to generate more value from the system. Valuing domestic and environmental water needs is complex and requires considerable expertise.

The next sub-sections provide more detail on the likely impacts and adaptation options for water scarcity for sectors. Modelling approaches and tools for assessing different options are discussed in section 3. Further information on sector impacts and adaptation (section 1.6). Detailed analysis by sector prepared for background paper to UNFCCC (2007). See also the TNA Guidebook series (UNEP-Risø 2011) on technologies for climate change adaptation within different sectors, and FAO 2008 for vulnerability and adaptability in agriculture.

60-second summary...

- Water scarcity is expected to become more severe, particularly in already arid and semi-arid regions.
- Water scarcity mitigation options themselves are similar to those without the impacts of climate change, but the selection and design of options need to increase resilience under uncertainty.
- An effective adaptation strategy may include a mix of supply-side and demand-side measures, both structural and non-structural.

Table 2.4.1: Supply and demand side adaptation options (IPCC 2008)

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

Identifying adaptation options

2.4 Options for water scarcity

Impacts and options: Water and Agriculture

Agriculture is extremely vulnerable to climate change, which is expected to impact rain-fed, irrigation and livestock agriculture. However, not all impacts will be negative, with regional differences (section 1.6).

Adaptation options can be categorized as:

- Shifts in management practices (e.g. earlier planting dates
- Changes in enterprises employed at a particular site (e.g. adoption of more drought tolerant crops)
- Adoption of new technology involving direct capital investment and/or practice improvements developed by research (addressing plant/animal species or varieties, genetic improvements, water retaining or application efficiency enhancing practices, improved tillage, better methods of fertilization, pest management practices etc.) (McCarl 2008).

See also FAO 2008, IFPRI 2009, and UNEP-Risø 2011.

Impacts and options: Water and Energy

Water and energy are linked: water supply and treatment requires energy, and energy production requires water. The energy sector accounts for about 40% of water withdrawals in the USA and Europe, and in developing and emerging economies, energy demand is expected to increase by a staggering 84% between 2007 and 2035 (DHI 2010). The expected impacts on the hydrological cycle (section 1.5) also pose a significant risk to energy production, predominantly through less reliable water supply. Furthermore, climate policy can have significant impacts on water resources. For example, climate mitigation policies such as increasing the proportion of biomass-fuelled electricity and hydropower are likely to increase water demand and alter river flows.

More variable water supply may make hydropower more vulnerable to climate change. Decreased snow cover and retreating glaciers will reduce the natural regulation in some basins and lead to the demand for expensive extension of artificial storage to maintain production. Run-of-the-river schemes may be particularly vulnerable to increased variability.

Adaptation options include:

- Increase water and energy efficiency
- Shift to less water-dependent renewable sources of energy (e.g. wind, solar PV).
- Use cooling systems that require less water (e.g. hybrid and dry cooling)
- Use alternative water sources for cooling (e.g. treated municipal and industrial waste water).

Impacts and options: Water & urban areas

Climate change is expected to impact negatively on reliable water supply in many areas (section 1.5) (Hunt and Watkiss 2011).

Adaptation options include: demand management, water-use efficiency, rainwater harvesting, water storage and conservation techniques; water re-use; desalination (Lankao 2008).

Impacts and options: Water & the environment

The environment typically receives a lower priority than other sectors. Of all ecosystems, freshwater ecosystems will have the highest proportion of species threatened with extinction due to climate change (Millennium Ecosystem Assessment, 2005). Climate change and other drivers are expected to decrease water resources availability for the environment.

There are some adaptation options available to address this decreasing trend. On the one hand these partly involve the recognition that all sectors compete for scarce water resources and that measures taken to mitigate water scarcity in other sectors can lead to increased water availability for the environment. On the other hand there are some policy options available such as formally allocating a proportion of flows to the environment (i.e. reducing possible withdrawals). This has been implemented successfully in some locations, including the state of Victoria in Australia, which included environmental water entitlements as part of the Water Act as early as 1989 (VicGov 2011).

2.5 Screening options

Having derived a long list of options as discussed in previous sections, it is important to undertake an initial screening of options from this long list in order to narrow down to fewer options which can be assessed in more detail. All options should come under one or more of the four categories in table 2.5.1. Options falling under more than one category are likely to be preferable. Guidelines for initial screening of options are shown in the grey box on the following page.

As climate change is usually only one of many drivers impacting water resources (section 1.7), most options should already be considered in the context of existing climate variability. For example, water conservation, demand management and efficiency measures reduce stress on all sectors, including the environment, and reduce vulnerability to predicted changes, and are likely to be consistent with existing initiatives by municipalities, irrigation districts and government. So while the options themselves may not be particularly new, the importance of implementing them is likely to increase under climate change. Many countries are working on integrating climate change policy within regular planning cycles by establishing appropriate law and policy (UNFCCC 2008).

Table 2.5.1: Adaptation option categories (LUC 2006)

Adaptation option category	Symbol	Description
Win / win		Win / win measures deliver multiple benefits e.g. for economic development or wider sustainability as well as adapting to climate change. E.g. increasing irrigation efficiency requires less energy for pumping and also means lower operational costs.
No / low regrets		No / low regrets measures deliver benefits now and in the future whatever the extent of climate change. They may be low cost but have the potential of delivering high benefits. No / low regrets measures do not rule out options for further adaptation in the future.
Flexible		Flexible measures are part of an adaptive management approach—a sequential process of making the best decision at each stage, without constraining options for further adaptation in the future.
High resilience		High resilience measures provide the ability to prevent or recover quickly from climate change impacts (e.g. building which are designed to cope with flooding of basements).

2.5 Screening options

Are there any methods for choosing which adaptation options to assess in more detail?

Here we consider an initial screening of adaptation options, rather than a detailed comparison of options, which is discussed in section 5. There are a range of methods for undertaking an initial screening of options, though none are definitive. Essentially they involve a list of criteria (questions) against which to undertake assessment of options (see grey box).

Relatively low cost, demand side win/win options (e.g. those which should be implemented as part of good water resources management practice) are likely to be prioritised. Major infrastructure projects are likely to be more complex, and carry more risk. They are likely to be expensive, can increase vulnerability (by promoting maladaptive behaviours), have the potential for significant environmental impacts, and can represent a form of subsidy. Therefore, in terms of the near future (and perhaps even the long-term), their benefits need to be carefully weighed up against their costs.

For more detailed analysis of options see section 2.6 and chapter 5.

Working with Initial Screening of Options

This method can be used to relatively quickly screen available options and select suitable ones for further assessment, without having to use quantitative evaluation techniques (e.g. benefit–cost analysis, multi-criteria evaluation).
The basic method is to prepare a list of criteria against which to make a quick assessment of whether or not it is worth considering the options further.

Below is a list of criteria that may be adapted for any given project or planning cycle, dependent on specific needs and objectives.

- Win/win; No/low regrets; Flexible; Resilient (see table 2.5.1)
- Positive environmental impacts (current or potential)
- Politically acceptable
- Cost effective
- Feasible
- Equitable (promote participation and equal access to opportunities and benefits among men and women, as well as being pro-poor).
- Effective
- Sustainable
- Synergies with national/international or sectoral plans
- Potential for up-scaling/replication;
- Immediate impact / response to urgent needs.

To this list should be added a selection of the criteria developed as described in section 2.6. However, not all criteria need necessarily be used. A short-list of criteria can be used for the initial screening.

It is recommended that a table be created as shown below and a qualitative description is made of how each option addresses each criteria. Options should always be compared to the 'do nothing' option. The number and range of individuals involved in creating this table depends on the size of project or scale of the planning process. The inputs are likely to be based on the expertise and experience of the individuals involved rather than more complex studies. Based on how well each option meets each criteria, options should be ranked and a short-list developed.

Table 2.5.2: Example screening template

	Win/win	No/low regrets	Flexible	High resilience	Criteria X	Criteria Y	Comment
'Do nothing'							
Option A							
Option B							

2.6 Developing criteria for decision making

This section deals with developing criteria to compare options. This is a more detailed approach than the initial screening of options described in section 2.5, but is considered here as it builds on the initial screening and may affect the formulation of the water resources modelling approach (section 3), and will be utilized when making decisions under uncertainty (section 5).

Which criteria need to be defined?

Development of decision making criteria should include criteria against which options will be appraised and rules for decision making. It may also be useful to define "climate thresholds" that define unacceptable levels of risk, such as a maximum flood level.

What are criteria that can be used to assess options?

Criteria that can be used to assess options can include monetary benefits, costs, equity, public acceptability and ease of implementation. If it is believed that all benefits and costs associated with an option can be quantified in monetary terms, then cost-benefit analysis techniques may be appropriate for overall assessment and comparison of different options. If other criteria besides monetary costs and benefits will be used, then multi-criteria analysis may be appropriate. Multi-criteria analysis refers to a set of techniques that have been developed for comparing criteria that are measured using different units. If a project or study is being driven by regulatory or policy constraints, then a cost-effectiveness analysis may be appropriate.

The criteria used to assess options and the method used for overall appraisal and comparison may depend on the problem type. If the project or study is driven by a climate adaptation problem, then regulatory or policy constraints may be present and a cost-effectiveness analysis approach should be used. If the project or study can be classified as a general water resources planning problem, then it is likely that decisions will be made on the basis of whether benefits outweigh costs and cost-benefit analysis or multi-criteria analysis may be more appropriate.

What are some examples of rules for decision making?

Rules chosen for decision making should be related to risk preferences. If a risk-neutral approach is preferred (section 1.4), then it may be appropriate to base decision making on benefit maximization or cost minimization, with benefits and costs measured using either cost-benefit analysis or multi-criteria analysis. If the decision-maker is risk averse (section 1.4), then other approaches such as the minimax or maximin rules may be useful. These rules are described in section 5.

What are "climate thresholds"?

It may be useful to define "climate thresholds" that represent tolerable limits to climate risk. Thresholds link events to climate states. A threshold event can be either a biophysical event, such as a flood or a drought, or a behavioural event. A behavioural event is a change of legal, regulatory, economic or cultural behaviour that is triggered by climate states. An example of a behavioural event is a critical minimum crop yield that is need for production of a particular crop to be economically viable; if yields fall below this level, a behavioural change is triggered because farmers will have to shift to another crop or land will go out of production. Many systems are characterized by adaptive capacity that delays the onset of behavioural thresholds (e.g., efficient irrigation practices or substituting other inputs for water. Estimates of behavioural thresholds should consider how thresholds might change as a result of adaptation actions.

60-second summary...

- Criteria that can be used to assess options can include monetary benefits, costs, equity, public acceptability, and ease of implementation.
- Tools for comparison of options include cost-benefit analysis, cost-effectiveness analysis, and multi-criteria analysis. Cost-effectiveness analysis may be appropriate for climate adaptation problems, while cost-benefit analysis and multi-criteria analysis may be more appropriate for general water resources planning problems.
- Decision making rules should be formulated to account for risk preferences.

3. Formulating the water resources modelling approach

3.1 Introduction to formulating the water resources modelling approach

How might modelling approaches be different in a climate change context?

Design and evaluation of new infrastructure and/ or management alternatives will often require the use of modelling to predict future performance and compare alternatives. Likewise, assessment of potential climate change impacts may also require modelling. Depending on the type of problem, models used can include representations of rainfall-runoff relationships, flood frequencies, river hydraulics, reservoir operations, crop water use, groundwater flow, or integrated models of surface water and groundwater. When developing these models for use with climate change projections, model development may need to be approached differently. The following considerations apply generally to most models:

1) **Models should be driven by data that are simulated reasonably by climate models.** In some cases, it is common to use historical timeseries of runoff directly for infrastructure design and water resources management projects. Although climate models produce estimates of runoff, these projections are not calibrated to observed runoff and are produced at coarse scales that are not appropriate for detailed studies. For projections of runoff in such cases it is necessary to establish rainfall-runoff models driven by projected rainfall.

2) **Data sets of historical data should be developed because of downscaling and statistical correction requirements.** Precipitation projections and other outputs from climate models require downscaling and statistical correction. These procedures require historical data at spatial scales appropriate for input to impact models.

3) **Modelling approaches should be set up to accommodate multiple scenarios or ensembles of input data.** Uncertainty assessment approaches (section 5) may require multiple model runs using different assumptions. Modelling approaches should be set up to multiple runs with different assumptions in an efficient manner.

4) **Model- and input assumptions should be evaluated to ensure validity of calibration in a future scenario**. Model calibration and scenario analysis are only valid if assumptions do not change. Under climate change this might not be the case and changes in e.g. ecosystem structures might have significant impact why assumptions should be evaluated and projected into the future.

5) **Other drivers should be projected into the future and incorporated into the modelling.** Assumptions about economic growth, population growth, and other drivers may have impacts on water resources that are equal to or greater than climate change impacts. These should be projected into the future in a way that is consistent with assumptions associated with emissions scenarios. However, local projections of drivers may deviate significantly from these global assumptions.

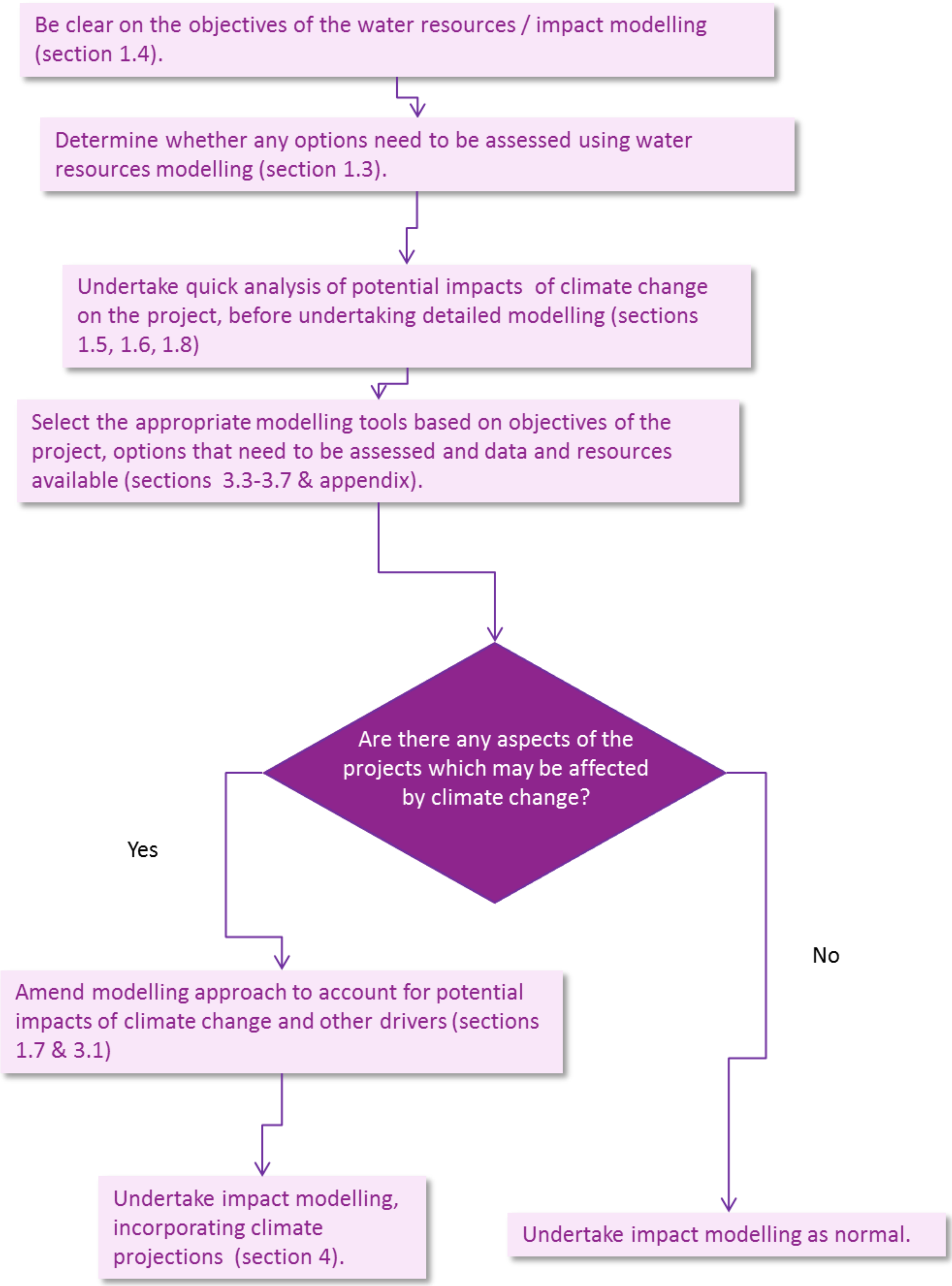
60-second summary...

Assessment of alternatives will often require the development of simulation models that can be used to compare how alternatives will perform under future conditions. Model development may require additional considerations in a climate change context.

Uncertainty in impact modelling

The choice of model and the way in which the model is structured and parameterized is an additional source of uncertainty in the study of climate change. The relative contribution of impact model uncertainty compared to the uncertainty in climate projections (including uncertainty in climate forcing scenario, GCM, RCM and statistical downscaling; see Uncertainty cascade) depends on several factors, including (i) the climate variable and associated characteristics governing the impact being considered (e.g. impact mainly driven by average conditions or by extreme conditions), (ii) availability and quality of data to properly constrain calibration of the impact model, and (iii) credibility of impact model for extrapolation to a changing climate. As an example, in a study in Norway, Lawrence and Haddeland (2011) analysed the relative impact of different uncertainty sources on the projection of extreme river flow. They found that for catchments where rainfall is the dominant contribution to extreme flows, hydrological parameter uncertainty is relatively more important compared to other uncertainty sources. In catchments where spring snowmelt dominates the generation of extreme flows, and hence is controlled by temperature, uncertainties in climate scenario and statistical downscaling are dominating.

3.2 Flow chart for formulating the water resources modelling approach



3.3 Flood protection

In many cases, flood protection systems and vulnerable regions will have to be assessed for changes to flood risks resulting from climate change. It may also be necessary to design new flood control structures or other measures to reduce flood risk. The following considerations apply in developing models for the design and assessment of flood risks.

1) **Flood frequency analysis should be based on rainfall-runoff models and not on historical river flow data.** Climate change may have impacts on average precipitation levels, the frequency and intensity of extreme precipitation events, and both seasonal and annual variability of precipitation patterns. All of this suggests that the statistical distributions of extreme rainfall and flow events may be different from those estimated from historical data. For this reason, flood frequency analysis should be based on rainfall-runoff models driven by projections of future precipitation, and not on historical river flow data.

2) **Flood frequency analysis in coastal areas should consider sea-level rise impacts.** In coastal areas, river flood levels can be affected by sea level rise. Climate change projections of mean sea level rise should be coupled with rainfall-runoff model projections of peak river flows to assess flood risks. If storm surge impacts also affect sea water levels, then potential climate change impacts on storm surge intensities should be included in the modelling approach. The Vidaa case study (see section 6.1) provides an example of a coupled river and coastal modelling approach.

3) **Climate change may give rise to morphological changes in rivers.** In coastal areas, sea level rise will give rise to river bed aggradation that will migrate upstream. This process is similar to the backwater sedimentation that takes place where a river flows into a reservoir. The bed aggradation will affect the water level in the river. The rate of bed aggradation and hence increase of water level will depend on the rate of sea level rise and sediment transport rate and will be very significant in for instance the mega-deltas of the world. This climate change impact should be investigated using morphological models.

How can DHI tools help? MIKE FLOOD, MIKE 11, MIKE 21C (see DHI Tools section)

3.4 Reservoir design and operations

The design of new reservoirs and the operation of existing reservoirs may be impacted by climate change. Assessment of climate impacts on designs and operating rules may require the development of modelling tools including: rainfall-runoff models to simulate changes to reservoir inflows; reservoir operations models to evaluate the performance of operating rules, soil erosion and reservoir sedimentation models, and water quality models. The following considerations apply to the use of models to evaluate reservoir design and operation in a climate change context:

1) **Models should be developed using time steps that are appropriate for capturing projected impacts on variability.** Considerable evidence exists that climate change will have impacts on seasonal and inter-annual patterns of climatic variability. Assessment approaches based on annual time steps or average monthly values may not capture important impacts resulting from changes to variability. For example, a projected increase in annual rainfall amounts could conceal decreases during summer months that could result in shortages when irrigation demands are high. A model based on average monthly values may still be sufficient for long-term drought analyses.

2) **Inflow predictions should be based on rainfall-runoff models and not on historical river flow data**. As with flood frequency analysis (see section 3.3), it should not be assumed that past inflow patterns are representative of inflow patterns under a climate change regime.

3) **Snowmelt and glacial melting processes should be included.** Rates of snow and glacial melting are expected to increase substantially due to increasing temperatures. In basins where snow and glacial melting are important contributors to the water balance, climate change impacts on accumulation and melting rates should be represented explicitly.

4) **Sediment load may change.** Changing precipitation intensity as well as increased snow-free areas may increase catchment sediment yield and accelerate reservoir sedimentation. The effect of climate change on catchment sediment yield and reservoir sedimentation therefore has to be quantified through application of appropriate soil erosion and sedimentation models.

5) **Environmental management will be challenged.** From an ecological and environmental point of view a number of issues could change with a changing climate. These issues cover:

- Changes in nutrient loadings
- Changes in nutrient retentions
- Thermal stratification
- Changing of habitats
- Potential development of toxic algae species (eg. cyano-bacteria)
- Introduction of new or increased survival of pathogens (in case of drinking water or recreational waters)

The above challenges are addressed in more details in the section *Ecological, Environmental & Water Quality Management*. Specifically for reservoirs, are potentially increases in water level extremes (high and low water levels). This could lead to a significant reduction in bottom vegetation and hence changing habitats.

How can DHI tools help? MIKE 11, MIKE 21, MIKE 21C, MIKE 3, MIKE BASIN (see DHI Tools section)

Formulating the modelling approach

3.5 Irrigation water use

In a climate change context, it may be necessary to revise projections of irrigation water use and crop yields, which are needed for irrigation system planning, reservoir design and operations studies, and river basin planning. The following considerations apply to simulations of crop water use.

1) **River basin planning and reservoir operations models should calculate crop water use dynamically, based on a soil moisture balance.** Climate change is expected to increase evaporation rates, depleting soil moisture and increasing crop water requirements. Changes to precipitation patterns could change rates at which soil moisture is depleted. Crop water requirements should not be fixed or based on historical values but rather computed dynamically from a soil moisture balance model forced by climate projections.

2) **Temperature and CO_2 impacts should be included in crop yield models.** There is evidence that changes in temperatures and CO_2 concentrations associated with climate change and greenhouse gas emissions will have impacts on crop yields. Changes to these parameters may have impacts on crop water requirements, as the amount of water needed to maximize crop yields may change. Research in this area is continually developing, so relative impacts of these parameters should be carefully investigated.

3) **Changes to cropping patterns should be considered.** Under a different climate regime, it may no longer be profitable to grow some crops. It may be useful to develop an economic model that can be used to predict how cropping patterns might change in response to climate change

4) **Increases in salinity in coastal areas should be considered.**

5) **Changes in storms and increased wash out of nutrient should be considered.** Increase in extremes like storms will result in increased surface run-off, and hence increased erosion and transport of pollutants from land to water bodies, as well as increase the bank erosion. This has to be addressed in the load estimation associated with the different climate scenarios. Furthermore, increased wash-out of nutrient will potentially affect crop yields and use of fertilizer.

How can DHI tools help? MIKE BASIN (see DHI Tools section)

Formulating the modelling approach

3.6 Groundwater

There is still considerable uncertainty about the potential impacts of climate change on groundwater. Furthermore, impacts on groundwater systems are expected to take place more slowly than in surface water systems. In general, recharge rates are expected to decrease, and risks of salinization are expected to increase (IPCC 2007c). The following items should be considered when developing groundwater models in a climate change context.

1) **Groundwater recharge estimates should be based on climate change projections.** Groundwater recharge will be impacted by projected changes in rainfall, evapotranspiration and runoff patterns. It may be particularly important to use projected changes to estimates of recharge rates for unconfined aquifers in arid and semi-arid regions, which are likely to have shifting annual balances between precipitation and evapotranspiration and a general drying trend under most climate change projections. In regions where seasonal snow melt is predicted to change from spring towards winter, recharges rates may also increase if more infiltration is taking place during periods with lower evapotranspiration potential. Changes to climate variability, especially in precipitation, could also have substantial effects on recharge and groundwater levels.

2) **Coastal aquifer studies should consider impacts of sea level rise.** Projected increases in mean sea levels could have impacts on salt-water intrusion in coastal aquifers, exacerbated by slower recharge rates.

3) **Salinization of shallow aquifers in arid and semi-arid regions should be considered.** Shallow aquifers in arid and semi-arid regions may be at risk of salinization due to increased evapotranspiration.

4) **Groundwater/surface water interaction should be included.** Changes in precipitation and runoff patterns will impact the surface water/groundwater balance and may cause zones of recharge and discharge to shift. Particularly in regions where surface ecosystems are dependent on groundwater, a detailed representation of surface water-groundwater interaction may be required.

How can DHI tools help? FEFLOW, MIKE SHE (see DHI Tools section)

3.7 Environmental Management

Climate change may have significant impacts on freshwater habitats including rivers, lakes, and wetlands. According to the fourth IPCC report (2007), out of all ecosystems, freshwater aquatic ecosystems appear to have the highest proportion of species threatened with extinction by climate change.

The following considerations apply when developing models to address ecological, environmental and water quality management :

1) **Climate impacts on lake ecosystems should be investigated using an ecosystem/biogeochemical modelling approach .** Increasing temperatures associated with other effect of climate change could reduce oxygen concentrations in lakes, potentially leading to anoxic conditions in deep, stratified lakes. In deep as well as shallow lakes the climate change can turn the ecosystem into a more heterotroph ecosystem and thereby increase net production of greenhouse gasses. The increased temperature can also stimulate nuisance algae blooms especially of cyanobacteria (blue-green algae). These impacts should be modelled using a combined hydrodynamic and biogeochemical model approach.

2) **Climate impacts on river habitats should be investigated using temperature modelling.** Aquatic species rely on a set of parameters defining their preferred habitats. In this perspective, temperature is an important parameter for almost all living organisms, and changes in temperature might change living conditions for a number of aquatic species directly or indirectly through the potential changes in food web. These impacts should be investigated using a temperature modelling approach using boundary conditions from climate projections, and combining with knowledge on key species and their preferred habitats.

3) **Increased difference between high flow and low flow in rivers and wetland areas should be addressed.** Some species rely on flows within a certain range. In some regions we will experience an increase in extremes (high flows and low flows and even draughts). Change of periods with flooding and drying out will have significant impact of wetland areas. Special attention has to be paid to highly protected areas such as Nature 2000, Ramsar areas, etc. This might influence biodiversity in general and threaten species in particular.

4) **Changing morphology will influence habitats of some species.** Erosion and changes in river morphology can be important to some habitats like e.g. spawning grounds for salmonide species. Salmon and many trout species as well as a number of other species rely on specific bottom substrates as good spawning conditions for the eggs to successfully develop into viable fry. Changes in morphology can change these areas and potentially influence the recruitment of new adults. In models calibrated to mimic present in-river habitat conditions, morphological changes in terms of erosion and alteration of composition of bottom substrates, may not be explicitly simulated and thus predictions of the influence of climate change need to be evaluated.

5) **Changes in diffuse loadings of nitrogen and phosphorous directly due to changes in precipitation should be addressed with dynamic hydrological models**. There is most likely not a linear correlation between the changes in the predicted meteorological forcing and predicted changes in diffuse loads. With the predicted changes in precipitation the relative importance of the individual runoff components (i.e. surface run-off, storm water overflow on sewage systems, run-off through drains and groundwater run-off etc.) will change and enhance the resulting loads of N and P. This can be evaluated through dynamic hydrological models like NAM, MIKE Basin or MIKE SHE.

6) **Changes in diffuse loadings of nitrogen and phosphorous indirectly due to changes in types of crops, cultivation practises and fertilizer application should be addressed using process based model.** Changes in crop type may result in radically change the inter-correlated water and nutrient balances in the soil through complex biological processes. Adding changes to cultivation practises and fertilizer application will add to the complexity. Given that changes in the composition of crop types can be predicted as a result of climate change the impact on N and P leaching can be evaluated through process deterministic models such as DAISY, MIKE SHE or ECO LAB.

3.7 Environmental Management

7) **Besides changes in nutrient loads lakes faces changes due to temperature changes.** The different functional lake ecosystem groups will most likely be challenged by temperature changes. The interaction between phytoplankton, zooplankton and fish is a fine balance that temperature might interrupt. And the response will most likely be different between deep lakes, shallow lakes and between geographical regions. Hydrodynamic modelling including heat balance processes and ecological modelling can help address some of these impacts due to climate change. However some assumptions might change with respect to the ecosystem why existing (calibrated/validated) ecosystem models will not be applicable in a future climate scenario.

8) **Thermal stratification.** One important issue when evaluating water quality in a reservoir or deep lake is the potential forming of a thermocline. We do not expect large changes in the seasonality in a future climate, however, changes in river inputs, increasing temperatures and potential changes in wind speed and direction might impact a reservoir in different ways and allow for the thermoclines to form or degrade with climate changes. When thermocline forms, potential anoxic conditions might develop with potential large impact on the water quality. Furthermore, an increase period of stratification will increase the period of surface nitrogen exhaustion and hence the likelihood for the occurrence of cyano-bacteria. Thus, it is important that models are sufficiently validated in terms of their ability to reflect the effects of changes in inflow, wind and temperature on the thermal stratification. This could lead to a more heterotrophic system with negative feedback on the climate changes themselves.

9) **Nutrient retention in lakes:** Climate change can influence the nutrient retention in lakes and reservoirs. It is however not a simple task to evaluated and simulate such change because it highly depends on how the ecological balance and the biological processes is impacted and are acting together. The change in retention of P and N respectively may be very different. In stratified lakes and reservoirs the climate change may increase the risk of oxygen depletion in deeper water masses. If the oxygen becomes critical low it may result in release of phosphorus from sediment and reduced retention of P. It will however highly depend on the chemistry of sediment and water. The oxygen balance also influence the nitrate cycle in the water body. The biological processes ammonification, nitrification and denitrification will be stimulated by increased temperature. Anaerobic condition will inhibit the nitrification processes but stimulate the denitrifcation. The resulting effect on N-retention from climate changed can in a lake or reservoir be positive as well as negative depending on the balance between these processes.

10) **Potential hazards due to changing health risks.** Generally, temperature is expected to increase worldwide, and temperature is a very important parameter for a number of organisms. From a drinking water perspective pathogens/parasites/vira might be able to survive for longer periods of time or new ones might be introduced.. Is the water also used for irrigation the introduction of potential pathogens could influence both the health of the farmers as well as the product quality. Also, the risk of harmful algae blooms (HABs) will most likely increase with temperature. Furthermore, changes in nutrient and suspend solids inputs will impact both survival and forming of these organisms

11) **Investigations of wetland ecosystem impacts should also include climate impacts on catchment inflows and regional groundwater flows.** Wetland ecosystems are sensitive to water balance changes, particularly in regions where precipitation does not greatly exceed evapotranspiration. It is important to capture all changes to the water balance that might result from climate change. This includes inflows from upland catchment areas as well as regional groundwater flows. Climate change impacts on catchment and regional groundwater flows should be estimated using rainfall-runoff and groundwater models driven by climate projections. This is particularly important for seasonal wetlands, which may be impacted by shifts in precipitation and evapotranspiration patterns.

12) **Increased surface runoff and erosion along rivers will affect phosphorous transport.** Phosphorous is strongly linked to soil particles why change in surface runoff and erosion in the riparian zone will greatly affect phosphorous loads downstream these areas. To be able to address these issues MSHE ECOLAB or SEAGIS models should be applied.

Other considerations discussed in sections 3.3 to 3.6 may also be relevant for environmental management studies.

How can DHI tools help? MIKE SHE, MIKE 3, ECOLAB, MIKE FLOOD, MIKE 11 (see DHI Tools section).

Formulating the modelling approach

4. Developing projections

4.1 Introduction to developing projections

All climate change studies will require some future projection of climate variables. Here, we focus on changes in variables most relevant for water resources: temperature, rainfall, evapotranspiration and sea level.

These projections may be used directly, such as to investigate precipitation for city drainage systems, or in impact models to characterise changes in other variables, such as changes in irrigation demand for agriculture, water supply or flood risk.

Projections may be taken from global climate models (GCMs) or regional climate models (RCMs) which are driven by the global models. These results must then be processed and downscaled to represent climate at the site of interest, before being used in an impact model. The development of climate projections is illustrated in figure 4.1.1.

Studies with smaller scopes may use published changes in climatic variables or sensitivity analyses to investigate future climate scenarios.

In some cases, developing projections of extremes may be necessary to investigate whether infrastructure will still provide an adequate level of protection in future or for the design of new infrastructure. Joint probability analysis may be necessary to investigate the risk of multiple climate hazards occurring simultaneously.

This section provides background information and practical guidance on how to develop projections of climate variables and sea level rise.

Other projections may be necessary to investigate future scenarios such as population or land-use change, but these are not directly discussed here.

This section starts with a flow chart aimed at assisting practitioners in the various stages of developing climate projections. It is designed to be applicable to projects of different scopes.

The background information necessary to develop climate projections is organised in the 9 sections of this chapter, which can be seen in the menu on the left.

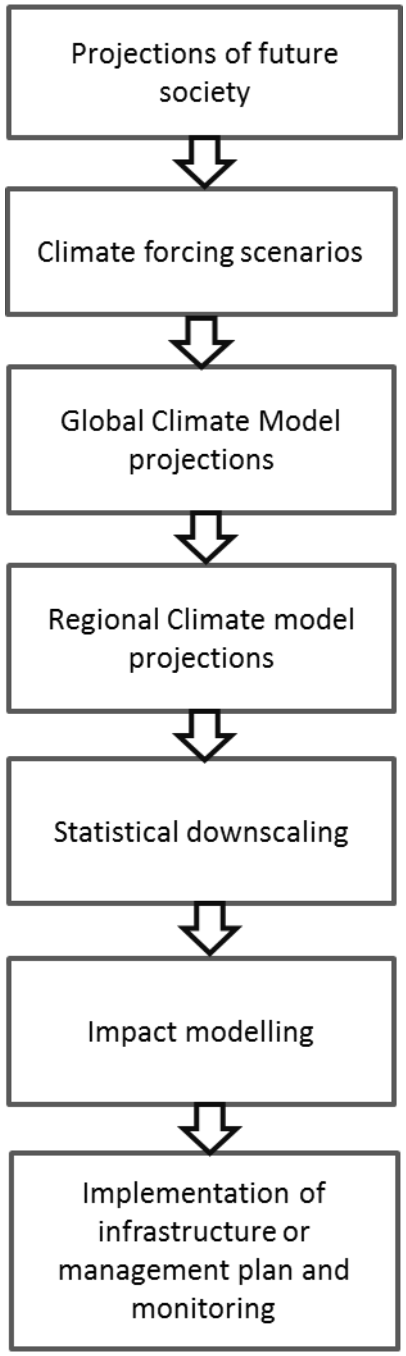
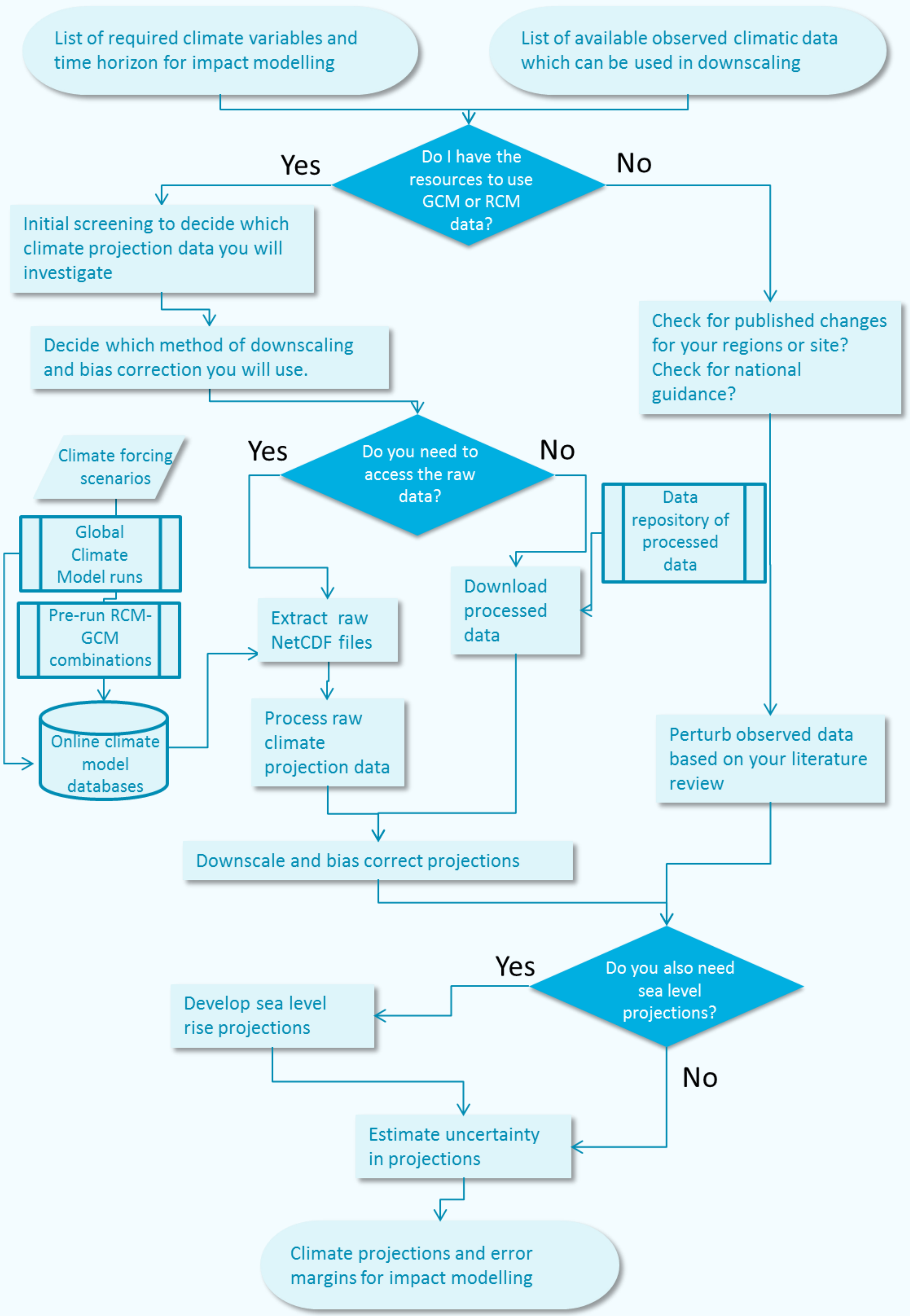


Figure 4.1.1: The flow of information in developing climate projections

4.2 Flow chart for developing projections



4.3 Climate forcing scenarios

Climate forcing refers to anything which forces a change in the climate system. Here it refers to emission scenarios or representative concentration pathways providing projections of atmospheric concentrations of greenhouse gasses. These scenarios are used as the driving input to global climate models as greenhouse gas concentrations influence the balance between incoming and outgoing radiation. Thus, each set of climate projections is valid under a specific assumption of future atmospheric greenhouse gas concentrations.

What are the various scenarios?

There are three main sets of climate forcing scenarios : SRES scenarios, non-SRES scenarios and the latest RCP scenarios.

There are 40 ***SRES scenarios*** grouped into four families (A1, B1, A2, B2) based on narratives of demographic, social, economic, technological, and environmental development. There are 6 widely used illustrative scenarios: A1B, A1F1, A1T, A2, B1, B2 (Table 4.3.1). The global greenhouse gas emissions and the corresponding projected increase in global surface temperature for the six SRES scenarios are shown in Figure 4.3.1.

More information on SRES scenarios can be found in the IPCC Special report on emissions scenarios.

Non-SRES scenarios are not based on narratives but simulate various changes in concentrations.

Representative Concentration Pathways RCPs are the latest scenarios developed. There are 4 RCP pathways shown in Table 4.3.1 based on a range of radiative forcing scenarios rather than emissions. They provide a wider range of futures than the previous scenarios (Van Vuuren et al., 2011). More information can be found in Moss et al 2010.

How do the new RCP scenarios compare to the SRES scenarios?

The CO2 emission rates for the RCP scenarios are compared to the emission rates for the SRES scenarios B1, A1B and A2 in Figure 4.3.2. The RCP4.5 scenario has similar emission rates as the SRES B1 scenario, and RCP6.0 and RCP8.5 are comparable to, respectively, SRES A1B and A2.

Why are some scenarios more widely reported than others? Are they the more likely scenarios?

Studies which have focussed on comparing climate model projections have limited the number of scenarios used to reduce the number of model runs necessary. However, no scenario was developed as the “most likely” option, but rather the scenarios are designed to show the range of possible trajectories.

Who developed the scenarios?

The SRES and RCP scenarios are developed by the IPCC.

60-second summary...

- Results are available for a range of scenarios. The most widely available are those in table 4.3.1. They are not probabilistic but simply represent a range of possible futures.
- New scenarios called Representative Concentration Pathways are being used for the latest climate modelling effort. There are 4 RCP pathways which cover a wider range of futures than those from the SRES scenarios.
- It is generally recommended to include several scenarios in the analysis. Depending on the climate variable, region and projection horizon differences between scenarios may be less important compared to natural variability and variability of climate model projections

4.3 Climate forcing scenarios

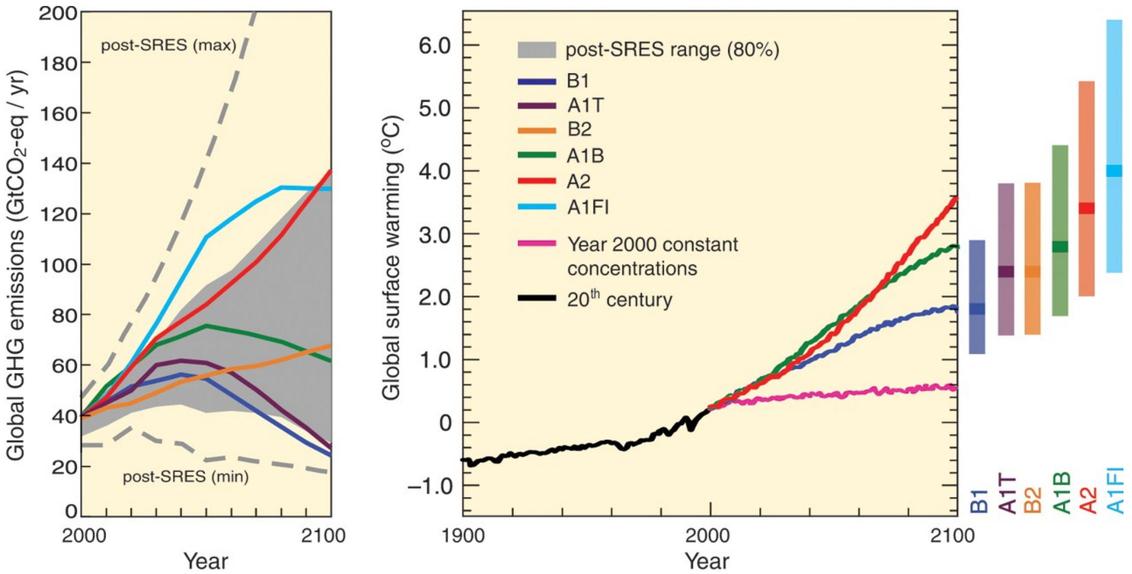


Figure 4.3.1. Taken from IPCC AR 4 report (http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html) showing the range of global greenhouse gas emissions (left) and corresponding global warming (right) for different SRES scenarios. The bars on the right show the likely range of temperature increase in 2100 (relative to the period 1980-1999).

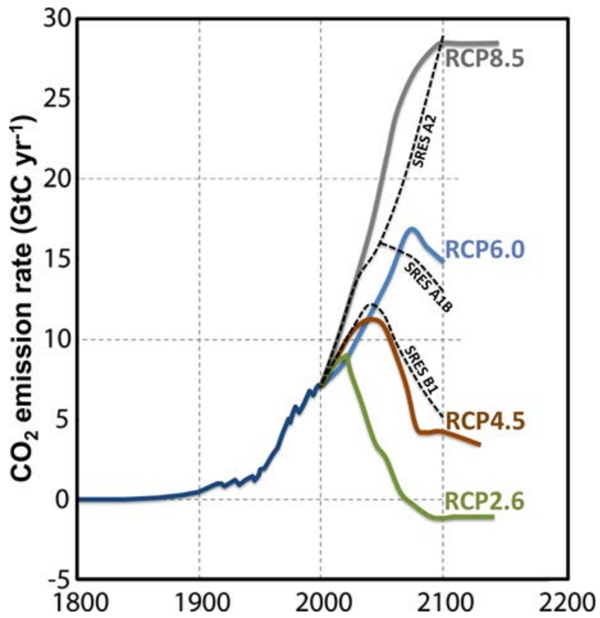


Figure 4.3.2 Comparison of CO_2 emissions for SRES and RCP scenarios (van Vuuren et al, 2009)

Uncertainty in climate forcing scenarios

The climate forcing scenarios rely on many factors which cannot be predicted easily, such as population growth, energy use and energy sources and, as such, they have a large degree of uncertainty associated with them. However, this uncertainty is partly addressed by the wide range of futures which the scenarios collectively represent.

The relative importance of climate forcing scenario uncertainty compared to other uncertainty sources in climate projections depends on the variable being studied, the time horizon of the projection and the region of the world. In general, scenario uncertainty becomes relatively more important for increasing projection horizon, and differences in scenarios have relatively larger impacts on temperature than on precipitation.

4.3 Climate forcing scenarios

If SRES emission scenarios were developed in 2000, how are current emissions tracking relative to those projections?

We are tracking towards the higher end of the range of SRES illustrative scenarios (Figure 4.3.3). However, short-term variations in emissions do not determine the long-term pathways and recent emissions cannot be used to select between long-term projections.

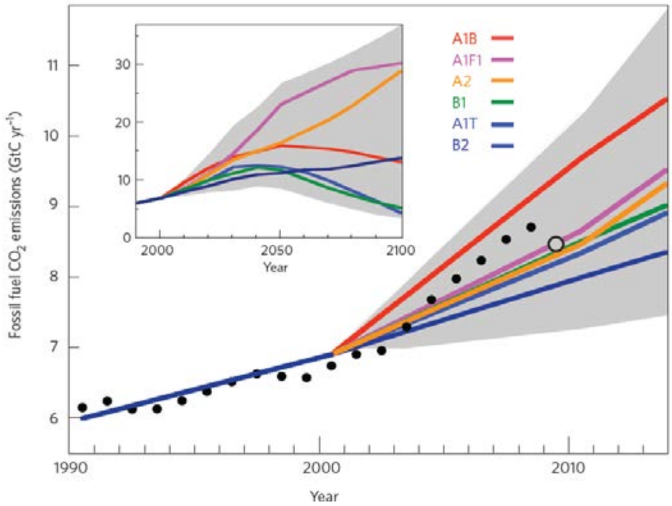


Figure 4.3.3: Black dots and white dot showing observed emissions relative to projections (Manning et al., 2010).

Table 4.3.1 Some of the main climate forcing scenarios and their assumptions

Scenario	Assumptions (Source IPCC website)
The SRES scenarios (2000)	
A1B	A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality. Energy technologies balanced across energy sources.
A1FI	As A1B but with fossil-intensive energy technologies.
A1T	As A1B but with predominantly non-fossil energy sources.
B1	A convergent world with the same global population as in the A1 storylines but with rapid changes in economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource-efficient technologies.
A2	A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.
B2	A world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change but a strong emphasis on community initiative and social innovation to find local solutions.
RCPs (2011)	
RCP8.5	Rising radiative forcing pathway. Leading to 8.5 W/m2 in 2100.
RCP6	Stabilization without overshoot pathway. Leading to 6 W/m2 at stabilization after 2100.
RCP4.5	Stabilization without overshoot pathway. Leading to 4.5 W/m2 at stabilization after 2100.
RCP2.6	Peak in radiative forcing at about 3 W/m2 before 2100 and then a decline.

4.3 Climate forcing scenarios

Working with climate forcing scenarios

Which emissions or concentration scenario should I use for my project?

In practice, datasets available will be based on one of the scenarios in table 4.3.1. Newer runs will likely use one of the RCP scenarios and older runs will use the SRES and other scenarios. It is recommended to use the latest available datasets for your climate variable and model of choice. If focus is on changes in air temperature, differences between scenarios are small up to around 2050, depending on the region. In this case it may be sufficient to include only one scenario in the analysis. For longer projection horizons it is generally recommended to include more scenarios, e.g. a median, low and high scenario, which cover the range of scenarios. If focus is on changes in precipitation, differences between scenarios are, in general, smaller than differences between different climate models. In this case it may be sufficient to consider only one scenario up to 2100, depending on the region.

4.4 Global Climate Model projections

What is a GCM?

Global climate models (GCMs) are used for projection of future climate. GCMs are coupled models, which simulate numerically the processes of heat, moisture and momentum exchange across the ocean, atmosphere, sea ice and land surface, based on physical principles. They simulate climate response to different climate forcing scenarios of atmospheric composition of greenhouse gases (see climate forcing scenarios).

Which processes do they simulate?

GCMs run on a grid at a coarse scale, which means they cannot model small and meso-scale processes. Physical parameterisations are used to model sub-grid scale processes such as cloud processes, convection, boundary layer processes (turbulence), radiation fluxes and surface processes (surface-atmosphere interactions). Future scenarios used to force climate models do not include changes in solar forcing or volcanic eruptions. In the long term these effects are expected to be small compared to greenhouse gas emissions.

GCMs are constantly being improved, with new process descriptions, increased horizontal and vertical resolutions, and improved parameterizations of the physical processes.

How many GCM climate projections are available?

GCM climate projections from various modelling groups have been collected and made available in the Coupled Model Intercomparison Projects (CMIP). The 25 GCMs (from 18 modelling groups) which participated in the CMIP3 intercomparison project and reported in the IPCC 4th Assessment Report, are listed in the appendix. Details of the models can be found on the Program for Climate Model Diagnosis and Intercomparison (PCMDI) website. Most of the 25 GCMs have been run with the SRES scenarios A2, A1B and B1.

44 different GCMs from twenty modelling groups are involved in the current intercomparison study (CMIP5) which will be reported in the IPCC's 5th Assessment Report (scheduled for September 2013). The CMIP5 data archive is currently being populated with GCM results that are based on the new RCP scenarios.

How do GCMs perform and how different are the GCM projections?

It is generally accepted that GCMs provide credible estimates of climate change at continental and larger scales. The confidence in the model projections, however, varies for different climate variables. The confidence is generally higher for temperature than for precipitation (Randall et al., 2007). The models have significant errors at smaller scales but also large

60-second summary...

- Global climate models are coupled systems of ocean, atmosphere, sea ice and land surface that are forced by SRES emission scenarios or RCP scenarios for projection of future climate.
- GCM projections are made available in the Coupled Model Intercomparison Projects (CMIP); 25 GCMs for the CMIP3 project reported in IPCC 4th Assessment Report, and 44 GCMs for the CMIP5 project being prepared for the 5th Assessment Report.
- GCMs may have significant biases that vary between the different models, different climate variables and between different regions. There is no "best" model and the average of several models (ensemble average) generally outperforms any of the individual models..

To address the variability in GCM projections an ensemble of model results should be used for impact assessment. It is recommended to use at least three GCMs, corresponding to a low, median and high projection of change in the climate variables being considered.

4.4 Global Climate Model projections

errors are present in the simulation of large scale features. One important source of error is the parameterization of sub-grid scale processes. Due to these model deficiencies, GCM projections may have significant biases and cannot, in general, be directly applied for impact modelling.

Since the GCMs have different numerical cores, model resolutions, and physical parameterizations, they produce different projections. Model biases vary between the different models for different variables and in different regions. Several studies have been performed that evaluate the performance of GCMs. These studies show that there is no "best" model and that the average of several models outperforms any of the individual models (e.g. Gleckler et al., 2008). It is therefore recommended to use an ensemble of GCM projections for impact studies which also allows for the evaluation of uncertainty. To properly address the variability in GCM projections at least three GCMs should be selected, corresponding to a low, median and high projection of change in the climate variables being considered.

Working with GCM data

How do I get hold of GCM projections?

GCM projections that are included in the Coupled Model Intercomparison Project are available online. There are two main rounds of modelling which have datasets available: CMIP3 and CMIP5 (currently being populated). All GCM data are available for non-commercial use, and a subset of data is available for unrestricted use. GCM projections for a large number of climate variables can be obtained from the CMIP data archives. The IPCC Data Distribution Centre provides summary data in terms of monthly mean of a subset of climate variables for different time slices (twenty or thirty year averages). Full global data sets as well as data covering user-defined regions can be downloaded.

Use of GCM data

GCM projection data are not, in general, of sufficient resolution and reliability to be used directly for impact assessments. Typically, downscaling is necessary to obtain more reliable climate projections at the local scale, either by using dynamic downscaling (see Regional climate model projections) or by statistical downscaling (see Statistical Downscaling). For larger scale (continental) impact studies or for a first screening at regional or local scale GCM data can be applied. In this case, changes in the mean of the climate variables are estimated from the GCM simulations by comparing simulations over a baseline period, e.g. 1961-1990 (usually referred to as control period), with simulations in a future period (e.g. 2071-2100). For temperature absolute changes are usually applied, whereas for precipitation and potential evapotranspiration relative changes are applied.

Processed changes in mean temperature, precipitation and potential evapotranspiration from the CMIP3 GCMs for SRES scenarios A2, A1B and B1 have been made available in the MIKE by **DHI Climate Change tool** (see DHI Tools section). The tool can be used for fast assessment and screening studies by modifying baseline boundary data of the impact model with projected changes.

A list of the GCMs used for the 4th assessment report is shown in the appendix in table A1.

GCM data is available at:

http://www-pcmdi.llnl.gov/

http://www.ipcc-data.org/

Data can be visualized:

http://www.ipcc-data.org/maps/

Are the databases updated?

Yes, often errors are found in model outputs and they are corrected and the databases are updated. You should check the errata.

What format do the data come in?

Many results are stored in NetCDF format; however, some results such as averages or climatologies may be available in CSV format from the IPCC website.

Do I need specialist software to work with climate data?

To extract the data you may need tools for working with NetCDF files. Further information is available here: http://www.unidata.ucar.edu/software/netcdf/index.html.

4.4 Global Climate Model projections

Will the GCM models change in the near future?

One of the limitations of global climate modelling is the massive computational resources required. With the constantly increasing processing power GCMs can be run with higher resolution and more processes can be explicitly modelled rather than parameterized (see regional climate model section). One of the biggest additions in the latest modelling effort (CMIP5) is the focus on providing many runs of many models with different parameterisations to allow model uncertainty to be better characterized.

Figure 4.4.1 shows the mean annual precipitation based on the mean of the GCM ensemble from CMIP3 as compared to observations.

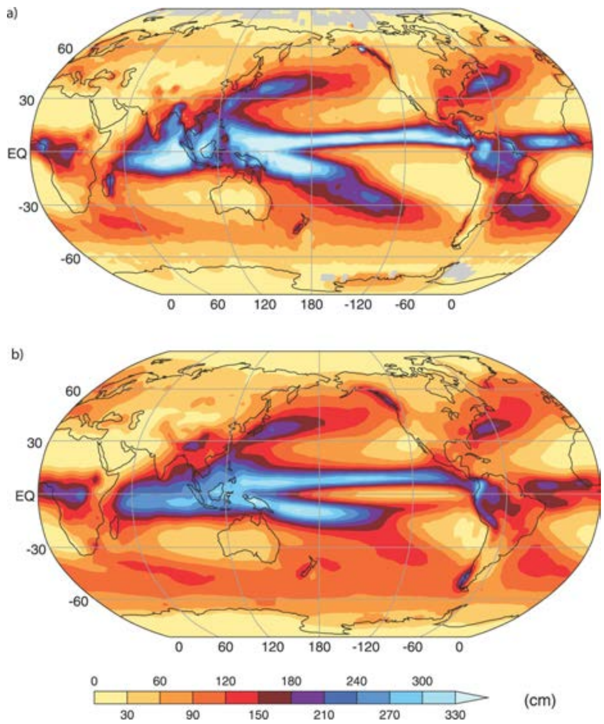


Figure 4.4.2. Comparison of the annual mean precipitation based on observations (a) and the GCM multimodel mean (b) (Randall et al., 2007).

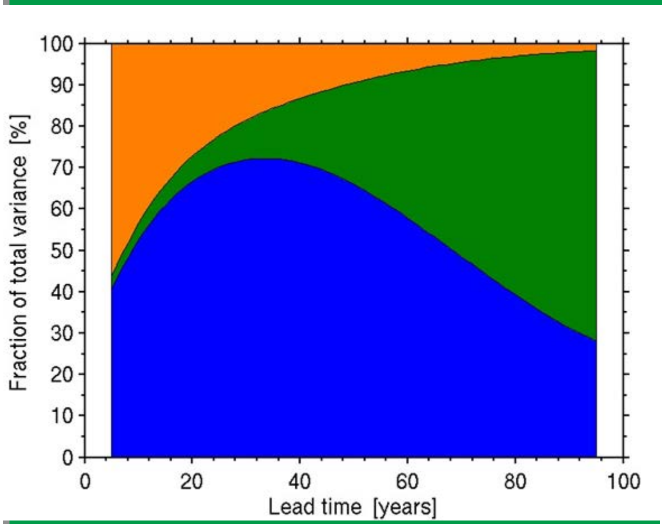
4.4 Global Climate Model projections

Uncertainy in GCMs

Uncertainties arise from various sources such as:

- Deficiencies in simulation of large scale patterns and teleconnections, including tropical precipitation and the El Niño-Southern oscillation
- Small-scale processes that cannot be represented explicitly (e.g. clouds, convection) but are included in an approximate form as physical parameterisations
- Limitations in understanding or missing observations of some physical processes (known unknowns)
- Any unknown physical and biophysical processes and interactions which may be important for climate change

GCM projections also inherit the uncertainties from climate forcing scenarios. The relative contributions to the total uncertainty from climate scenario and GCMs depend primarily on projection horizon and climate variable. In Fig. 4.4.3 is shown an example of the relative contributions of climate forcing scenario and GCM model uncertainty compared to the internal variability of the climate system for temperature and precipitation. For temperature, scenario uncertainty becomes more important and GCM model uncertainty less important for increasing projection horizon. For precipitation, scenario uncertainty has only a small contribution to the total uncertainty, also for large projection horizons. Internal variability has a large contribution to the total uncertainty for the first decades and is more important for precipitation than for temperature. This shows that any climate change signals cannot be detected on a shorter time scale due to natural climate variability.



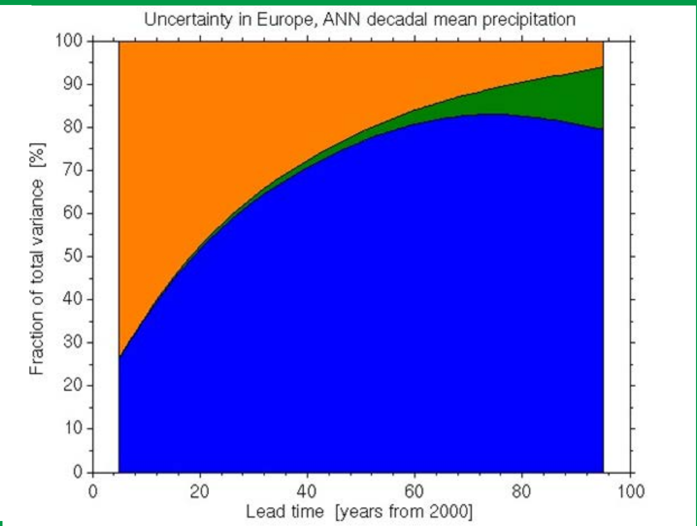


Fig. 4.4.3 Relative contribution to the total uncertainty of climate forcing scenario uncertainty (green), GCM model uncertainty (blue), and internal variability (orange) for temperature (top) and precipitation (bottom) for Europe (from http://climate.ncas.ac.uk/research/uncertainty/ based on Hawkins and Sutton (2009, 2010)). Results from other regions are available on the website.

4.5 Regional climate model projections

What is an RCM?

An RCM is a Regional Climate Model that covers a certain geographical area. As opposed to global climate models, an RCM typically only describes the atmosphere and uses prescribed states of the ocean, sea ice and land. They are based on a set of equations that models the motion of the atmosphere and a set of physical parameterisations that describes sub-grid scale processes, such as cloud processes, convection, boundary layer processes, and land surface-atmosphere interactions.

RCMs are used to dynamically downscale GCM simulations for producing higher resolution climate projections at a regional scale. GCM results for a given climate forcing scenario (see GCM projections) are used as boundary conditions for the RCM simulation. State-of-the-art RCM uses a horizontal resolution of about 10-50 km. This allows a better representation of topography and land surface heterogeneities and hence more realistic simulations of associated processes than GCMs. In this regard, RCMs are better able to simulate extreme events, such as extreme precipitation caused by orographic uplift.

How many RCMs are available and which areas do they cover?

RCM projections from different regions have been made available as part of international regional climate modelling studies. These include:

- The PRUDENCE project for Europe
- The ENSEMBLES project for Europe and Africa
- The NARCCAP project for North America
- The CORDEX project (ongoing) covering all continents, see Figure 4.5.2.

In these projects a number of regional climate model simulations have been carried out, combining different RCMs with different GCMs for different climate forcing scenarios. The PRUDENCE, ENSEMBLES and NARCCAP projects are based on the SRES scenarios, whereas CORDEX will be based on the RCP scenarios. An overview of available RCM projections is shown in the appendix.

How do RCMs perform and how different are RCM projections?

RCMs will, in general, provide more reliable climate projections at the regional scale than GCMs. However, significant errors may still be present. For instance, the RCM inherits the biases and other deficiencies of the driving GCM. Another important source of error is the physical parameterisations.

60-second summary...

- RCMs are regional climate models covering a certain geographical area and are driven by GCM simulations based on climate forcing scenarios. RCMs have higher resolution than GCMs, allowing a better representation of topography and land surface heterogeneities and hence more realistic simulations of associated processes
- RCM projections are available for different regions of the world. Existing data archives contain ensembles of RCM simulations, including different combinations of RCM and GCM models, and climate forcing scenarios. The ongoing CORDEX project will in coming years provide global coverage of RCM projections.
- RCM projections have different sources of error. They inherit the biases from the GCM projections, and additional uncertainty is added in the RCM model itself, especially related to the physical parameterisations used for describing sub-grid scale processes.
- To address the variability in RCM projections an ensemble of model results should be used for the impact assessment. It is recommended to use at least three RCMs, corresponding to a low, median and high projection of change in the climate variables being considered.

4.5 Regional climate model projections

Working with RCM data

Where can I find RCM climate model data?

RCM projections are available from different international projects and can be downloaded from online climate model databases. An overview of current data archives and available RCM projections are shown in the appendix. For the ongoing CORDEX project the data archive is currently being populated. For most data archives data are freely available with unrestricted use. Data may also be available directly from the research institutions developing the climate models.

The PRECIS RCM model, developed by the UK Met Office Hadley Centre, has been licensed to various countries around the world (see Figure 4.5.1) and results may be available for these countries. For details see the PRECIS website.

Use of RCM data

RCM projections have higher resolution and are, in general, more reliable than GCM projections. However, RCMs also have biases, and therefore RCM projections are usually not applied directly in the impact assessment. Bias correction and statistical downscaling is required prior to the use of RCM data in impact modelling (see Statistical Downscaling).

If RCM data are available, these data are generally to be preferred to GCM data for the impact assessment. In the case where no RCM data are available for the region in question, one has either to base the impact assessment using only the available GCM projections (see GCM projection) combined with statistical downscaling (see Statistical downscaling), or consider the possibility for performing dedicated RCM simulations for the region. Also in the case where results from only one RCM (for given GCM and climate forcing scenario) the use of GCM data or dedicated RCM simulations should be considered.

Which RCM model should I choose?

It is generally recommended to use an ensemble of regional climate model projections, including different RCM/GCM combinations. In this regard, existing information about RCM performance can be used for choosing appropriate RCM members to include in the analysis. For instance, for the ENSEMBLES data, the results of Christensen et al. (2010) as shown in Figure 4.5.3 can be used for making an assessment of RCM performance. In addition, GCM performance and variability must be properly accounted for, and balanced against the variability caused by the RCM. This balance will be case specific, depending on the climate variable and region being considered. In general, it is expected that the variability in mean temperature will be mainly influenced by the driving GCMs, whereas the variability in extreme precipitation will be mainly determined by the RCMs. To avoid common biases and underestimation of the variability, the recommendations for choosing GCMs should be followed (see GCM projections).

As a minimum, it is recommended to choose a subset of three RCM/GCM combinations, corresponding to a low, median and high projection of change in the climate variables being considered.

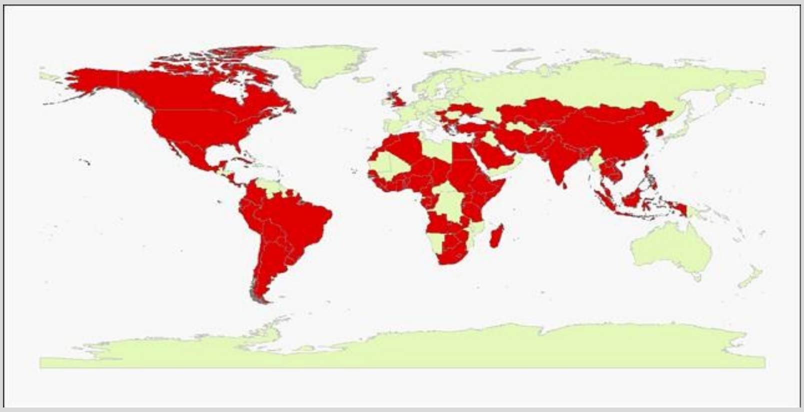


Figure 4.5.1 Red areas denote regions where the PRECIS model has been licensed

4.5 Regional climate model projections

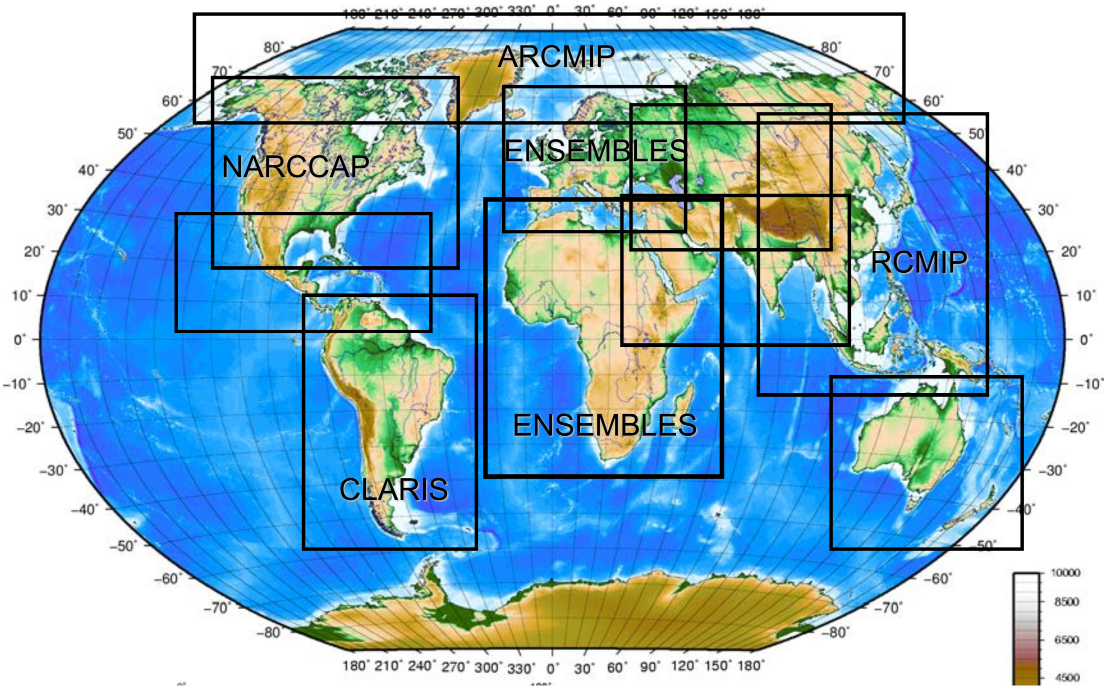


Figure 4.5.2. Map of regions for which RCM simulations will be performed as part of the CORDEX project (Giorgi et al., 2009). The map also shows the regions for which regional climate projects have been performed (although not all with RCM projections available).

For example, convective rainfall is not well simulated due to the parameterisation of microphysics and moist convection processes. To avoid physical parameterisations, higher spatial resolution is required in the RCM whereby convection can be explicitly simulated.

RCM results may have significant biases, and thus cannot, in general, be used directly in impact studies. Bias correction and statistical downscaling is required prior to using RCM projections in hydrological modelling (see Statistical downscaling). Model biases vary between the different models for different climate variables and in different parts of the modelling domain. In addition, different GCMs used to force the same RCM will provide different results. Several studies have advocated the use of an ensemble of model projections for impact assessment rather than relying on a single RCM projection (e.g. Fowler et al., 2007).

As part of the [ENSEMBLES](#) project, the performance of the participating RCMs was evaluated using different metrics (see summary and combination of the different metrics in Christensen et al., 2010). They analysed the performance of the RCMs for simulating current climate conditions using six different performance measures:

F1: Large-scale circulation patterns

F2: Seasonal mean temperature and precipitation

F3: Distributions of daily and monthly temperature and precipitation

F4: Extreme daily precipitation and daily minimum and maximum temperature

F5: Long term trends in temperature

F6: Annual cycle of temperature and precipitation

The results are shown in Figure 4.5.3. As can be seen, no model performs best with respect to all measures, thus emphasising the need for use of an ensemble of RCM projections for the impact assessment. The differences between the models are largest for the simulation of seasonal patterns and extremes (F2 and F4).

4.5 Regional climate model projections

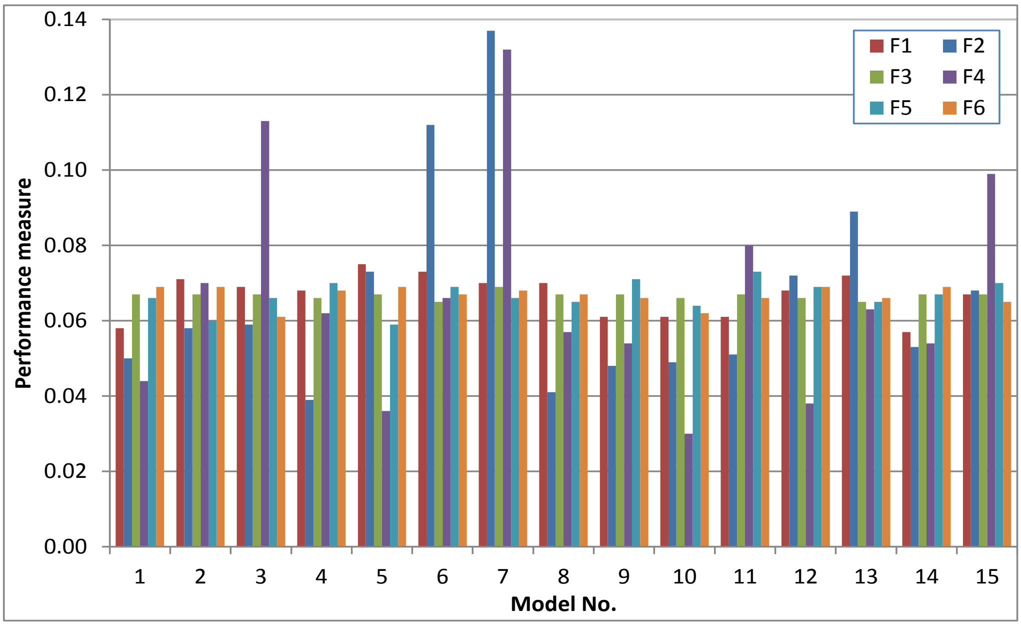


Figure 4.5.3. Performance measures for RCM models in the ENSEMBLES project (data taken from Christensen et al., 2010). Larger performance measures correspond to better performance. The performance measures have been normalised so that the sum of a measure for the 15 models equals 1. The models used here are listed in table A4 in the appendix.

Uncertainty in RCMs

Uncertainty in RCM projections are caused by uncertainty in the driving GCMs (section 4.4) and climate forcing scenarios (section 4.3). In addition, RCM inter-model uncertainty due to differences in the numerical cores and physical parameterisations used to describe sub-grid scale processes add to the total uncertainty (section 5.3).

As part of the PRUDENCE project, an uncertainty analysis was performed, quantifying the contributions to the total uncertainty from RCMs, GCMs, climate forcing scenarios, and internal model variability (different RCM runs with the same RCM/GCM/scenario combination) (Déqué et al., 2007). Results for the whole European model domain are shown in Figure 4.5.4. The results show that different sources are dominant depending on the climate variable and season considered. For instance, for temperature GCM variability is more important than RCM variability, whereas for precipitation RCM variability has a larger contribution. Especially for summer precipitation where convective precipitation is dominating the RCM variability has the largest contribution.

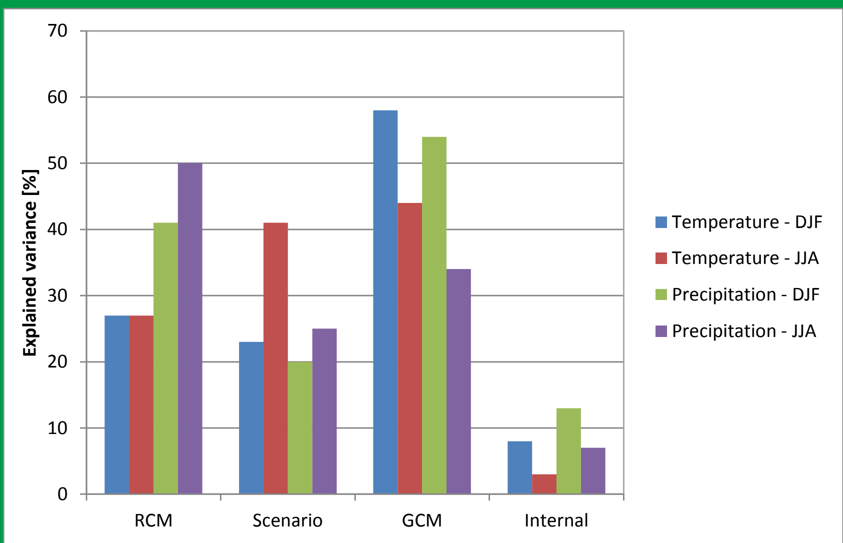


Figure 4.5.4. Percentage of the total variance explained by RCM, scenario, GCM and internal RCM variability (data taken from Déqué et al., 2007). Results are shown for mean temperature and precipitation in winter (DJF) and summer (JJA). The different contributions do not sum up to 100% since the covariance terms have not been included in the variance decomposition.

4.6 Sea level projections

Why are sea levels rising and what are the impacts on water resources?

One important impact of global warming is sea level rise. This is mainly caused by thermal expansion of seawater and melting of land-based ice, including glaciers and the Greenland and Antarctica ice sheets. Sea level changes are not uniform. Regional changes are caused by differences in the rates of oceanic thermal expansion, changes in wind and atmospheric pressure, and changes in ocean circulation (meteo-oceanographic factors) as well as changes in the gravity field of the Earth due to melting of ice. In addition, important non-climate processes may add to the relative change of the sea water level, such as glacial isostatic adjustments, tectonics, and subsidence (e.g. by overexploitation of groundwater). In addition to changes in the mean sea level, changes in storm characteristics may influence the frequency and magnitude of storm surges.

Sea level rise may have significant impacts on water resources. These include increased risk of flooding/ inundation caused by direct flooding from the sea (storm surges) and fluvial flooding due to backwater effects, saltwater intrusion of both surface waters and groundwater, and impeded drainage and increase in groundwater table.

Sea level projections

The projected global mean sea level rise from IPCC's 4th Assessment Report (Meehl et al., 2007) is given in Table 4.6.1. Considering the six SRES scenarios a sea level rise in the range of 0.18-0.59 m has been projected. The regional variation in sea level from the global mean due to meteo-oceanographic factors is shown in Figure 4.6.1.

Regional changes in the gravity field are caused by redistribution of mass from Greenland and Antarctica. When an ice sheet melts, the volume of water in the ocean increases, but the gravitational pull on the ocean close to the ice sheet decreases. The net effect is that sea-level rise occurs faster in areas further away from the ice sheet. Regional variations of sea level rise caused by changes in the gravity field have not yet been studied in detail, but the effect

Table 4.6.1. Projected global mean sea level rise for the different SRES scenarios reported in the IPCC 4th Assessment Report given as the 5% to 95% range in [m] between 1980-1999 and 2090-2099 (Meehl et al., 2007).

	B1	B2	A1B	A1T	A2	A1F1
Lower (5%)	0.18	0.20	0.21	0.20	0.23	0.26
Upper (95%)	0.38	0.43	0.48	0.45	0.51	0.59

60-second summary...

- A number of projections of sea level rise exist. These are based on physically-based models (reported in the IPCC 4th Assessment Report) and palaeo analogue and empirical methods that relate sea level rise to changes in temperature or other climate variables.
- Besides changes in global sea level, changes in regional and local sea level due to changes in ocean density and circulation, and non-climate changes such as isostatic adjustments and subsidence, should be taken into account. For assessment of flooding and inundation, changes in the frequency and magnitude of storm surges should be addressed.
- There are large uncertainties in the sea level projections. Current knowledge suggests that the projections reported in the IPCC 4th Assessment Report of a global sea level rise of 18-59 cm by 2100 is probably at the lower end. Newer projections report sea level rise in the range 0.5-2.4 m.
- Choice of projections will be case specific, depending on the vulnerability and associated risk of sea level rise for the region being considered. It is recommended to apply a range of sea level rise for the impact assessment, representing a lower, upper, and e.g. a median change. For studies with large potential impacts, it is recommended to use a high-end scenario.

4.6 Sea level projections

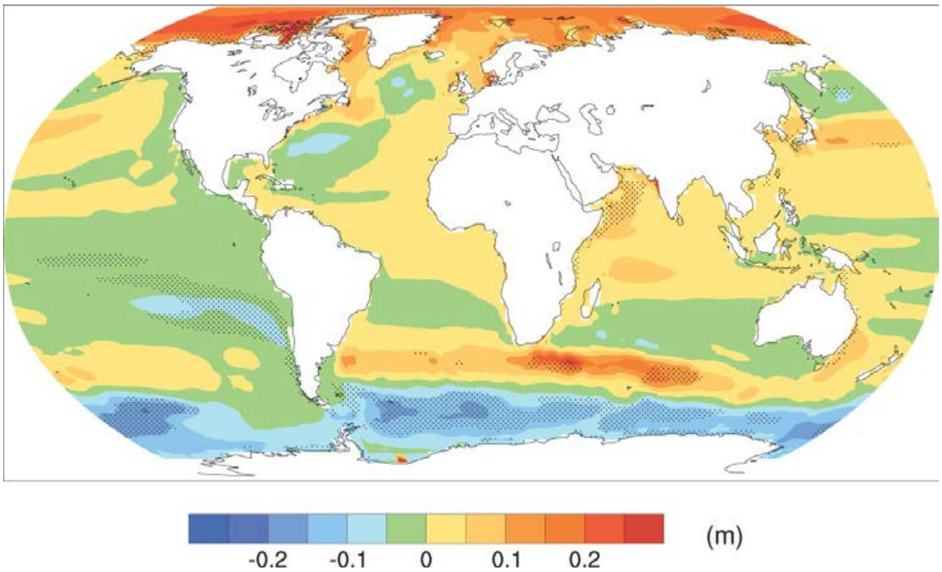


Figure 4.6.1. Regional sea level change due to meteo-oceanographic factors relative to the global average sea level rise calculated as the difference between 2080-2099 and 1980-1999, as an ensemble average over 16 GCMs forced with the SRES A1B scenario (Meehl et al., 2007).

Table 4.6.2. Recently published global sea level rise projections in 2100 relative to the period 1980-2000.

Range of sea level rise by 2100 [m]	Method	Source
0.18-0.59	Physically-based modelling	Meehl et al. (2007)
0.5-1.4	Semi-empirical	Rahmstorf (2007)
0.8-2.4	Palaeo-climate analogue	Rohling et al. (2008)
0.55-1.1	Synthesis	Vellinga et al. (2008)
0.8-2.0	Physical -constraint analysis	Pfeffer et al. (2008)
0.56-0.92	Palaeo-climate analogue	Kopp et al. (2009)
0.75-1.9	Semi-empirical	Vermeer and Rahmstorf (2009)
0.72-1.6	Semi-empirical	Grinsted et al. (2009)
0.5-2.0	Synthesis	Nicholls et al. (2011)

Table 4.6.3. Projected sea level rise in [m] by 2100 for the RCP scenarios (Jevrejeva et al., 2011). The sea level rise is given relative to the period 1980-2000.

	RCP8.5	RCP6	RCP4.5	RCP2.6
Lower (5%)	0.81	0.60	0.52	0.36
Median (50%)	1.10	0.84	0.74	0.57
Upper (95%)	1.65	1.26	1.10	0.83

could be significant (Nicholls et al., 2011).

Since the publication of the 4th Assessment Report, the sea level projections have been debated. Observations of accelerations of the ice sheet discharges in Greenland and Antarctica could not be explained by state-of-the-art ice sheet models, suggesting that the IPCC projections underestimated the sea level rise. A number of studies have been conducted following the 4th Assessment Report using different approaches for projecting sea level rise. These modelling approaches include use of palaeo-climate analogues and semi-empirical methods that relate changes in global sea level with changes in temperature or other climate variables. An overview of projected changes is shown in Table 4.6.2. Recently, Jevrejeva et al. (2011) has published projected sea level rise based on the new RCP scenarios using the semi-empirical methodology by Grinsted et al. (2009). The results are reported in Table 4.6.3.

All newer projections indicate higher sea level rises by 2100 than reported in the IPCC 4th Assessment Report. However, large uncertainties exist. With respect to the temporal evolution of the global sea level rise Nicholls et al. (2011) suggest using a quadratic function, assuming zero sea level rise in 1990.

4.6 Sea level projections

Uncertainty in sea level rise

There are large uncertainties related to the projection of sea level rise as seen in the reported results in Tables 4.6.1-4.6.3. One of the largest uncertainty sources is the lack of knowledge of key processes and feedbacks between climate and the ice sheets. Acceleration of the ice sheet discharge above the linear rate used in the 4th Assessment Report (Meehl et al., 2007) may lead to significantly larger sea level rise. In recent years, much research has been directed to improvement of the modelling of ice sheet dynamics (Church et al., 2011).

The local and regional variation of sea level rise is another major source of uncertainty. This may contribute up to about 25% of the total sea level rise (Church et al., 2011) and the uncertainty in the changes of oceanic density may be up to several tens of centimeters relative to the global mean value (Nicholls et al., 2011). The uncertainty in local non-climate changes that will affect the change in sea level rise may be substantial (e.g. isostatic changes and subsidence).

If extreme sea water level is of concern, the change in storminess and storm surge characteristics are important. In this regard, there are large uncertainties in current projections of changes in the intensity and frequency of tropical cyclones and extratropical storms. The increase of mean sea level will also affect tides and storm surge propagation in shallow waters.

Working with sea level rise

Where can I find sea level projection data?

Projections of changes in global sea level can be found in IPCC 4th Assessment Report and in newer studies, see overview in Tables 4.6.1-4.6.3. The projections are typically given as a range with a lower (5%) and upper (95%) percentile. With respect to regional changes in mean sea level due to changes in ocean density and circulation, projections are uncertain and fewer projections exist. Projections are available in IPCC 4th Assessment Report and are shown in Figure 4.6.1.

The global projections are usually given as sea level rise by 2100 relative to the sea level in 1990. For estimation of the temporal evolution, a quadratic function can be used. If non-climate factors such as isostatic changes and subsidence are important, these should be estimated and included in the projection of the sea water level. For assessment of flooding, projections of extreme sea water level should be taken into account. For some regions, modelling studies have been conducted for analysing changes in storm surge statistics.

Choice of projections

The projections of sea level rise have large uncertainties. The choice of projections will be case specific, depending on the vulnerability and associated risk of sea level rise for the region being considered. For instance, in UK a scenario of up to 2m sea level rise by 2100 has been developed (denoted the H++ scenario). The probability of this scenario is unknown but was found to be relevant due to large potential impacts of such sea level rise (Nicholls, 2011).

In general, it is recommended to apply a range of sea level rise for the impact assessment, representing a lower, upper, and median change. Current knowledge suggests that the projections in the IPCC 4th Assessment Report are probably in the lower end, and it is recommended to consider the newer estimates (reported in Tables 4.6.2-4.6.3) in the analysis. For studies with large potential impacts, it is recommended to use a high-end scenario such as the UK H++ scenario.

4.7 Key variables for water resources

Which variables are available from climate models?

Key climate variables for water resources application include air temperature, precipitation, evapotranspiration, wind, and sea level. Air temperature (2m), precipitation and wind (10 m wind speed and directions) are basic variables from global climate models (GCM) and regional climate models (RCM). Different quantities for total precipitation, including snowfall, convective and non-convective rainfall may be specific output variables.

Evapotranspiration is often not available directly as an output variable because it depends on land cover. Potential evaporation can be calculated from the basic variables using different equations, such as the Penman Montieth equation.

Alternatively, simple empirical equations can be used for calculation of potential evapotranspiration from air temperature alone. In a study in the UK, Kay and Davies (2008) showed that using a simple empirical model based on temperature gave a better fit to observed data than Penman Montieth, probably due to the fact that some of the variables needed for Penman Montieth are poorly estimated by the climate models.

Sea level data are output from GCMs but normally not from RCMs, since RCMs usually only consider the atmosphere and use prescribed states of the ocean, sea ice and land (see RCM projection). For projection of sea level also other models are used based on palaeo-climate analogues and semi-empirical methods (see Sea level projections).

Resolution and projection horizon?

The available raw GCM and RCM model data usually have output of basic variables on a daily time step, and in some data archives also sub-daily data are stored (e.g. 3-hourly and 6-hourly data). Hourly or sub-hourly data are normally not readily available but may be obtained directly from the modelling groups.

Typically, GCM and RCM projections are available up to 2100, some only up to 2050, and few models have projections available beyond 2100. Newer GCM and RCM simulations are transient with output available from 1950 to 2100. Some simulations have output only for specific time slices, typically for 30 year periods, e.g. 1961-1990 (often referred to as baseline or control period) and 2071-2100. For interpolation between time slices the temporal evolution from a transient simulation with another climate model may be used, e.g. a transient GCM simulation can be used to interpolate time slice simulations of an RCM.

How are climate projections validated?

Climate projections are predictions of the future and thus cannot be explicitly validated. Models can only be validated to an extent by comparing performance over a historic period with observed data. However, this validation assumes that the models which are able to reproduce characteristics of historic climate (which has certain ranges of temperature and rainfall and certain climate patterns) are also better able to characterise future climate. Validation of specific outputs against local data can be undertaken after downscaling. However, it is important to note that this this will be a validation of both the performance of the climate model and downscaling method. Validation and comparison of GCMs and RCMs are further discussed in GCM projections and RCM projections.

General information of climate change

For initial screening or fast qualitative assessments of the impact of climate change, information about climate change for the considered key hydrological variables and region in question may be available in international or national assessment reports or from more detailed local studies. A general overview of climate change in different parts of the world can be found in the IPCC 4th Assessment Report (Christensen et al., 2007).

4.8 Statistical downscaling

What is statistical downscaling?

Statistical downscaling methods establish links between large-scale climate phenomena and observed local-scale climate. Statistical downscaling is necessary because GCM and RCM projections are produced at scales that may not be appropriate for studying local impacts. In addition, statistical downscaling is used to correct biases in GCM and RCM projections. This is often referred to as bias correction. In some applications, temporal downscaling also has to be considered (e.g. downscaling of daily climate variables from GCM and RCM projections to hourly or sub-hourly resolution at the local scale).

A large number of statistical downscaling procedures have been proposed for climate change impact studies. This review uses the classification given by Maraun et al. (2010), who grouped statistical downscaling methods using the categories perfect prognosis (PP) , model output statistics (MOS), and stochastic weather generators (WG).

PP methods establish links between ***observed*** large-scale climate and observed local-scale climate and use these relationships to downscale large -scale climate model projections. MOS methods establish links between ***simulated*** climate and local-scale climate to downscale climate model projections.

PP methods are usually used to post-process GCM output, while MOS methods are normally used to post-process RCM output. However, it is possible to use either approach on both RCM and GCM projections.

The two approaches are compared in figure 4.8.1. The figure also differenti-

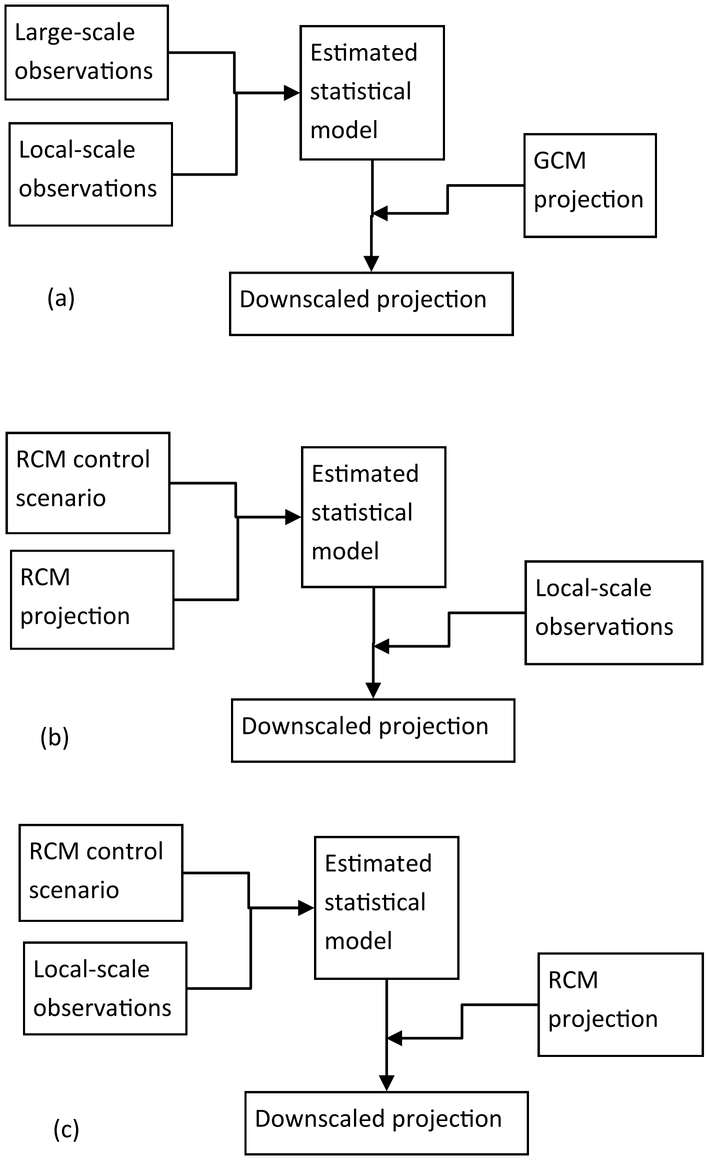


Figure 4.8.1. *Classification of statistical downscaling methods. (a) In Perfect prognosis (PP), a statistical relationship is developed between observed large-scale weather and observed local scale weather. This relationship is then used to downscale GCM projections. (b) In model output statistics (MOS), for the Type 1 approach, a statistical relationship is developed between an RCM control simulation and an RCM projection. This relationship is then used to develop a downscaled projection using local-scale observations. (c) In MOS, for the Type 2 approach, a statistical relationship is developed between an RCM control simulation and local observations. This relationship is then used to downscale RCM projections.*

4.8 Statistical downscaling

60 second summary...

- Statistical downscaling of climate model output is used to project climate model projections to local scales and to remove biases associated with climate model simulations of weather variables.
- Perfect prognosis methods develop relationships between observed large-scale climate variables and observed local climate and are most often used to downscale GCM output.
- Model output statistics methods develop relationships between simulated climate variables and observed local climate and are most often used to downscale RCM output.
- Stochastic weather generators represent a versatile class of statistical downscaling methods that include changes in different statistical characteristics to downscale climate model output and allow generation of time series of projected variables of unlimited length.
- Choice of statistical downscaling method is crucial if focus is on extremes and less important in the case where the impacts are determined mostly by average conditions on larger scales.

ates between Type 1 and Type 2 MOS (see below).

Perfect Prognosis (PP) methods

In PP, a statistical model is built that relates observed local-scale climate variables (predictands) to observed large-scale climate variables (predictors). This model is then used to downscale GCM projections of the future climate. The implicit assumption of PP methods is that GCM projections of the future are physically plausible and that relationships between observed phenomena in the past will continue to be valid in the future.

The predictor variables used in PP methods should be variables that are simulated reliably by GCMs; otherwise, the perfect prognosis assumption is not reasonable. Predictor variables are usually elements of the large-scale circulation, such as geopotential heights or measures of humidity.

Types of statistical models used in PP include linear regression models, weather-typing schemes, non-linear methods, and analog methods.

Linear regression models

Linear regression models establish a linear relationship between large-scale predictors and a local-scale predictand. Because not all elements of local-scale variation can be explained by large-scale predictands, the model should include a noise term. In the most basic approaches, the noise term is assumed to be normally distributed. For downscaling precipitation, other distributions have been applied, such as a gamma distribution.

Weather typing schemes

Weather typing schemes are a special case of statistical model in which continuous predictor variables are replaced by discrete weather types. Weather typing schemes can be used to develop direct statistical relationships between large-scale weather types and local weather or to develop probability distributions of local weather phenomena.

Nonlinear regression

Nonlinear regression methods can be used to model nonlinear and nonadditive relationships between predictors and predictands (e.g., using artificial neural networks (ANNs)).

Analogue methods

In analogue methods, relationships are developed between large-scale weather patterns and historical local-scale observations. Then, when large-scale weather phenomena are simulated in the future, it is assumed that the resulting local scale weather is identical to the historical weather sequence most closely related to the simulated large-scale weather. A limitation of analogue methods is that only local weather sequences that have already occurred in the past can be projected to the future.

For more information on downscaling see the ENSEMBLES Downscaling Portal (https://www.meteo.unican.es/downscaling/ensembles). The web portal facilitates statistical downscaling using perfect prognosis methods. It provides access to calibration data sets, tools for developing statistical models, and GCM projections for downscaling. The products are not available for commercial use.

Model Output Statistics (MOS)

In MOS, simulated weather variables are linked to observed local variables. In contrast to PP, the predictor variables used in MOS are generally the same as the predicands. For example, simulated precipitation would be used to predict local scale precipitation.

Because precipitation simulated in GCMs and RCMs is unrealistic at local

4.8 Statistical downscaling

scales, MOS can be used to correct GCM and RCM precipitation estimates. MOS is normally used to correct RCM precipitation, as RCMs are capable of resolving important physical processes relevant to regional-scale precipitation (e.g., orographic effects) that are not resolved by GCMs.

When estimating an MOS model, both predictors and predictands may refer to the same spatial scale. In this case, MOS is used only for statistical correction. However, gauge data are typically used as local information and, in this case, MOS is also used to downscale RCM output from a regional scale to the local scale.

MOS methods typically establish relationships between statistical characteristics (e.g., mean and variance) or the full probability distribution of the simulated and observed variables. These relationships can then be used to generate projections of downscaled time series for impact modelling.

An implicit assumption of MOS methods is that the climate model represents changes in climate variables better than absolute values (i.e., climate model biases are assumed to remain constant in a changing climate). This assumption is questionable, and recent research shows that biases may not be time invariant in a warming climate (Christensen, et al., 2008).

MOS methods include change factor methods and quantile mapping, and can be formulated in two different ways. In the first approach (referred to as the Type 1 approach in the following), estimated changes from a climate model simulation between a control period (representing current climate) and a future period are imposed on the local climate variable to generate the downscaled projection (see Figure 4.8.1b). In the second approach (Type 2), estimated changes between the local observed climate variable and the climate model simulation in the control period are imposed on the simulated climate variable for the future period to generate the downscaled projection (see Figure 4.8.1c).

Change factor methods

Change factor methods are the most commonly used methods for statistical downscaling. In Type 1 approach, the change in the mean of the variable from current to future climate simulated by the climate model is used to provide downscaled projections, . This method is often referred to as the ”delta-change” or ”perturbation” method. In the case of precipitation, the relationship is given on the next page.

In case of temperature, the correction is additive rather than multiplicative. For potential evapotranspiration, a multiplicative correction is applied.

When using change factors, the changes in statistical characteristics are typically estimated for different seasons or months so that differences in seasonal projections are taken into account.

Working with Perfect Prognosis (PP)

1. Identify the spatial domain of the predictor data set. The spatial domain should be large enough to include the large-scale variables that impact local weather while excluding regions with few local impacts.

2. Identify an appropriate large-scale data set. The large-scale data set can consist of observed or reanalyisis data. The large-scale data set should not be a GCM control simulation, or the resulting statistical relationship will only be valid for that GCM.

3. Identify predictor variables. Predictor variables can be continuous elements of the large-scale data set or discrete weather classes. The selected predictor variables should be simulated with reasonable accuracy by GCMs and sensitive to climate change signals.

4. Identify the spatial domain of the predictand data set. The spatial domain can be a single point, multiple points, or a grid.

5. Estimate a statistical model that relates predictor and predictand data sets.

6. Apply the statistical model to a GCM projection of predictor values in order to estimate projected values of predictands.

4.8 Statistical downscaling

$$p_{i+T}^{fut} = p_i^{obs} \cdot \frac{\overline{p^{fut,sim}}}{\overline{p^{con,sim}}}$$

Where

p_{i+T}^{fut} = precipitation at time $i+T$ in the future

p_i^{obs} = precitation at time i in the observed record

$\overline{p^{fut,sim}}$ = average simulated precipitation in future period

$\overline{p^{con,sim}}$ = average simulated precipitation in control period

In the Type 2 approach, the difference between average observed values and average values simulated in the control period is used to downscale the future simulation:

$$p_i^{fut} = p_i^{fut,sim} \cdot \frac{\overline{p^{obs}}}{\overline{p^{con,sim}}}$$

Where

p_i^{fut} = precipitation at time i in the future

$p_i^{fut,sim}$ = precitation at time i in future simulation

$\overline{p^{obs}}$ = average observed precipitation

It is important to note that in the Type 1 approach, the temporal precipitation structure (dry-wet sequences) of the observed precipitation is preserved in the projection, while the future simulated structure is applied in the Type 2 approach.

In the case of multiplicative correction (e.g. precipitation correction), the "delta-change" approach assumes that the coefficient of variation (CV) of the distribution will be unchanged in the future. Changes to future variability are important for predicting changes to extreme values (e.g., floods and droughts). A method that specifically considers changes in both the mean and variance using the Type 1 approach was proposed by Sunyer et al. (2011). In this case, downscaled future precipitation can be estimated using a non-linear empirical relationship.

$$p_{i+T}^{fut} = a \cdot \left(p_i^{obs}\right)^b$$

Where a and b are estimated from changes in the mean and CV from climate simulations. While this method accounts for changes in both mean and variance, the temporal structure (wet-dry sequences) of the historical precipitation record remains unchanged.

It is possible to formulate a similar method for the Type 2 approach (Leander and Buishand, 2007), although details are not presented here. Methods that adjust both mean and variance have also been developed for temperature (e.g., Leander and Buishand, 2007).

Quantile mapping

An MOS approach that considers correction of the entire probability distribution of the climate variable is quantile mapping. In this method, using the Type 2 approach, the cumulative distribution function (CDF) for the control period simulation is adjusted to match the observed CDF. The resulting mapping is then used to map the distribution of simulated future values to a projected distribution of local-scale climate. The mapping is done using empirical quantiles or by fitting a probability distribution. To put special emphasis on the extreme tail of the distribution, combined distribution functions have been proposed, e.g., by fitting one distribution up to the 95th percentile and another distribution for the upper 5% (e.g., Yang et al., 2010). The quantile mapping method can also be formulated using the Type 1 approach.

Working with Model Output Statistics (MOS)

1. Identify the GCM or RCM simulation for which the MOS model will be developed. MOS is usually used with RCM output but can also be used with GCM output. The MOS model will only be valid for the GCM/RCM simulation that is used to estimate the model.

2. Identify the predictands (observed values) to be downscaled. Normally, predictand values will be observed time series but can also be properties of observed distributions.

3. Identify the spatial domain of the predictand data set. The spatial domain can be a single point, multiple points, or a grid.

4. Select a downscaling method, e.g., the change factor method or quantile mapping, and type of downscaling approach (Type 1 or Type 2).

5. Apply downscaling method to RCM/GCM and observed data sets in order to estimate a statistical model.

6. Apply the statistical model in order to estimate projected values of predictands.

4.8 Statistical downscaling

Weather generators

Different stochastic weather generators (WG) have been applied for statistical downscaling of climate model projections. Some WGs use climate characteristics derived directly from RCMs, resembling MOS methods, while other WGs use large-scale predictors as in PP methods.

For statistical downscaling of precipitation from RCMs, the most widely applied WGs are Markov chain and Poisson cluster process models. Changes in the statistical characteristics used to parameterise the WGs are estimated from the RCM simulations, and these changes are then superimposed on statistical characteristics estimated from observed record to obtain WGs for generation of downscaled precipitation in the future climate. Markov chain WGs typically include changes in the transition probabilities between dry and wet states, and the statistics of precipitation intensity (e.g. mean and variance). For Poisson cluster process WGs, changes in the temporal structure of precipitation events, wet/dry state probabilities and statistics of precipitation intensity (mean, variance and skewness) are usually applied. The inclusion of skewness is important for generation of extreme events.

Compared to the change factor-based MOS methods described above, WGs utilise changes in different statistics representing both the temporal structure (wet-dry sequences) and the distribution of precipitation intensity. Another advantage of WGs is that they can be used for generation of synthetic time series of arbitrary length. This is important when considering changes in extreme events where long time series can be generated by a WG to obtain robust projections of the extreme value distribution. However, WGs may introduce biases in the generated precipitation series, which should be addressed in the calibration of the WG.

For impact studies where climate variables other than precipitation are important (e.g. temperature and wind speed) simultaneous generation of these variables may be important in order to preserve a physically consistent dependence between the variables. For generation of time series of multiple weather variables, models have been developed that combine WGs for precipitation with statistical models of other climate variables conditioned on precipitation (e.g. Kilsby et al., 2007).

Recommendations

For the impact analysis, it is important to identify the climate variables and associated characteristics (e.g. mean value, variability or extremes) that are most sensitive for the problem at hand and therefore should be accurately

Uncertainty in statistical downscaling

Sunyer et al. (2012) and Madsen and Sunyer (2011) analysed five different downscaling methods with four different RCM simulations from the ENSEMBLES data archive. A separation of the total variability into contributions from the RCMs and the statistical downscaling methods showed that RCM variability contributes the most when considering the mean precipitation, whereas statistical downscaling is much more important for the extremes (see Figure 4.8.1).

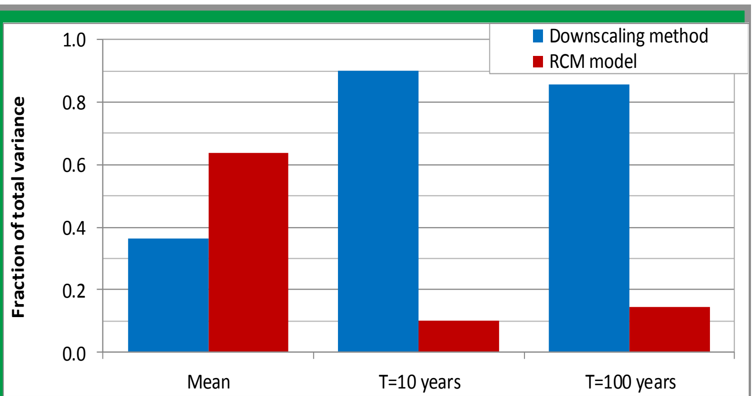


Figure 4.8.1 Fraction of the total variability related to the statistical downscaling method and the RCM model for mean precipitation and for extreme precipitation for 10-year and 100-year return periods (adapted from Madsen and Sunyer, 2011)

These results suggest that the choice of statistical downscaling method is less important in the case where the impacts are determined mostly by average rainfall properties. On the other hand, when the properties of extreme precipitation are important, the choice of the statistical downscaling method is crucial.

4.8 Statistical downscaling

Case study: Statistical downscaling

Statistical downscaling was used by DHI to help develop estimates of how climate change might impact flood risks in the Vidaa River catchment. Fifteen RCM/GCM projections from the ENSEMBLES data archive were downscaled to produce estimates of precipitation, temperature and potential evapotranspiration. For all three variables, MOS models were developed from RCM simulation of the historical climate and observed data.

For temperature and potential evapotranspiration, a change-factor method was used to develop a relationship between average monthly simulated and observed values. For precipitation, a method that uses both changes in the mean and changes in the variance was applied. Since the impact assessment focuses on changes in extreme precipitation, the change in the variability of precipitation were important to include in the downscaling.

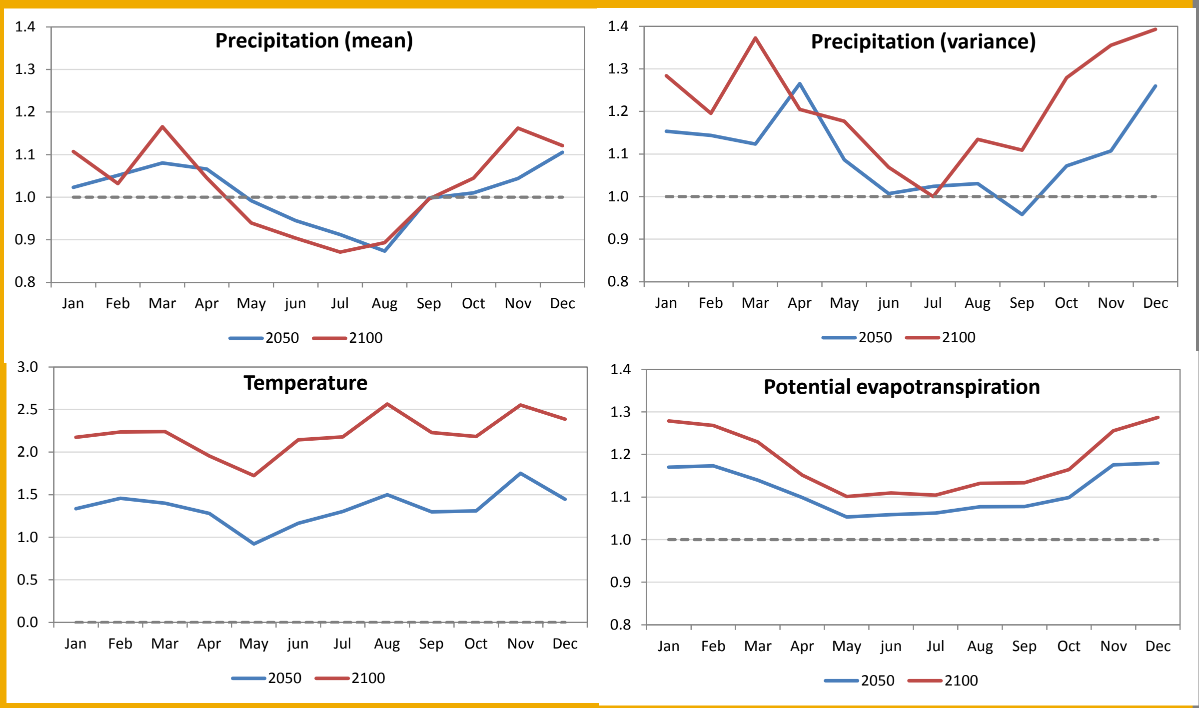


Figure 4.8.2 Relative change in mean and variance of daily precipitation and mean potential evapotranspiration, and absolute change in temperature (degree Celsius) for future (2050 and 2100) climate.

For calculation of the change factors, catchment averages of daily precipitation and temperature from the RCM/GCM models were used. The changes were based on 30-year periods of climate model data, respectively, 1980-2009 representing the present climate, 2035-2064 representing the future climate in 2050, and 2070-2099 representing the future climate in 2100. To take seasonal variations into account, monthly change factors were calculated. Results shown in Figure 4.8.2 are based on weighted aver-

downscaled. In this regard one should be aware of the limitations and advantages of the different statistical downscaling methods. In general, choice of statistical downscaling method is less important in the case where the impacts are determined mostly by average conditions on larger scales. On the other hand, when the properties of extremes are important for the impact assessment, the choice of statistical downscaling method is crucial.

Statistical downscaling with PP methods based on GCMs has less skill for downscaling extremes, and is therefore not, in general, recommended if focus is on the extreme tail of the distribution. With respect to MOS methods, the widely applied delta change method implicitly assumes that the change in the extreme tail is the same as the change in the mean. Thus, this method is not recommended for analysing changes in extremes. MOS methods that include also changes in the variance or changes in the full distribution using quantile mapping are generally expected to provide a better representation of the change in extremes. The performance of WGs is highly dependent on the underlying statistical models and parameterisations but have the potential for better describing changes in different characteristics as well as relations between different variables.

4.9 Developing projections of extremes

How well are extremes simulated in climate models?

Extremes are by definition unusual events, and it is hard to accurately describe them statistically even from observed historic records. Some processes such as convection that is the governing process of short-duration rainfall extremes may take place on scales much smaller than modelled by climate models. GCMs are operating on a spatial scale that cannot reliably simulate rainfall extremes. RCMs have the potential for better representation of rainfall extremes. The improved resolution will provide a better simulation of orographic uplift, but the resolution of state-of-the-art RCMs is still too coarse to explicitly simulate convection, and physical parameterizations are needed.

What methods can we use to analyse data?

In general, climate model data cannot be used directly for impact assessment, and bias correction and statistical downscaling is needed (see Statistical downscaling). This is particularly important when considering extremes. For downscaling extreme precipitation, statistical correction methods using mean and variance correction or quantile adjustments, or stochastic rainfall generators are preferable. Especially, use of rainfall generators allows simulation of ensembles of long time series, which can be used for a more reliable assessment of the extreme value statistics (although at the cost of potential introduction of model bias via the rainfall generator). For projection of droughts, standard statistical correction procedures cannot be used since they project the same dry-wet spell properties as in the observed record. Rainfall generators explicitly include changes in dry-wet spell properties and are therefore better suited for drought analysis. Alternatively, rather than downscaling rainfall time series, one can estimate changes in the extreme value statistics directly by comparing the extreme value distributions fitted to climate model data in a baseline period and future period, respectively.

Standard extreme value analysis methods have the underlying assumption of stationarity, which is inappropriate in a changing climate. The standard approach to non-stationary extreme value analysis is to analyse time slices, assuming stationary conditions within each period, and then compare the differences in extreme value statistics.. Usually, 30-year periods are used for analysing time slices. For a more detailed estimation of the temporal evolution in the extreme value statistics, a moving window approach can be used. Recent research in non-stationary extreme value analysis attempts to describe non-stationarity using standard extreme value distributions (such as the generalized extreme value distribution) with time varying parameters (e.g. Hanel et al., 2009).

60-second summary...

- Estimation of changes in extremes is particularly challenging due to large uncertainties in the projection of extreme events in climate models, non-stationarity of extreme value statistics, and use of small samples for estimation of rare events.
- More advanced statistical downscaling procedures should be used to downscale RCM projections that consider changes in statistical properties relevant for generating extremes and not only changes in average characteristics.
- If higher temporal resolution is required than the resolution of the climate model projection, temporal downscaling or disaggregation should be applied.
- In some countries guidelines have been published that provide recommended change factors in extreme value statistics to be used to adjust design rainfalls and design floods for assessing impacts of existing and design of new infrastructure.

Developing projections

4.9 Developing projections of extremes

What about the probability of two separate events occurring at the same time for example high sea levels and heavy rainfall? How do we estimate these extremes?

In some cases a combination of two (or more) relatively large events can have a significant impact and needs to be investigated. For example high sea levels, high rainfall or a combination of the two may lead to elevated levels in a river and overtopping of a flood defence. In these cases it is important to consider the probability of the events (of different variables) occurring at the same time. If the two variables are independent, the combination of their probabilities is straightforward, given as the product of their probabilities. However, in many cases the variables are not independent and in these cases the estimation of the joint probability is more complex. One method used in the UK is the calculation of joint probability by defining a dependence factor which describes how dependent variables are (DEFRA 2005). In recent years, Copula methods have found widespread use within hydrology for estimation of joint probabilities.

Uncertainty in projections of extremes

Projections of extremes from climate models inherit the underlying uncertainties in the climate forcing scenario, GCM and RCM. Especially, in relation to projection of extremes, climate models may have large uncertainties related to the different parameterization schemes used to describe sub-grid processes (see RCM projections).

The extreme value statistics have large sampling uncertainties, especially when extrapolating to return periods much larger than the available record used for the estimation. The sampling uncertainty will become even larger when using climate model projections in the estimation due to non-stationarity of the extreme value statistics.

4.9 Developing projections of extremes

Working with projections of extremes

Creating your own projection

Statistically downscaled RCM projections should be used as input to hydrological/hydraulic simulation models for projection of hydrological extremes and assessment of the impact of changes in extreme value statistics. For input to continuous simulation models, statistical downscaling methods based on correction of historical climate time series using either mean and variance correction or quantile mapping are recommended (see Statistical downscaling). Stochastic weather generators may also be used, but they should be carefully calibrated using changes in RCM statistics to provide a proper description of the extreme value characteristics. However, a particular advantage of using a stochastic weather generator is its ability to generate long climate time series to better represent the simulation of extreme events.

For input to event-based simulation models used in design flood studies, changes in design rainfall can be estimated by statistical extreme value analysis of the downscaled rainfall time series using the methods recommended above. Alternatively, one can perform a statistical extreme value analysis directly on the RCM rainfall data. In this case, extreme value analysis is performed on a control period and a future period, representing the required projection horizon. The difference between the two analyses then represents the change in the extreme value statistic to be added to the current design event that is then used as input for the event-based simulation model.

Typically, RCM data with daily resolution are available for the statistical downscaling. If higher temporal resolution is required, temporal downscaling or disaggregation should also be included in the statistical downscaling. In this case, stochastic weather generators may be used.

Using existing guidelines

In some countries guidelines exist on how to incorporate changes in hydrological extremes in the assessment of climate change on existing infrastructure and for design of new infrastructure. Typically, these guidelines provide a recommended change (expressed in terms of a climate change adjustment factor) in the design quantity (e.g. design rainfall or design flood) compared to current design basis as a function of design life time and design return period. Some examples of guidelines are shown below.

Table 4.9.1 Summary of some existing European guidelines on climate change adjustment factors on design floods and design rainfall (adapted from Madsen et al., 2012).

Country	Variable	Guideline	Reference
Belgium	Design floods	30% increase for 2100	Boukhris and Willems (2008)
Belgium	Design rainfall	30% increase for 2100	Willems (2011)
Denmark	Design rainfall	20%, 30% and 40% increase for return periods 2, 10 and 100 years for 2100	Arnbjerg-Nielsen (2008)
Germany (Bavaria)	Design flood (100-yr return period)	15% increase for 2050	Hennegriff et al. (2011)
Germany (Bdn-Württ'berg)	Design floods	Increase between 0% and 75% for 2050 depending on location and return period	Hennegriff et al. (2011)
Norway	Design floods	0%, 20% and 40% increase for 2100 based on region, flood season & catchment size	Lawrence and Hisdal (2011)
UK	Design floods	20% increase for 2100	DEFRA (2006)
UK	Design rainfall	10, 20 & 30% increase for 2040, 2070 & 2100	DEFRA (2006)

5. Decision making under uncertainty

5.1 Introduction to decision making under uncertainty

This chapter presents approaches to decision making under uncertainty that may useful in the climate change context. It does not provide guidance on how to compare different adaptation options using methods such as cost-benefit analysis or multi-criteria analysis.

Why use an approach for decision making under uncertainty?

Water resources planners and managers have always had the need to make design and management plans without an exact knowledge of future conditions, and uncertainty regarding future conditions is likely to increase because of climate change. Although the current level of uncertainty in climate projections might be considered unsatisfactory by decision-makers, other processes such as economic development may be equally important and more unpredictable. Despite the uncertainty associated with projecting the future, impacts of climate change and other drivers of water resources development may be significant and reasonable methods exist for using uncertain information in decision making.

What are some approaches that can be used?

Three approaches to climate-related decision making under uncertainty are described: scenario analysis, classical decision analysis and robust decision-making. Although these approaches are thought to represent the state of the art for decision making under climate change uncertainty, other approaches exist and may be useful (for a recent review, see Dessai and van de Sluijs, 2007).

In scenario analysis, a few key uncertain factors are identified and the impact of uncertainty is then characterized by estimating the performance of alternatives under different levels of the uncertain factors. Scenario analysis offers the advantage of conceptual simplicity and can be an effective way to engage with a variety of potential futures. However, the process of selecting scenarios is somewhat arbitrary and there is no established way to use scenarios to make decisions.

Classical decision analysis uses probabilistic information to select among alternatives based on maximum expected utility or other criteria. Classical decision analysis provides a rational framework for decision making. However, despite ongoing research efforts, probabilistic climate change projections are not yet mature, and characterizing uncertainties in terms of probabilities may be distrusted by decision-makers and stakeholders.

To counter some of the limitations of scenario analysis and classical decision analysis, other approaches have been developed. An emerging method that is presented here is robust decision making. Robust decision-making uses a rational approach to develop scenarios that characterize future conditions under which proposed alternatives are most likely to fail. These scenarios are then used to select an alternative that is least vulnerable to failure or refine alternatives to reduce vulnerability. Robust decision-making offers the advantage of a rational approach to scenario development and a decision framework that does not rely on probabilistic estimates.

60-second summary...

- Water resources planners and managers may benefit from using an approach to decision making under uncertainty, particularly given climate change uncertainty.
- Scenario analysis is the approach that is most commonly used with climate change uncertainty, but is somewhat arbitrary and lacks clearly defined rules for decision making.
- Although classical decision analysis using probabilistic estimates of future conditions offers a rational framework for decision making, probabilistic projections of climate change have probably not matured to a point where these forecasts are trusted by decision makers and stakeholders.
- An emerging method, robust decision making, uses a rational approach to identify conditions under which alternatives are likely to fail; this information can then used to identify and design alternatives that are less vulnerable to failure.

5.2 Flow chart for decision making under uncertainty

Gather all necessary information and results from water resources modelling.

↓

Understand the adaptive management approach and the options available in your context (section 5.7).

↓

Involve the necessary stakeholders and partners.

↓

Decide which approach to decision making should be adopted (section 5.1, 5.4, 5.5, 5.6).

↓

Understand the uncertainties inherent in the analysis (section 5.3).

↓

Apply the decision making approach, involving relevant stakeholders as appropriate.

↓

Document the decision making process and make decisions and reasoning publicly available.

↓

Monitor the implementation of the decisions and adjust as necessary based on results and new information. Further analysis may be necessary. (section 5.7)

5.3 The uncertainty cascade

Climate change is analysed using projections of future climates based on scenarios of future development and greenhouse gas concentrations. The uncertainty in climate change projections and responses comes from many sources and is accumulated in each stage of the study (see Figure 5.3.1).

The assessment and communication of uncertainty can ensure better risk assessments, decision making and risk communication.

Uncertainty can be categorised according to three dimensions: nature, level and source (Refsgaard et al., 2012). The nature of uncertainty is categorised into epistemic uncertainty (due to imperfect knowledge), aleatory uncertainty (due to inherent variability) and ambiguity (due to different ways of understanding and interpretation). Aleatory uncertainty can be reduced by gaining more knowledge, whereas aleatory uncertainty is by nature stochastic and irreducible. The uncertainty related to ambiguity can be reduced by knowledge sharing between stakeholders to obtain a common perception of the problem.

The level of uncertainty is related to how uncertainty can be described, such as statistical uncertainty (can be described using statistical theory), scenario uncertainty (cannot be described statistically but possible outcomes can be quantifed using scenarios), qualitative uncertainty (possible outcomes cannot be quantified), recognised ignorance (lack of knowledge is recognised but cannot be further quantified), and total ignorance (lack of awareness). The uncertainty can be divided into different generic sources, such as uncertainty in data, model uncertainty, and context and framing uncertainty.

For climate change impact and adaptation analysis different uncertainty sources are prevalent as illustrated by the uncertainty cascade in Figure 5.3.1. The different sources have different nature and level of uncertainty, which are important to acknowledge for consistent uncertainty assessment and robust decision making. For instance, climate forcing scenarios cannot be treated statistically since they depend on future decisions and are therefore characterised by a range of possible outcomes according to the SRES and RCP scenarios. Uncertainty in GCMs and RCMs is usually treated statistically using an ensemble modelling approach. However, this approach assumes that the available ensemble provides a sufficient representation of the uncertainty and ignores uncertainties due to lack of knowledge of processes and their interaction in the climate system that we are aware of (recognised ignorance) or are not aware of (total ignorance). Thus, as a consequence, the statistical uncertainty obtained from the ensemble modelling approach may underestimate the total uncertainty.

For a given study, some of the uncertainty sources may be more important than others. It is important to understand the relative importance of the various sources of uncertainty, which may be achieved by doing some form of sensitivity analysis. Resources can then be focussed on understanding the impacts of the dominant sources of uncertainty. For example, this may mean using different emissions scenarios, different GCM and RCM projections and using more than one impact model parameterisation.

Although the relative importance of the different uncertainty sources is problem specific, some general observations and examples have been reported and are summarised in the uncertainty boxes in the previous sections:

- The relative contribution of impact model uncertainty compared to the uncertainty in climate projections (section 4.3)
- The relative contributions of climate forcing scenario and GCM model uncertainty compared to the internal variability of the climate system (section 4.4)
- The relative contributions from RCMs, GCMs, and climate forcing scenarios
- The relative contributions from RCMs and statistical downscaling methods (sections 4.5 & 4.8)

The accumulation of the different uncertainty sources in the uncertainty cascade may result in very large uncertainties in impact assessment and adaptation measures. The resulting uncertainty is

5.3 The uncertainty cascade

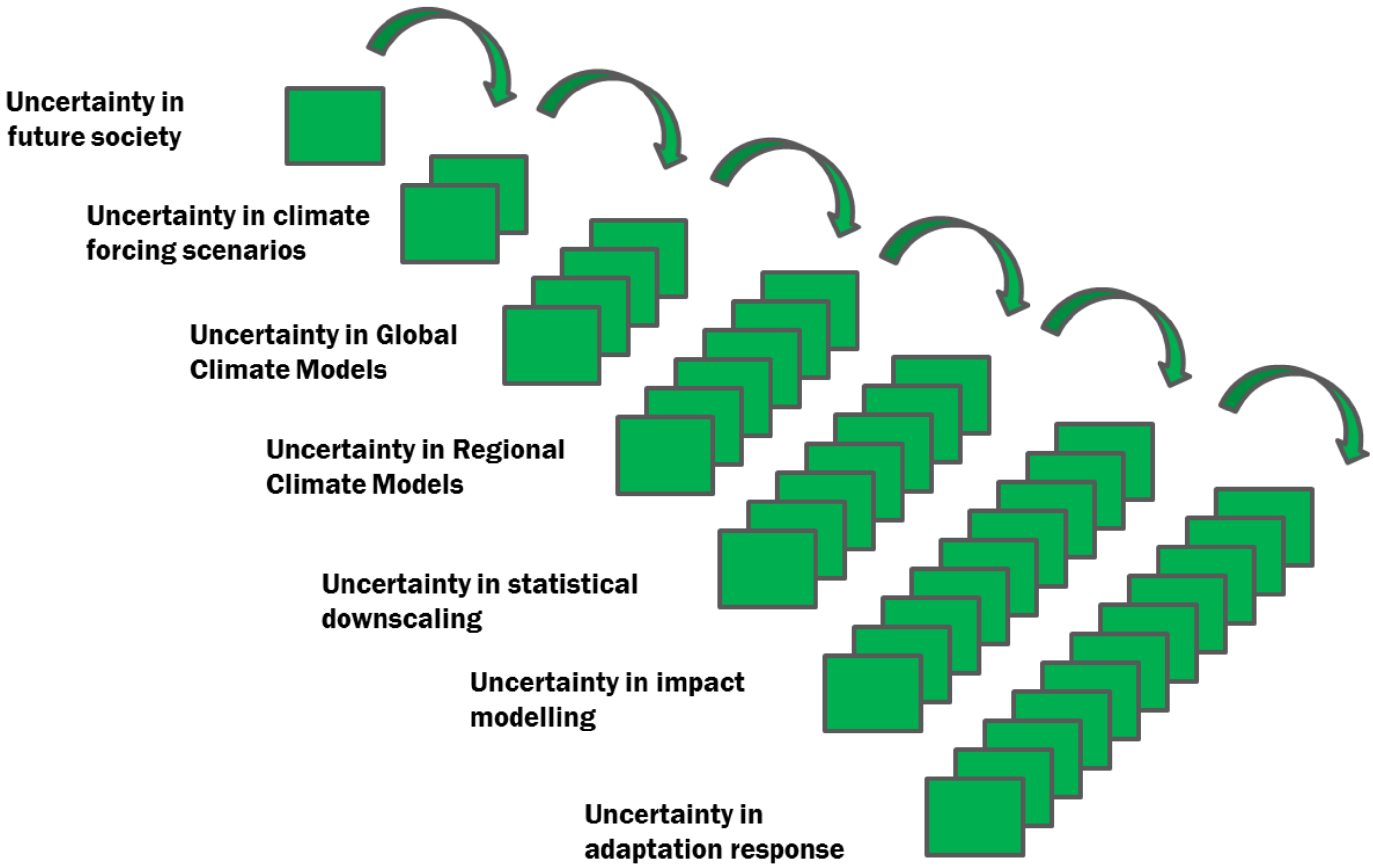


Figure 5.3.1. The uncertainty cascade shows that uncertainty accumulates at each step.

important to address in the decision making process, and large uncertainties should not be used as an argument for postponing decisions until more knowledge becomes available. Often sufficient knowledge is available for the decision making.
As a way of addressing the various uncertainties in the process and ensuring that this uncertainty is in someway communicated, we recommend that as a minimum, more than one set of results is reported and that the dominating uncertainty sources are reported where possible.

Dessai and van der Sluijs (2007) argue that the communication of only statistical uncertainty can mean that more policy relevant uncertainty is ignored, because in principle it cannot be quantified.

60-second summary...

- The resulting uncertainty on impact assessment and adaptation measures includes a number of uncertainty sources related to the future scenarios, climate projections and impact modelling.
- The different uncertainty sources have different nature (e.g. non-reducible natural variability or reducible by gaining more knowledge) and level (e.g. can be described statistically, as scenarios or only qualitatively).
- The relative importance of the different uncertainty sources on the impact assessment and adaptation measures is problem specific.
- The resulting uncertainty may be large but is important to address and communicate in the decision making process, and large uncertainties should not be used as an argument to postpone decisions.

5.4 Scenario analysis

What is a scenario?

A scenario is a projection of future conditions developed to inform decision-making under uncertainty. In scenario analysis, a number of scenarios that are believed to be representative of a range of potential future conditions are developed. These scenarios are then used to estimate the performance of different alternatives across the range of possible outcomes represented by the scenarios. These estimates can be used to compare and perhaps to refine alternatives. The emissions scenarios developed as part of the IPCC process are probably the best-known example of scenario development in the climate change context; however, scenarios can be developed to represent any type of uncertainty.

What is the difference between a scenario and an alternative?

It is important to be clear about the difference between scenario and alternative. As presented here, scenario refers to a projection of future conditions that could affect the performance of a project or management plan. Alternative refers to a potential project or plan that is under consideration in a decision-making process. 'Alternatives' are often called 'scenarios' or 'options' in normal water resources management, but this is not what is being discussed here. Here we are providing a method for dealing with uncertainty, not how to compare alternative interventions or options.

How are scenarios developed?

Scenario development begins by selecting 2 or 3 key uncertain factors that are thought to impact the performance of infrastructure or management alternatives under consideration. These factors are then combined at different levels into a number of scenarios, which are then used to compare alternatives.

How are climate change scenarios typically developed?

Nearly all methodologies for assessing the impact of climate change or evaluating climate adaptation options for water resources use climate model projections and water resources models using a scenario-based approach. In the climate change context, a scenario is usually a single path from emissions→GHG concentrations→global climate→regional climate→local climate→impact. There are a number of uncertainties at each stage (section 5.3).

What are some strengths and weaknesses of scenario analysis?

Scenario analysis requires subjective judgments about which uncertainties should be investigated. As a result, scenarios are vulnerable to bias and criticism. A transparent development process, can limit bias in scenario production and focus debate on underlying uncertainties.

The critical pitfall of scenario analysis is that there is no way to ensure that the selected scenarios represent all future conditions that are relevant to the al-

Working with scenario analysis

1. Identify infrastructure or management alternatives that will be compared.
2. Develop performance metrics that can be used to measure success of failure of alternatives. These should be mapped to a common scale using techniques from cost-benefit analysis, multi-criteria analysis, or some other method for combining difference performance measures.
3. Identify two or three key uncertain factors that will affect the performance of alternatives under consideration. Examples of factors that could be investigated include projections of future climate or projections of the effectiveness of management measures.
4. For each uncertain factor, identify two or three different levels that will be compared.
5. Develop scenarios by combining factors and levels so that each possible factor-level combination is represented by a scenario.
6. Estimate the performance of each alternative under each scenario.
7. Use results to select alternative or refine alternatives and repeat.

Decision making

5.4 Scenario analysis

ternatives under consideration. In addition, there is no established systematic way to use scenarios to rank and select alternatives. However, depending on the risk preferences of decision makers, decision rules such as the maximin and minimax rules may be useful

Despite these drawbacks, scenario analysis can help decision-makers understand and respond to uncertainty. In particular, scenario analysis may help decision-makers consider potential futures that they might otherwise reject as unpleasant or unlikely.

What are some decision-making rules that could be used with scenario analysis?

If decision makers are risk-averse (section 1.4), the minimax and maximin decision rules could be useful in a scenario analysis context. If decision makers are risk-averse with respect to climate impacts, then the minimax rule may be appropriate. If the minimax rule is used, the alternative that minimizes costs (or maximizes benefits) under the maximum climate change scenario is selected. If decision makers are risk-averse with respect to over-adaptation to climate change, then the maximin rule may be appropriate. If the maximin rule is used, the alternative that minimizes the maximum cost (or maximizes the minimum benefit) under all scenarios is selected.

The US Climate Change Science Program report "Global-change scenarios: their development and use" (Parson, 2007) provides information on the use of scenario analysis for decision making under undercertainty. More information is available at http://www.climatescience.gov.

60-second summary...

- Scenarios are projections of future conditions developed to inform decision-making under uncertainty.
- In a scenario analysis, different infrastructure and management alternatives are compared across a range of conditions that might be expected in the future. Each set of future conditions is represented by a scenario.
- Scenario analysis offers the advantage of conceptual simplicity. However, there is no way to ensure that the selected scenarios represent all future conditions that are relevant to the alternatives under consideration.
- The minimax and maximin decision rules may be useful for decision making in a scenario analysis context.

Case study: Scenario analysis

DHI and project partners conducted an assessment of climate change impacts on flood risks in the Vidaa River catchment, a transboundary basin that straddles southern Denmark and northern Germany. Lower portions of the catchment are impacted by flooding, particularly when peak river flows coincide with elevated sea levels. The analysis estimated the extent to which peak flood levels might change as a result of climate change impacts on peak river flows, sea level rise, and storm surge levels.

Scenario analysis was used to characterize uncertainty related to climate impacts on sea level rise and storm surge levels, while a quasi-probabilistic approach was used to characterize uncertain climate impacts on peak river flows.

Two scenarios were developed to characterize uncertainty about changes to mean sea levels. Both climate impacts and changes resulting from isostatic changes were included in the scenarios. To characterize climate impacts on storm surge levels, a single GCM/RCM scenario was used as input to a hydrodynamic model of the coastal ocean.

To estimate impacts of uncertainty on peak river flows, a suite of 15 GCM/RCM projections from the ENSEMBLES project data archive were used to represent a range of potential future climates. Likelihoods of each projection were estimated based on the extent to which each GCM/RCM combination could reproduce features of the historical climate. A likelihood-weighted average was then used to drive a hydrological model of the catchment.

The case study is described in more detail in section 6.1.

Scenario	Projection horizon	Change in mean sea water level		Change in storm surge statistics	Change in precipitation, temperature and potential evapotranspiration
		Climate change	Isostatic change		
1	2050	+10 cm	+5 cm	Based on hydrodynamic model run 2035-2064	Based on ENSEMBLES data 2035-2064
2	2050	+34 cm	+5 cm		
3	2100	+30 cm	+11 cm	Based on hydrodynamic model run 2070-2099	Based on ENSEMBLES data 2070-2099
4	2100	+100 cm	+11 cm		

Table 5.4.1 Summary of scenarios used to characterize future uncertainty

5.5 Classical decision analysis

What is classical decision analysis?

In classical decision analysis, probabilistic estimates of future conditions are used to estimate likelihoods of future conditions. Performance metrics are developed to measure the utility of infrastructure or management alternatives. The alternative with the highest expected utility is selected.

Classical decision analysis is often used in a risk assessment context. In this case, the performance metrics used in decision-making are risk thresholds, which are computed from probabilistic estimates of driving factors.

What rules can be used for decision making?

A number of criteria are available for selecting a preferred alternative based on probabilistic information. One of the most commonly used, and probably the most appropriate in the climate change context, is Bayes' decision rule. Under Bayes' decision rule, the expected outcome of each alternative is calculated. The alternative with the maximum expected outcome (or the highest probability of success if a binary success/failure metric is used) is then selected.

Is it possible to assign probabilities to climate projections?

Recent increases in computing power have permitted some useful efforts in quantifying, at least in part, uncertainties associated with climate model projections. These are based on multi-model ensembles, perturbed physics ensembles, statistical emulators, etc. This has led to probabilistic climate projections. Providing probability distributions of climate change impacts has the advantage that uncertainties can be framed in a statistical way and can also be used in risk-based approaches.

60-second summary...

- In classical decision analysis, probabilities are assigned to projections of future conditions and the alternative with the highest expected utility is selected..
- Classical decision analysis offers a rational framework for decision making under uncertainty. However, it may not be possible to assign probabilities to all of the uncertainties influencing water resources planning outcomes in a climate change context.

Working with classical decision analysis

1. Identify infrastructure or management alternatives that will be compared.
2. Develop performance metrics that can be used to measure success of failure of alternatives. These should be mapped to a common scale using techniques from cost-benefit analysis, multi-criteria analysis, or some other method for combining difference performance measures.
3. Identify key uncertain factors that will affect the performance of alternatives under consideration.
4. Identify range of values associated with each uncertain factor. Assign probabilities to each value. Discrete probabilities can be used together with discrete values, or a continuous distribution can be used.
5. Compute joint probability of each factor-value combination.
6. Evaluate performance of each alternative under each factor-value combination.
7. Estimate probability that each alternative will be successful by summing probabilities of each factor-value combination that meets criteria outlined in the performance metric.
8. Use probabilities of success and failure to select alternative according to selected decision criterion.

Decision making

5.5 Classical decision analysis

However the proper interpretation of the probabilistic climate information is highly disputed. Hall (2007) argues that this approach misrepresents uncertainty and may lead to poor decisions. The results have shown to be highly dependent on the assumptions made (such as the combination of GCMs or RCMs used). Furthermore they are incomplete in the sense that current climate models do not represent all climate feedbacks or it is simply not feasible to map the full range of uncertainty (section 5.3).

For more information on probabilistic climate projections, see the EU ENSEMBLES project (2004-2009) http://www.ensembles-eu.org/. Multi-model ensemble simulations were used to develop probabilistic estimates of climate change in Europe.

What are the advantages and disadvantages of classical decision making?

Classical decision analysis offers the advantage of a rational framework for decision-making under uncertainty. However, despite progress in developing probabilistic climate projections, it may not be possible to assign probabilities to all of the uncertain factors influencing water resources planning outcomes in the climate change context. If probabilities are uncertain and unvalidated, probabilistic estimates may be distrusted by decision-makers and generate controversy among stakeholders who hold different expectations about the future.

Case studies: Classical decision analysis

Because of the many uncertainties associated with climate change projections, DHI is not aware of any comprehensive application of classical decision analysis to water resources planning under climate change. However, a number of efforts have attempted to develop probabilistic estimates of uncertainty associated with different elements of climate change projections. Among the most challenging elements to define in probabilistic terms are projections of future emissions.

Webster et al. (2008) developed probabilistic estimates of uncertainty associated with emissions scenarios. A distribution of future emissions was developed by propagating uncertainty through a general equilibrium model of the global economy. Uncertain factors included productivity growth rates, energy efficiency trends, costs of advanced technologies, fossil fuel resource availability, and trends in emissions for urban pollutants. However, the model was conditioned on assumptions about climate mitigation policy; it was believed to be too difficult to characterize policy futures in terms of probabilities. Under a baseline scenario assuming no climate policy, it was found that most of the IPCC forcing scenarios are outside the 90% probability range.

It is thought that uncertainty due to GCM/RCM formulation, parameterizations, and the natural variability of the climate system can be addressed using ensemble simulations (section 5.3).

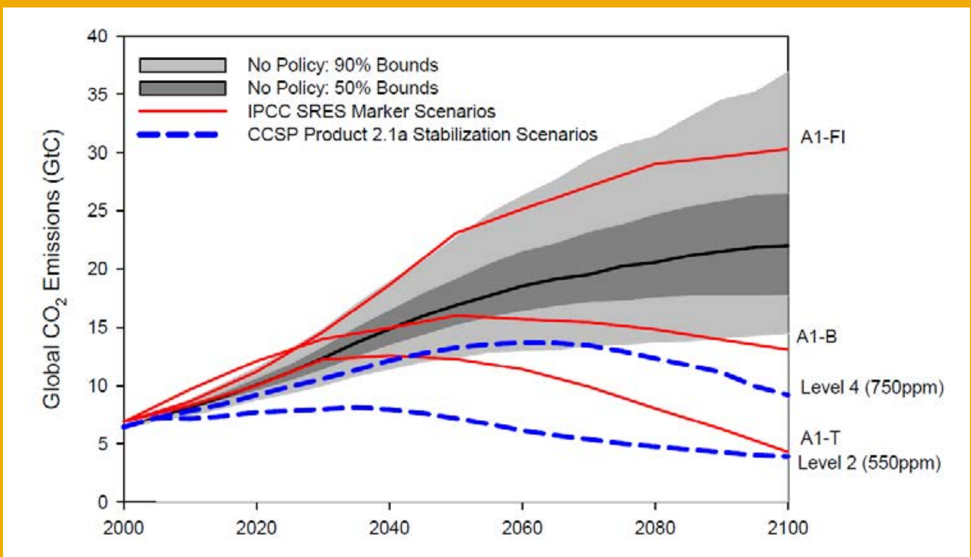


Figure 5.5.1 Comparison of baseline probabilistic emissions projections to IPCC and CCSP scenarios.

5.6 Robust decision making

60-second summary...

- Robust decision-making is an emerging approach that seeks to identify alternatives that will perform reasonably over a wide range of future conditions.
- The method uses computer simulation to explore the uncertainty space and identify "policy-relevant" future scenarios under which proposed alternatives are vulnerable to failure. These scenarios are then used to select an alternative or help design new alternatives that are less vulnerable

What is robust decision-making?

Robust decision-making is an emerging approach to decision-making that may be useful for decision-making in a climate change context. The approach was developed to address two perceived weaknesses of the scenario analysis approach: 1) there is no clearly defined methodology for deciding what to include in scenarios, and 2) there is no clear way to assess the likelihoods of different scenarios. Robust decision-making proceeds from the observation that decision-makers often manage uncertainty by developing alternatives that will perform reasonably over a wide range of future conditions.

What are "policy-relevant" scenarios?

The problem of deciding what to include in scenarios is addressed by using computer simulation to explore a larger combination of uncertain factor levels and combinations than is feasible under scenario analysis. The resulting ensemble is then used to identify ranges of factor values that lead to poor performance of alternatives. This information is used to develop a number of so-called "policy-relevant" scenarios that can then be used to identify vulnerabilities and modify alternatives.

Working with robust decision-making

1. Identify infrastructure or policy alternatives that will be compared.
2. Develop performance metric that can be used to measure success or failure of alternatives.
3. Identify uncertain factors that will affect the performance of alternatives under consideration.
4. Identify range of values over which each uncertain factor might be expected to vary. No probabilities are assigned to different values at this point.
5. Sample different combinations of all possible uncertain factors to generate an ensemble of possible outcomes for each alternative.
6. Identify ensemble members in which alternatives fail to meet criteria outlined in performance metric.
7. Use search algorithm to identify clusters of factor-value combinations that cause alternatives to fail to meet performance criteria.
8. Use clusters identified in step 7 to develop scenarios representing factor-value combinations that fail to meet performance criteria.
9. Identify best alternatives as a function of scenario probabilities.
10. Discuss likelihoods of scenarios identified in step 8 with stakeholders. Use the range of likelihoods identified by stakeholders and the functional relationships identified in step 9 to identify a best alternative. If no alternative is best, use information to refine alternatives or identify adaptive strategies that can perform well over a wider range of potential futures.

5.6 Robust decision making

How are alternatives selected?

The problem of assigning probabilities to scenarios is addressed indirectly. Instead of assigning probabilities to scenarios, likelihood thresholds are identified that would trigger a change from one alternative to another. For example, if a single policy-relevant scenario has been identified and two alternatives are under consideration, stakeholders could agree that the first alternative is best if the likelihood of the scenario is greater than 50%, while the second alternative is preferred if the likelihood of the scenario is believed to be less than 50%.

This information can then be used in consultation with stakeholders to identify a preferred alternative. If stakeholders can agree on a range of likelihoods for the policy relevant scenario(s), then the alternative that covers this range can be selected. To continue the example above, if one group of stakeholders thinks the likelihood of the scenario is 75%, another thinks it is 60%, and a third thinks it is 90%, then all groups think that the likelihood of the scenario is greater than 50% and the first alternative should be selected. However, if one group thinks the likelihood of the scenario is less than 50%, then the stakeholders do not agree on which alternative is proposed. In this case, the scenario could be used to design a new, robust alternative that is preferred regardless of the likelihood of the scenario.

What are some advantages?

Robust decision-making offers advantages over both scenario analysis and classical decision analysis. In contrast to scenario analysis, it offers a rational method for developing scenarios that reduce the likelihood of being surprised by vulnerability to unforeseen uncertainties. In contrast to classical decision analysis, it does not rely on probabilistic estimates, providing common ground among stakeholders with differing expectations of the future and acknowledging the large uncertainty underlying many future projections.

For more information on robust decision making see http://www.rand.org/ise/projects/improvingdecisions/water_planning.html. Since 2005, the RAND Corporation in California, USA has undertaken a research effort to develop methods to support decision making under uncertainty in the water resources planning context, including the robust decision making approach described here.

Case study: Robust decision-making

The RAND Corporation (Groves, 2008) recently tested a robust decision-making approach on a real-world case study in California, USA. The study team worked with an urban water agency to investigate whether the approach could help the agency's decision-making process. Robust decision-making was used to compare four policy alternatives: the agency's baseline master plan, and three alternatives combining the master plan with initiatives to use recycled water for landscaping and/or replenishment of groundwater aquifers.

A total of six uncertain parameters were varied to generate an ensemble of scenarios: future climate, the extent to which recycling goals are met, the extent to which replenishment goals are met, the extent to which water conservation increases, changes in percolation to groundwater due to urbanization, and changes in imports from outside the area.

From the scenario ensemble, "policy-relevant" scenarios were developed using parameter combinations that caused the baseline alternative to fail in a significant number of the ensemble simulations. In one of these parameter combinations (shown), the agency fails to meet its recycling goals, the future climate is drier, and groundwater percolation is predicted to decrease. It was estimated that the baseline alternative should be rejected if the likelihood of this scenario occurring is less than 25%. Participants in a workshop indicated that this approach was more useful for making choices among plans than scenario analysis or classical decision-making.

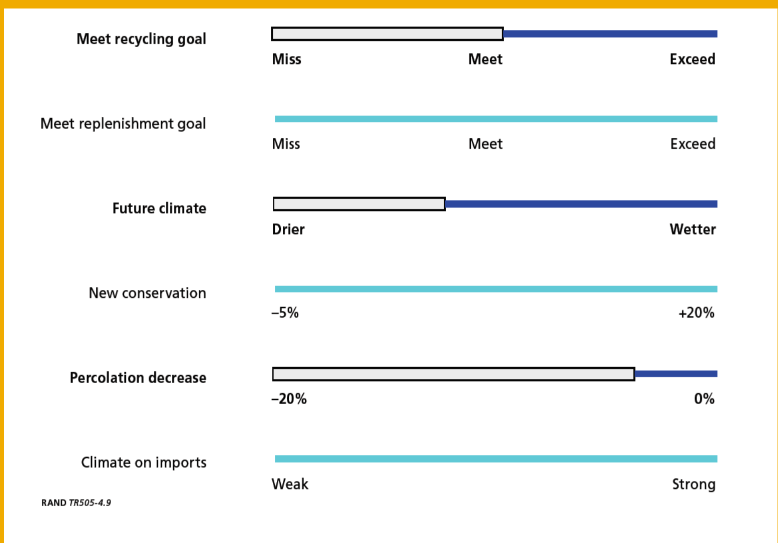


Figure 5.6.1 Parameter ranges associated with failure of baseline alternative.

Decision making

5.7 Adaptive management

What is adaptive management?

Adaptive management strategies are designed to evolve over time in response to new information. In the case of climate change, where considerable uncertainty exists and progress in climate science has the potential to reduce uncertainty, adaptive management strategies should be included among alternatives that are compared in a decision-making process.

An adaptive management strategy can be defined as a set of sequential decisions in which an initial action is taken, new information is obtained and a new action is taken in response to this information.

In environmental management, approaches to adaptive management emphasize learning. In this context, near-term actions can be designed as experiments that aim to produce information useful for designing subsequent steps.

Adaptive strategies have been recognized as useful for building consensus among parties with different expectations about the future, as plans can evolve appropriately as more is learned about future conditions. However, some decisions taken in the present may close future paths. In addition, the selection of an adaptive management strategy must acknowledge that implementation relies on the actions of future decision-makers, who may behave in irrational ways.

How can adaptive strategies be designed?

The design of adaptive management strategies can be problematic in practice. Ideally, a simulation used to guide the design of adaptive strategies would be able to predict how infrastructure or management actions perform, what future decision-makers learn over time, what actions decision-makers will take in the future and how agencies may implement those actions. It is difficult to achieve all of these objectives in a real-world simulation exercise.

The RAND Corporation (Lempert and Groves, 2010) demonstrated how robust decision-making could be used in the design of adaptive management strategies. In this demonstration, a computer simulation approach was used to identify adaptive management actions that could be delayed without reducing vulnerability. If future conditions turn out to be worse than expected, these actions could then be implemented. The analysis suggested that such a strategy would be considerably easier to implement than a strategy in which all actions to reduce vulnerability were implemented at once. Another example of the design of an adaptive management strategy in the climate change context is the Thames Estuary 2100 plan (see box below).

Case study: Adaptive management

The Thames Estuary 2100 plan (UK Environment Agency, 2009) is an example of the use of adaptive management to plan for climate change impacts. The plan was developed in order to provide a framework for improving flood defenses in the Thames River estuary, which is subject to flood risks from a combination of river flooding, urban flooding, tidal storm surges, and rising sea levels.

The plan identified a number of measures to reduce flood risk and scheduled the implementation of measures over three phases: 2010-2034, 2035-2070, and 2070 onwards. The plan is flexible because measures can be brought forward in time and/or adjusted as new information becomes available. In addition, structures are to be designed so that they can be adapted to changing circumstances.

The Thames barrier, London

Ten indicators were identified as “triggers” that could bring about changes in the implementation of the plan. These indicators include mean sea level, the peak surge tide level, peak river flows, conditions of flood defenses, the frequency with which the Thames barrier (shown) and other barriers must be closed, the extent to which people and property are at risk, erosion/deposition rates, tidal ecosystem health, land use planning, and public risk perception.

6. Case studies

6.1 Flooding in Vidaa, Denmark

Climate change impact assessment of dike safety and flood risk in the Vidaa River system

1. Defining the Problem

The Vidaa River catchment is a cross-border catchment located in the southern part of Jutland, Denmark and northern Germany. The river discharges to the Wadden Sea through a tidal sluice. Extreme water levels in the downstream part of the river system occur during storm surges where the sluice is closed over a prolonged period and at the same time increased runoff from the catchment take place due to heavy precipitation. The low-lying, downstream part of the catchment is protected by river dikes. The current flood protection level corresponds to a return period of about 1000 years along most parts of the main river. The area is also protected by coastal dikes. However, coastal flood risk was not considered in the study.

Climate change is likely to increase the mean sea level, storm surges, and extreme rainfall and therefore extreme catchment runoff, thus increasing the risk of flooding in the downstream part of the catchment. The main purpose of the study was to assess the risk of overtopping of the existing river dikes under current conditions, using the most recent climate observations, and the expected changes in this risk in 2050 and 2100 under future climate conditions.

Figure 6.1.1 Vidaa River Catchment

2. Identifying options

The main motivation of this study was to determine whether there is a need to upgrade the current level of flood protection provided by the existing dikes. Based on the risk analysis for future climate conditions different potential adaptation options were investigated. These include increase of storage capacities in flood polders and increase of flood protection in selected river sections by building new dikes.

3. Formulating the modelling approach

In order to estimate flood risks in the Vidaa River system an integrated hydrological and hydraulic model (MIKE 11) was set up and calibrated. This model formed the basis for simulation of water levels in the river system using meteorological forcing and sea water level data for current (using observed records) and future (using projected records) climate conditions. Extreme value analysis of water levels was applied to estimate the risk of dike overtopping at different critical locations.

To assess the impacts of future climate change on the flood risk both changes in the meteorological forcing (precipitation, temperature and potential evapotranspiration) and changes in sea water level have to be considered. Since extreme water levels in the downstream part of the catchment are caused by a combination of extreme sea water level and extreme precipitation, the correlation between these is crucial for the

Case studies

6.1 Flooding in Vidaa, Denmark

60-second summary...

- Extreme water levels in the downstream part of the catchment are caused by a combination of prolonged periods with high sea water levels where the sluice is closed, and heavy precipitation and hence large runoff from the catchment. Flood risk was analysed for current and future climate conditions (2050 and 2100 time horizons).
- Future projections of meteorological forcing (rainfall, temperature and potential evapotranspiration) were statistically downscaled using the weighted mean of fifteen RCM/GCM projections for the A1B emission scenario from the ENSEMBLES data archive. Sea levels were projected using a high and a low estimate of mean sea level change, local estimates of isostatic change, and a regional hydrodynamic model of the local ocean conditions forced by a single RCM for storm surge projections.
- To estimate the changes in flood risk an integrated hydrological and hydraulic model was set up and calibrated and forced with recent climate observations and climate projections for 2050 and 2100. Extreme value analysis of water levels was performed at critical locations in the river system for estimation of the risk of dike overtopping.
- The risk of dike overtopping was found to increase substantially for all future scenarios tested. For the worst case scenario in 2100, annual exceedance probabilities increase from less than 0.1% to 5% or more in the downstream part of river system.

flood risk analysis. For evaluation of the flood risk under current conditions the correlation is explicitly given by the observed records of sea water level and precipitation used to force the hydrological and hydraulic model. It was decided to preserve the current correlation structure for assessing future flood risk. This was done by using a statistical downscaling method that perturbs the observed records with projected changes in sea water level and precipitation statistics.

The flood risk is more sensitive to changes in sea water level than changes in the meteorological forcing. Thus, it was decided to address climate projection uncertainties by using: (1) A low and high scenario for changes in sea water level, and (2) An ensemble of climate projections for estimation of the expected “median” changes in meteorological forcing

4. Developing Projections

Fifteen RCM/GCM projections from the ENSEMBLES data archive were used for downscaling precipitation, temperature and potential evapotranspiration. For statistical downscaling of temperature a mean correction methodology (delta change approach) was applied (see Statistical downscaling, section 4.8). For estimation of changes in potential evapotranspiration a temperature-based method was used (Kay and Davies, 2008) (see Hydrological variables). For statistical downscaling of precipitation a method that uses both changes in the mean and changes in the variance was applied (see Statistical downscaling, section 4.8). Since the impact assessment focuses on changes in extreme precipitation, the change in the variability of precipitation is important to include in the downscaling.

For calculation of the change factors, catchment averages of daily precipitation and temperature from the RCM/GCM models were used. The changes were based on 30-year periods of climate model data, respectively, 1980-2009 representing the present climate, 2035-2064 representing the future climate in 2050, and 2070-2099 representing the future climate in 2100. To take seasonal variations into account, monthly change factors were calculated. Weighted average change factors were applied where weights for the 15 different RCM/GCM models were determined based on the skills of the models for simulation of present climate, considering the monthly variability of mean precipitation, variance of daily precipitation, and mean temperature. The weighted average change factors for 2050 and 2100 are shown in Figure 6.1.2.

Changes in the sea water level at the Vidaa sluice are a combination of changes in the mean sea water level, isostatic changes and changes in storm surge levels. The Danish Meteorological Institute has estimated an increase in mean sea level for Danish waters in the range 0.3 to 1.0 meters in 2100. Due to the large uncertainties in the projected sea level rise, two scenarios were applied in the analysis corresponding to, respectively, an increase of 0.3 and 1.0 meter in 2100. For estimation of the mean sea level rise in 2050, the temporal development reported in Grindsted et al. (2009) was used. Due to isostatic changes there is a continuous relative increase in the mean sea level in the area. The current annual increase of

6.1 Flooding in Vidaa, Denmark

6.1 Flooding in Vidaa, Denmark
6.2 Hydropower in Lao Cai, Vietnam
6.3 Water management in the Okavango Delta, Botswana
6.4 Groundwater in Berlin, Germany
Case studies

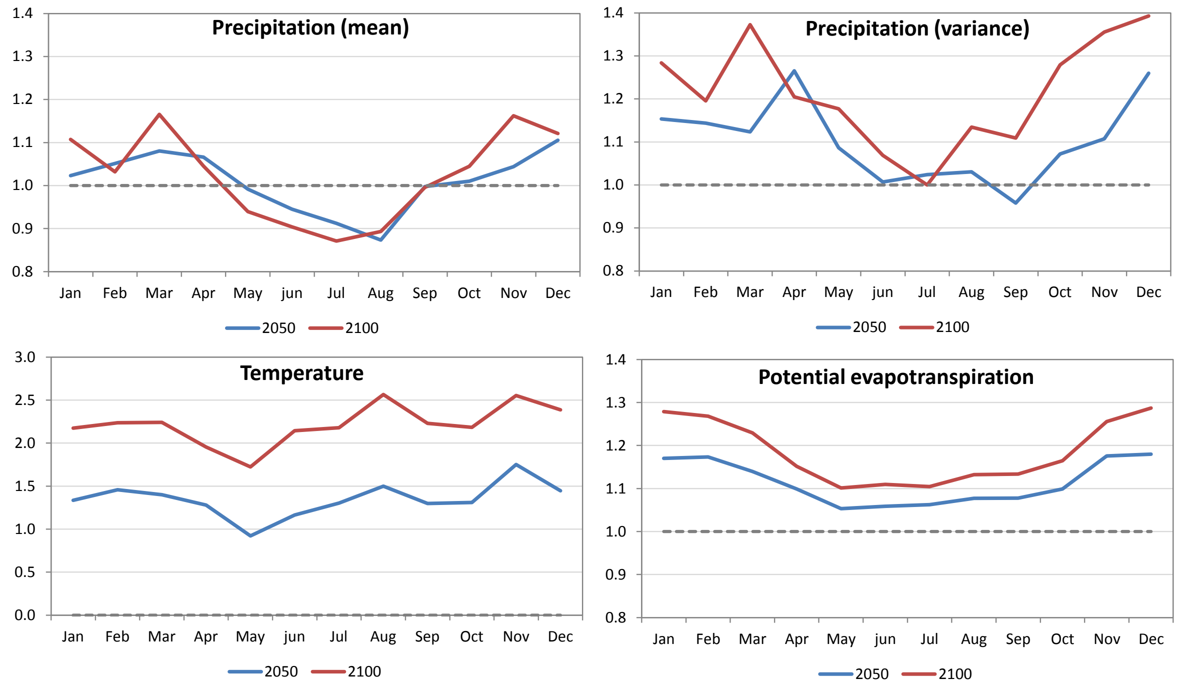


Figure 6.1.2 Relative change in mean and variance of daily precipitation and mean potential evapotranspiration, and absolute change in temperature (degree Celsius) for future (2050 and 2100) climate.

0.11 cm per year was assumed to continue up to 2100.

For estimation of changes in storm surges, model simulations based on a hydrodynamic model covering the North Sea, Baltic Sea and inner Danish waters was used. The model was forced by wind and atmospheric pressure fields from one of the RCM models from the ENSEMBLES data archive (Rugbjerg and Johnson, 2012). From the hydrodynamic model simulations time series of sea water levels at the Vidaa sluice were extracted. From this time series extreme water level statistics were calculated for 2010 (based on simulation results for the period 1980-2009), 2050 (2035-2064) and 2100 (2070-2099). Future extreme value statistics for 2050 and 2100 are then estimated by superimposing the changes in extreme value statistics to the current statistics and adding the projected mean sea level rise and isostatic changes, see Figure 6.1.3. Besides changes in storm surge levels, also changes in the duration of high sea water levels were calculated. The four different climate change scenarios applied in the risk analysis are summarised in Table 6.1.1 (below).

5. Decision-making

The integrated hydrological and hydraulic model was used for simulations using the observed records of meteorological data and

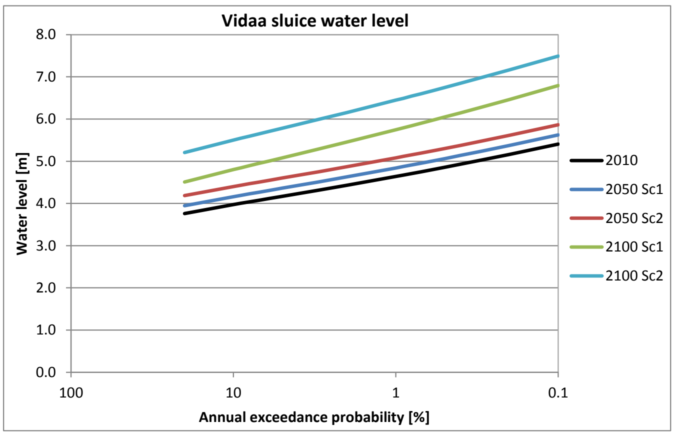


Figure 6.1.3. Estimated extreme sea water level statistics at the Vidaa sluice for current (2010) and future (2050 and 2100) climate. Sc1 and Sc2 correspond to, respectively, the low and high scenario of mean sea level rise.

6.1 Flooding in Vidaa, Denmark

sea water level at the Vidaa sluice, and the projected records representing 2050 and 2100 climate. From the simulations, water levels at selected critical locations in the river system were extracted and used for the extreme value and risk analysis. In Figure 6.1.4 the flood risks for current and future climate at the selected locations are shown.

The flood risk analysis shows that currently there is a relatively low risk of dike overtopping with annual exceedance probabilities of 0.1% or less in most parts of the river system. For the worst case scenario in 2100, pronounced changes in flood risk are seen with flood risks of 5% or more in the downstream part of river system. The results are currently used for evaluating different adaptation options for reducing future flood risks.

Table 6.1.1. Summary of applied climate change scenarios.

Scenario	Projection horizon	Change in mean sea water level		Change in storm surge statistics	Change in precipitation, temperature and potential evapotranspiration
		Climate change	Isostatic change		
1	2050	+10 cm	+5 cm	Based on hydrodynamic model run 2035-2064	Based on ENSEMBLES data 2035 -2064
2	2050	+34 cm	+5 cm		
3	2100	+30 cm	+11 cm	Based on hydrodynamic model run 2070-2099	Based on ENSEMBLES data 2070 -2099
4	2100	+100 cm	+11 cm		

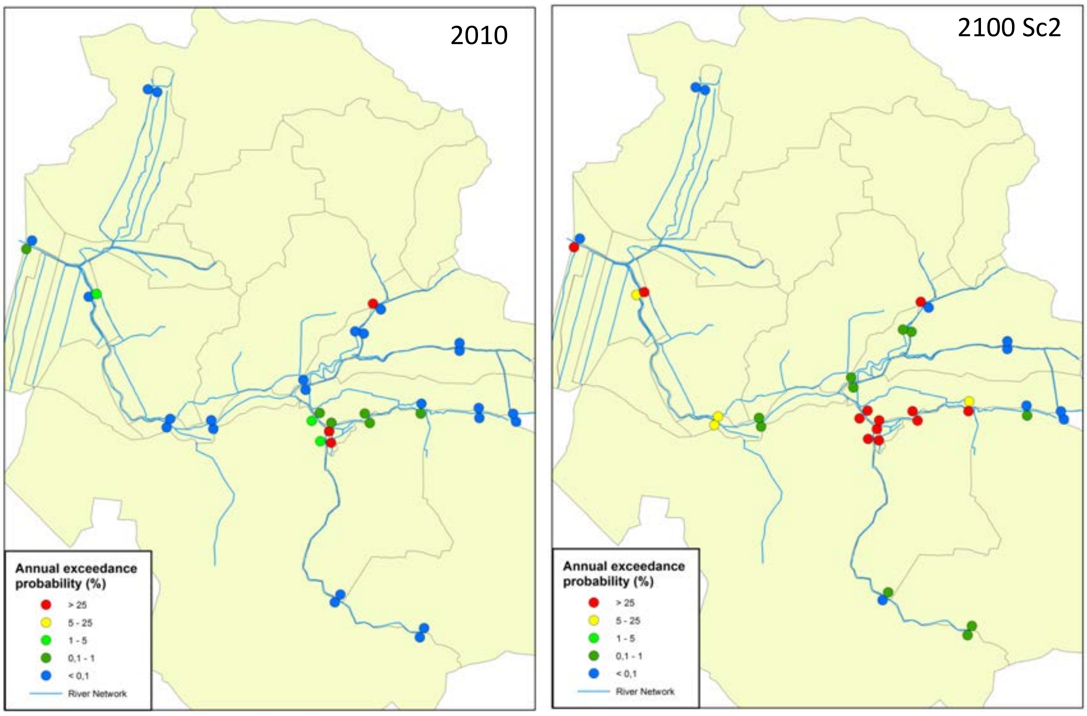


Figure 6.1.4. Estimated flood risk at selected locations in the Vidaa River system for current (2010) and future (2100 with high mean sea level scenario) climate. For each location the annual exceedance probabilities for overtopping left and right bank are show.

6.2 Hydropower in Lao Cai, Vietnam

Comparison of hydropower and environmental flow alternatives in Lao Cai province, northern Vietnam

1. Defining the problem

The Lao Cai province is a mountainous region located in northern Vietnam. The region has considerable potential for hydropower development. The population is poor and only 91 out of 164 community centers are connected to the national power grid. The Lao Cai region is also vulnerable to flooding and there are indications that climate change could increase the frequency and/or intensity of extreme rainfall events and resulting flood risks.

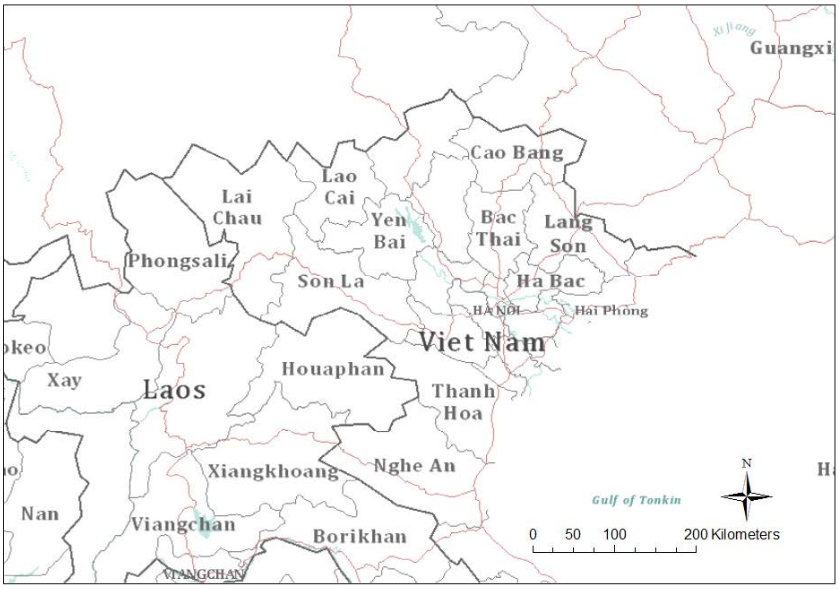


Figure 6.2.1 Map of northern Vietnam with Lao Cai province visible in north-west

2. Identifying options and assessment criteria

The development of small and medium size hydropower plants was identified as a way to spur economic development in the region. Furthermore, hydropower development may reduce the risk of extreme climate events, such as floods and droughts, through the construction of water storage facilities. Potential negative impacts of hydropower development included disruption of natural river flows, resettlement of rural populations, and pollution and land degradation during construction. In addition to improved electricity supply, benefits also included jobs during the construction phase and the development of access roads that could then be used by local communities.

3. Formulating the modelling approach

Two alternatives were developed for detailed analysis. In the first, a set of small- and medium-scale hydropower projects were evaluated together. In the second, the projects were evaluated together with environmental flow requirements added as constraints on operations. The alternatives were evaluated using a water allocation and hydropower model developed using MIKE BASIN. Inflows to the MIKE BASIN model were developed from discharge station records. A rainfall-runoff model was also set up using the NAM model in order to estimate climate change impacts on inflows.

4. Developing Projections

To estimate the impact of climate change on the performance of the two alternatives, projections of rainfall and temperature were developed. These projections were then used to drive a rainfall-runoff model, which was in turn used to estimate inflows to hydropower projects under different climate regimes.

Climate change projections were obtained from the MAGIC/SCENGEN internet portal. The MAGIC/SCENGEN portal offers simplified access to climate model output. Approximately 40 GCM simulations were obtained from the portal and an average projection of precipitation and temperature was developed. Average monthly changes in precipitation and temperature were then calculated for 2030 and 2050 relative to a historical baseline.

Because the MAGIC/SCENGEN results were available on a 5 degree grid, it was necessary to downscale results to a spatial scale reasonable for input to the rainfall-runoff

6.2 Hydropower in Lao Cai, Vietnam

model. A delta change factor approach was used for downscaling. The study area was split into 4 quadrants and estimates of average monthly changes in precipitation were estimated for each quadrant using linear interpolation. Changes in temperature were taken directly from the MAGIC/SCENGEN grid cell enclosing the study area. Downscaled precipitation and temperature data sets were then developed by adjusting observed precipitation and temperature time series values using average monthly delta change factors.

	Emissions scenario and projection year					
	Scenario B1		Scenario B2		Scenario A1FI	
Alternative	2030	2050	2030	2050	2030	2050
Hydropower development only	6%	10%	5%	8%	4%	10%
Hydropower development w/ environmental flow requirements	8%	12%	6%	10%	6%	14%

Table 6.2.1 Percent increase in energy generation relative to baseline

Potential evapotranspiration was estimated using the Penman-Monteith equation. In this calculation, projected temperature values were used together with historical measurements of wind, humidity, and radiation to project potential evapotranspiration.

5. Decision-making

A scenario analysis approach was used to estimate the impact of uncertain climate projections on the performance of the alternatives under consideration. The uncertainty analysis approach considered uncertainty in emissions scenarios only. Four scenarios were developed, including a baseline scenario driven by the historical climate and three climate change scenarios based on different emissions scenarios. The three emissions scenarios used in the scenario analysis were the B1, B2, and A1FI scenarios from the third IPCC Assessment Report.

The scenarios were used to estimate percent changes in hydropower generation that might be expected in the future relative to the observed baseline. The results suggest that hydropower production will increase under both alternatives because of climate change-induced increases in rainfall (Table 6.2.1). The results also suggest that the relative increase will be higher for the alternative that includes environmental flow requirements. Changes in greenhouse gas emissions resulting from hydropower production were also estimated.

Although not investigated using a scenario approach, the study also investigated the economic impact of introducing environmental flow requirements. It was found that the introduction of environmental flow constraints could cause about 25% of the plants under consideration to be uneconomical. In addition, storage projects associated with the hydropower development scheme were determined to be too small to impact flood risks. It was also found that resettlement impacts would be minimal because of the small areas inundated by the small- and medium-scale hydropower developments.

The project provided the following information to decision makers:

- Hydropower development can help mitigate GHG emissions by reducing use of fossil fuels
- Hydropower development can benefit local communities, if properly implemented, through job generation and easier access to electricity and transport.
- Although thought to be environmentally friendly, small and medium scale hydropower plants may have negative impacts on flows and the environment in large stretches of streams.
- Fulfilling environmental flow criteria may not be economically feasible for many small hydropower plants.
- The lack of storage associated with small and medium scale hydropower means that these projects

60-second summary...

- Two hydropower development alternatives were compared using climate projections for 2030 and 2050.
- The impact of emissions uncertainty on climate model projections was assessed using a scenario analysis.
- Results suggested that hydropower production would increase under climate change for all alternatives and scenarios because of increased rainfall. Results also suggested that increases resulting from climate change could partially compensate for impact of introducing environmental flow requirements.

6.3 Water management in Okavango Delta, Botswana

Vulnerability assessment in the Okavango Delta, Botswana

1. Defining the problem

The Okavango Delta is the largest inland delta in the world and supports a pristine ecological system comprising densely vegetated swamps, riparian fringe vegetation, woodlands, grassland, savannah, and barren land areas. The basis for the Delta's ecological diversity and abundance of wildlife is the dynamic presence of water distributed over a 4,000-15,000 km^2 area. The Delta is largely unaffected by development and its preservation is of key importance for ecosystem conservation, sustainability of livelihoods in the region, and the tourism sector in Botswana.

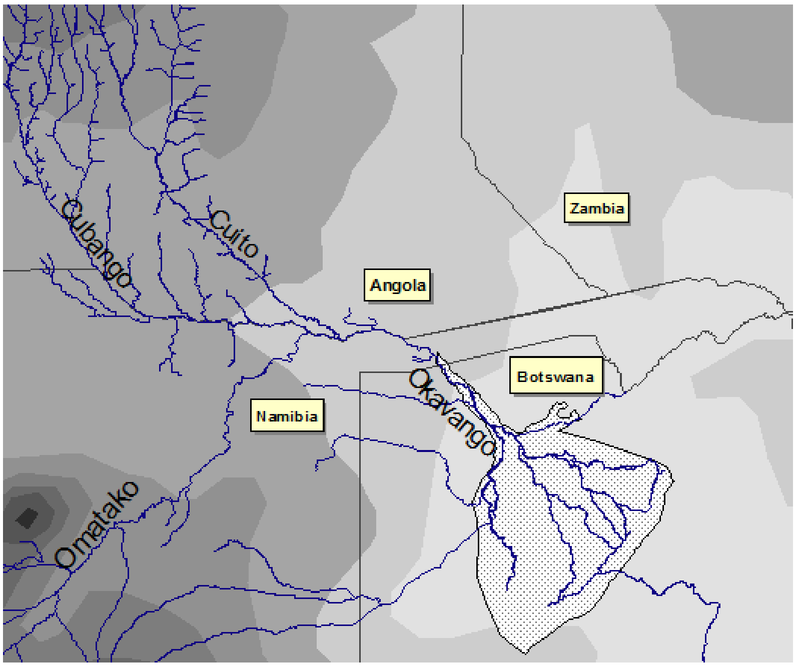


Figure 6.3.1 Okavango Delta and upstream basin

There is concern that deforestation and water resources development in the catchment that supplies water to the Delta, which is located in Angola and Namibia, could impact the water resources of the Delta. Within the Delta itself, increasing water abstraction and other developments could also have impacts, as could regional climate changes. In order to protect the unique ecological resources of the Delta, the potential impacts of these processes were investigated.

2. Identifying options and assessment criteria

Model simulations were used to estimate the impacts of development pressures and climate change on the Delta system . Five alternative scenarios were developed in order to cover a representative range of conditions that might arise in the future. The five scenarios included upstream development of dams and irrigation; deforestation in the upper catchment; increased water use within the Delta; clearing of major blocked channels; and regional climate changes. Combinations of the above scenarios were also developed. All scenarios were based on projected conditions in 2025.

3. Formulating the modelling approach

The Okavango Delta is a complex hydraulic and hydrological system. The Delta is characterized by two major features: a narrow panhandle to the northwest and a broad alluvial fan to the southeast. Flows from the upper catchment areas are routed through the panhandle to the alluvial fan, where these waters spill over large floodplain areas and split into separate channel systems. The channels and smaller flow paths link up to form a complex flow system of floodplains, back swamps, and lagoons that include numerous flow splits and confluences. Permanent flooded areas cover approximately 4000 km^2, while seasonally flooded areas may cover three times the permanently flooded area in years of high flows. The combination of limited topography-driven groundwater flow, low recharge rates, and physical flow barriers strongly limit regional groundwater flow beyond the Delta.

The key processes controlling the extent of the delta are the balance between water entering the delta upstream flowing in the channels and floodplains and losses via infiltration and evapotranspiration. These processes were represented using the MIKE SHE/MIKE 11 numerical modelling system. The subsurface was divided into an unsatu-

6.3 Water management in Okavango Delta, Botswana

Impact	Scenario: Baseline Dry years	Baseline Wet years	Irrigation development Dry years	Irrigation development Wet years	Climate change Dry years	Climate change Wet years	Irrigation development and climate change Dry years	Irrigation development and climate change Wet years
Minimum flooded area (km2)	2,770	4,776	1,675	3,526	900	1,575	145	346
Minimum flooded area (% change from baseline)	-	-	-40%	-26%	-68%	-67%	-95%	-93%
Maximum flooded area (km2)	10,400	14,424	11,285	13,527	9,406	7,966	9,063	5,574
Maximum flooded area (% change from baseline)	-	-	9%	-6%	-10%	-45%	-13%	-61%

Table 6.3.1 Comparison of flooded areas in wet and dry years

rated zone represented using 1-D vertical columns and a saturated zone represented using a 3-D groundwater flow model. Surface waters were represented using a dynamically coupled 1-D/2-D river/floodplain approach in which floodplain processes were represented with a 2-D model and the river network was represented in 1-D using MIKE 11. The extent of flooding simulated by the model was calibrated against dynamic flood maps derived from NOAA AVHRR satellite imagery. To estimate impacts of upstream developments and climate change on inflows to the Delta, the Pitman rainfall-runoff model was used to represent the hydrology of the upstream catchment.

4. Developing projections

To estimate climate change impacts on the Okavango Delta, a climate change scenario was developed. Projections of rainfall and temperature were used to drive the Pitman rainfall-runoff model to predict changes to Delta inflows. The projections were also used as direct input to the MIKE SHE/MIKE 11 model of the Delta to predict changes to evapotranspiration and water flows.

Climate change projections were obtained from the HadCM3 GCM. A downscaling and bias correction step was performed. Average monthly delta change factors were calculated for precipitation and temperature based on comparison of GCM projections with a simulation of the historical climate. Projected data sets were developed by adjusting historical timeseries data using the monthly delta change factors.

5. Decision-making

The five scenarios described in section 2 and two combined scenarios were used to assess the vulnerability of the Okavango Delta. Because of the key role of seasonal and permanent flooding to the Delta ecosystem, vulnerability was assessed in terms of the extent to which the flooded area might change. Of the five scenarios, it was concluded that irrigation development in the upper catchment and climate change have the greatest potential for negative impacts to the extent of flooding. A combined scenario including both irrigation and climate change suggested that the cumulative impact of these two pressures would be more severe than the impact of either individually (Table 6.3.1).

The analysis provided useful input to decision-makers and stakeholders involved in the development of a management plan for the Okavango Delta. It also highlighted the importance of engaging with water resources managers in the upper parts of the catchment to moderate the impact of irrigation development on the Delta ecosystem.

60-second summary...

- Vulnerability of the Okavango Delta ecosystem was assessed using a number of scenarios representing different pressures that might arise in the future, including climate change.
- Results suggested that upstream irrigation development and climate change may have significant impact to the water resources of the Delta, particularly with regard to the extent of permanent and seasonal floods.

6.4 Groundwater in Berlin, Germany

Climate change impact assessment on groundwater recharge and ecosystems in Berlin

1. Defining the problem

Water resources in Berlin and Brandenburg are considered to be particularly susceptible to climate change because of the low annual precipitation, the large area covered by surface water bodies, dominance of sandy soils with low water capacity, and the heavy demands of the Berlin metropolis. Significant decreases of the groundwater levels are already occurring in the region, threatening the local water supply. Furthermore, local ecosystems like the marshes and small rivers like Tegler Fließ and Fredersdorfer Mühlenfließ are strongly influenced by the depth of the groundwater, particularly in the dry season. The sustainability of the groundwater resource and these ecosystems will depend both on the balance between the future water demands and available water resource which in turn will depend on groundwater recharge.

It is expected that climate change in Berlin will eventually result in change of annual precipitation rates as well as changes in rainfall distribution during the year. There is like to be less annual precipitation, more extreme rainfall events and a shift in the monthly distribution causing drier summers and wetter winters. The increase of extreme rainfall events will result in a smaller rate of effective groundwater recharge, a larger share of direct runoff, especially in a densely populated city like Berlin. It is therefore likely that groundwater recharge will decrease even more than the change in average climatic water balance indicates.

As assessment of the impact of climate change on groundwater recharge and groundwater dependent ecosystems has been carried out as part of a larger project "Innovation network for climate adaptation in Brandenburg Berlin (INKA BB)". The overall aims are to ensure the sustainability of land and water use in the region under changing climatic conditions and to promote climate-adapted health management. In particular to identify the opportunities and risks involved in future climate change, and explore courses of action.

2. Identifying options and assessment criteria

In terms of water management this primarily involves the development of adaptation options at both local and regional levels. In addition to focusing on enhancing water availability, concepts to regulate water demand will be proposed, as well as institutional and technological control mechanisms for climate-adjusted water use. The assessment of impacts on the groundwater system will form the basis for development of methods and technical solu-

60-second summary...

- Changes in groundwater recharge and groundwater depth caused by climate change were analyzed by generating an SIWA on ArcView groundwater recharge model and transferring these results to an existing 3D FEFLOW® groundwater model.
- Results suggest that the average groundwater recharge in Berlin can likely decrease from 143 [mm/a] to 111 [mm/a] for the analyzed period of ten years (2051-2060) as a result of an average temperature increase of 2°K.
- As a result, the groundwater depth will increase in many parts of the study area. Exemplary, this is shown for the northern part of Berlin and to some small extent for parts of the federal state of Brandenburg.

6.4 Groundwater in Berlin, Germany

tions for water storage and artificial groundwater recharge in the urban area of Berlin as adaptation response.

3. Formulating the modelling approach

To evaluate the potential impact of climate change on groundwater recharge in Berlin and the closely related risks for groundwater depth sensitive areas, first an area-differentiated and dynamic groundwater recharge model using the DHI-WASY Software SIWA on ArcView (Monninkhoff, 2001) has been setup. With a representative set of climate data groundwater recharge for the period 2051-2060 was simulated. In a second step the groundwater recharge was transferred to an existing 3D finite element FEFLOW® model for the water works Tegel (Luo, 2010), located in the northern part of Berlin. With this model changes in groundwater depth were simulated and analyzed.

The precipitation distribution in Berlin has been measured over several decades by 97 climatological stations and shows a heterogeneous precipitation distribution with two local minima and two local maxima. To reflect the precipitation distribution in Berlin the city area was divided into 19 precipitation zones. Each zone was assumed to reflect a homogeneous precipitation distribution. For each zone three climatological stations were used in interpolating representative rainfall rates using an Inverse Distance Weighting method. These interpolated precipitation rates were then corrected (Richter, 1995) and multiplied with a derived zone-factor to fit with the observed long-term distribution (Figure 1). The SIWA on ArcView model consists of more than 25500 polygons and was verified using an existing long-term groundwater recharge model which has been used for many years by the Berlin Senate Department for Urban Development (SenSTADT, 2009), for the period 1961-1990. The resulting average groundwater recharge distribution calculated with SIWA on ArcView for this period is shown in Figure 2. Potential evapotranspiration

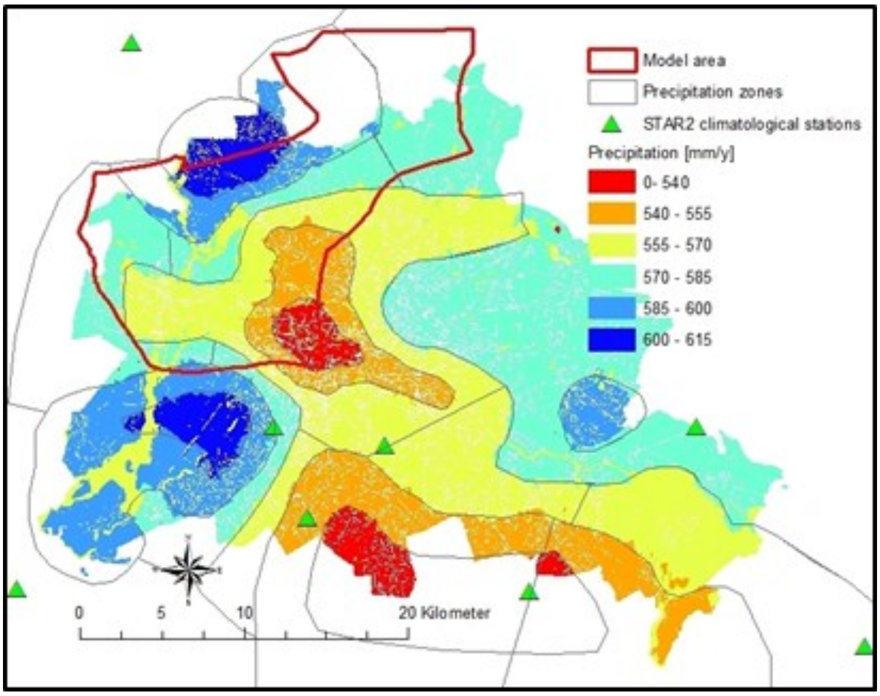


Figure 6.4.1: Distribution of precipitation in Berlin including available climatological stations (SenSTADT, 2009) and location of the analyzed study area

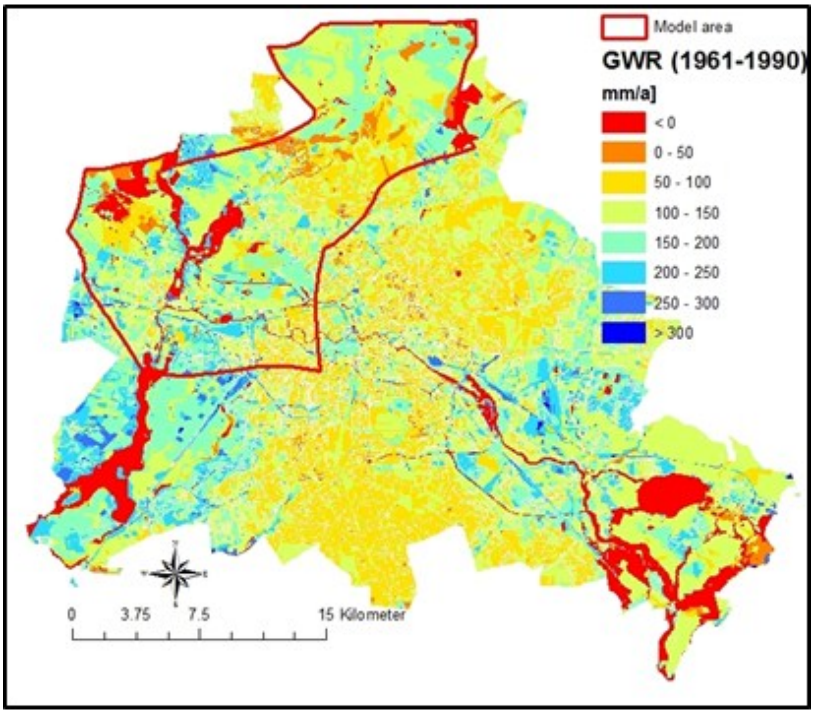


Figure 6.4.2: Simulated long-term groundwater recharge for Berlin and the study area

6.4 Groundwater in Berlin, Germany

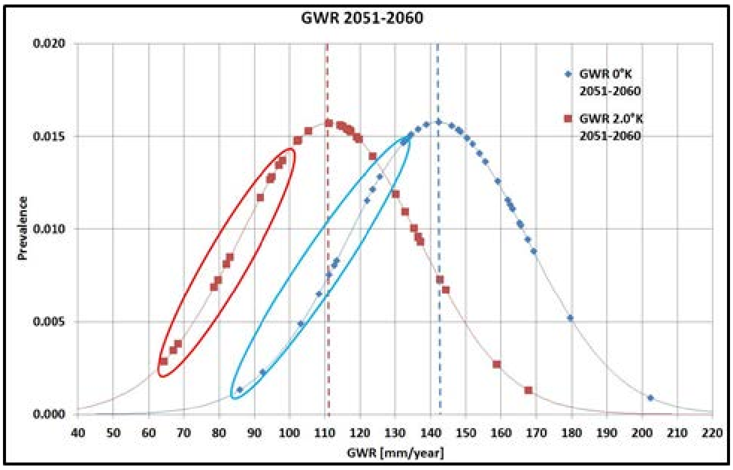


Figure 6.4.3: illustrative Gaussian distribution of groundwater recharge values of period 2051-2060 for 36 realizations from 0°K- and 2°K scenarios

was assumed to be homogeneous at the entire area of Berlin. The average long-term groundwater recharge for the total study area amounts ca. 142 mm/a.

4. Developing projections

Two climate scenarios are considered here. The first is the A1B Scenario, in which the global temperate in 2060 will increase about 2°K compared to the end of the trend in temperature of the reference period 1951-2006. The Potsdam Institute for Climate Impact Research (PIK) developed the statistical regional model STAR2 with which climate data for this scenario as well as a scenario without temperature increase were generated. This so-called 0° K Scenario follows the climate trend of the period 1961-1990 and is used as reference scenario to quantify the influence of temperature increase on different aspects of the water cycle.

From the STAR2 statistical regional climate model 100 realizations of climatic development for both scenarios (2°K and 0°K) were available. To reduce the computational effort, a subset of 36 realizations for each scenario was selected that was representative of the full range of realization. Based on the yearly groundwater recharge (2051-2060) 3 groups with 12 realizations for each scenario were extracted representing dry, wet and average conditions. The average of the simulated long-term, yearly and monthly groundwater recharge values (2051-2060) were calculated for each group and recharge entity (hydrotopes representing homogeneous landuse, soil type and groundwater depth). Figure 3 shows the groundwater recharge values for both scenarios assuming they can be represented by a Gaussian distribution. This figures show the clear shift in the mean between the two scenarios.

Analysis of the period 2051 – 2060 resulted in an average groundwater recharge of ca. 143 mm/a for the reference scenario 0°K (which is comparable with the present long-term average) while the 2°K scenario (only in the last 10 years the 2°K temperature increase is fully developed) showed an average of about. 111 mm/a. It can therefore be concluded that a 2°K temperature increase results in a reduction of groundwater recharge up to more than 30 mm/a. Further analyses showed that the contribution of the recharge within winter months (Jan – March) to the total yearly recharge will continuously increase while the contribution of the re-

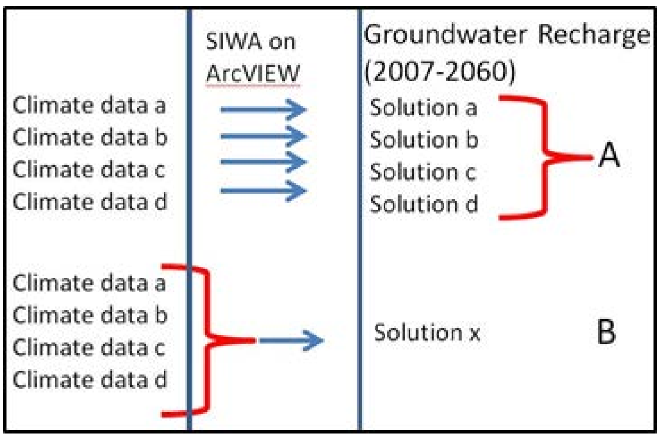


Figure 6.4.4: Comparison of workflows; upper workflow with high simulation costs (for each realization one model simulation); lower workflow with reduced simulation costs (climate data were averaged and consequently only one model simulation was performed)

6.4 Groundwater in Berlin, Germany

charge within the summer months will decrease.

To increase the representativeness of the results, more realizations could be taken into account. To increase the number of considered realizations and decrease simulation costs at the same time, a modified workflow was tested in which statistically modified climate data were prepared for a single groundwater recharge simulation rather than evaluating the results statistically of several simulations. The differences between both workflows are illustrated in Figure 4. The mean of the climate data (2051-2060) are equal in both workflows, but the simulated groundwater recharge is with much less in case of averaged climate data (B; 73 [mm/a]) than in averaged groundwater recharge data based on several climate realizations (A; 114 [mm/a]). The main reason for the reduced groundwater recharge values in case of summarizing daily climate data was that the climate averaging process reduces the number of dry days drastically, causing a dramatic increase in estimated evapotranspiration.

5. Decision-making

The calculated groundwater recharge rates were transferred to an existing 3D FEFLOW® groundwater model to predict changes in groundwater depths as a result of the temperature increase. First results have shown that a decrease in groundwater depth can be expected in range of 0.2 to 0.5 m for large parts of the study area (Figure 5). An assessment of possible risks for groundwater level depending ecosystems (like marshes) will be carried out in collaboration with other project partners (especially Freie Universität Berlin and SenGUV - Senate Department for Health, Environment and Consumer Protection). Furthermore, monthly trends in groundwater depths will be analyzed in order to identify potential ways to retain the surplus of water in the winter months in order to cover a potential deficit in the summer months. The results presented in this case study are intended to illustrate the workflow which has been followed in the course of the project. As these results are still preliminary and are based on an assumed climatic projection (2°K scenario), they do not necessarily describe the possible influence of climate change for the city of Berlin precisely.

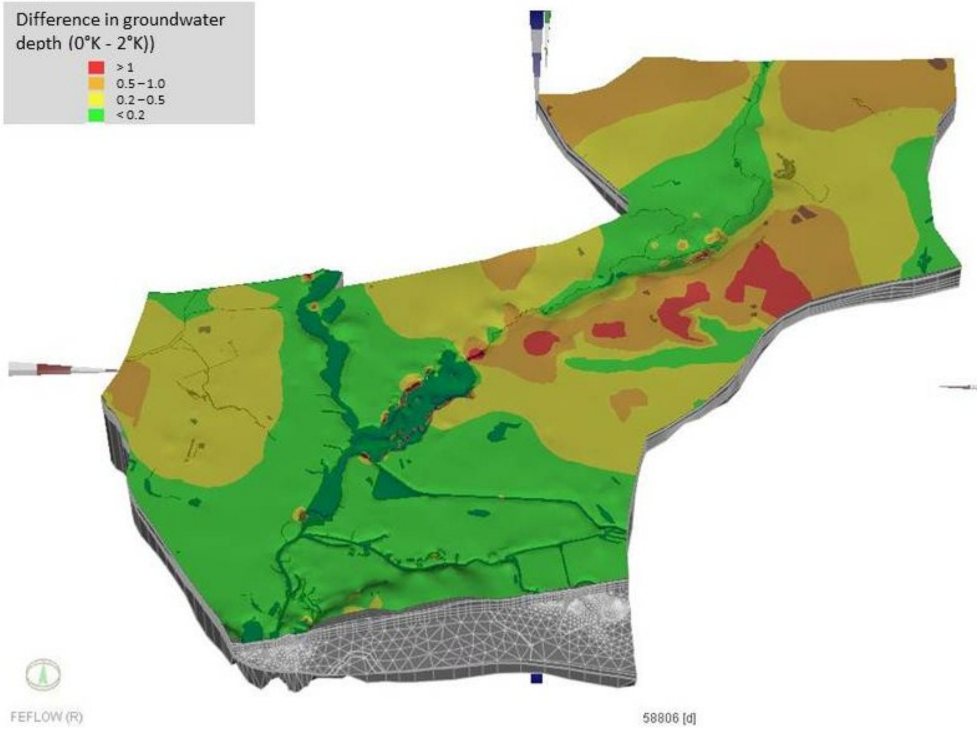


Figure 6.4.5: Change in groundwater depths; comparison of 2°K and 0°K scenario, mean values for the period 2051-2060

DHI tools, glossary, references and appendix

How can DHI tools help?

How can DHI tools help?

Climate Button

Global climate projections from 22 GCMs included in the Coupled Model Intercomparison Project CMIP3 and reported in the IPCC 4th Assessment Report have been made available in the MIKE by DHI Climate Change Tool. The tool can be used for larger scale impact studies and for a first screening at regional or local scale. For downscaling GCM projections, delta change factors for precipitation, temperature and potential evapotranspiration are available for the 22 GCM models for the SRES emission scenarios B1, A1B and A2.

The tool automatically modifies the climate time series of an existing model setup according to specified location (longitude, latitude), GCM model, emission scenario, and projection horizon. Projected climate time series are calculated using the delta change approach, i.e. precipitation time series are multiplied by the precipitation change factors, temperature change factors are added to the temperature time series and potential evapotranspiration time series are multiplied by the evapotranspiration change factors. Different scenarios (e.g. different GCMs, emission scenarios and projection horizons) can be defined within the same setup, allowing an easy evaluation and comparison of different climate change scenarios. The tool supports the selection of an ensemble of GCM models for calculation of ensemble average change factors.

For more information:

http://mikebydhi.com/~/media/Microsite_MIKEbyDHI/Publications/PDF/2-p%20flyer_generic_LR.ashx

How can DHI tools help?

MIKE FLOOD

MIKE FLOOD is a comprehensive flood modelling tool for urban, coastal and riverine flooding. By combining the strengths of 1D and 2D simulation engines it is possible to model flood problems involving rivers, floodplains, floods in streets, urban drainage networks, coastal areas and estuaries or any combination of the above. Efficient simulations of river channels and drainage/sewer networks using 1D models can be combined with 2D simulations of floodplains and coastal areas using rectilinear grids, efficient multi-cell solvers or flexible (finite volume) meshes.

Typical MIKE FLOOD applications include:

- Flood hazard mapping under climate change
- Rapid flood assessment
- Flood contingency planning, for planning of evacuation routes or infrastructure breakdown
- Impact assessments for climate change
- Flood defence failure (dam break, breaching, etc.)
- Integrated flood modelling of urban drainage, rivers, floodplains and coastal flood modelling

For more information:

http://www.mikebydhi.com/Products/WaterResources/MIKEFLOOD.aspx

How can DHI tools help?

How can DHI tools help?

MIKE 11

MIKE 11 is a river basin and river engineering modelling system for the simulation of flows, water levels, sediment transport and water quality for rivers, flood plains, irrigation systems, estuaries and other water bodies, (Havnø et al., 1995). This model includes distributed hydrological modelling through the rainfall-runoff (RR) component where the river basin of interest is divided into a number of sub-basins, to represent the spatial variations in the meteorological forcing (precipitation, potential evapotranspiration, temperature) and the sub-basin characteristics (elevation, land use, etc.). This includes irrigation modelling and distributed snow accumulation and snowmelt including lapse rate effects.

Typical applications include:

- Flood mapping, flood analysis and flood alleviation design
- Real-time flood forecasting
- Dambreak analysis
- Optimisation of reservoir and canal gate / structure operations
- Ecological and water quality assessment in rivers and wetlands
- Sediment transport and river morphology studies
- Salinity intrusion in rivers and estuaries
- Wetland and river restoration

For more information:

http://www.mikebydhi.com/Products/WaterResources/MIKE11.aspx

How can DHI tools help?

MIKE BASIN

MIKE BASIN is a modelling tool for integrated river basin analysis, planning and management. It is designed as a simple yet comprehensive tool box for analysing water allocation and water sharing at the international level (transboundary), national or local river basin level. The advantages of MIKE BASIN are its simplicity and integration with GIS and other facilities to provide clear and intuitive information for decision-makers and a powerful platform for investigating management options and consensus building amongst stakeholders.

Typical applications of MIKE BASIN include:

- Multi-sector solution and scenario analysis for water allocation and water shortage problems using different water allocation and sharing algorithms
- Evaluate and improve irrigation scheme performance using irrigation water demand and crop yield estimation
- Improve and /or optimize reservoir and hydropower operations
- Explore conjunctive use of groundwater and surface water
- Evaluate non-point and point nutrient pollution loads
- Establish and compare cost effective measures for water quality compliance.

For more information:

http://www.mikebydhi.com/Products/WaterResources/MIKEBASIN.aspx

How can DHI tools help?

DHI tools

Glossary

References

Appendix

How can DHI tools help?

FEFLOW

FEFLOW is an advanced and highly flexible finite element model for subsurface flow and transport and interactions with river systems. The advantage of the finite element approach is the flexibility to represent complex geologies with a high spatial resolution, including sloping layers and anisotropy and the ability to precisely represent features like rivers, fractures, tunnels and well locations. One of the other key strengths of FEFLOW is the number of advanced descriptions of subsurface processes such as variably saturated and density dependent flow, saltwater intrusion, multi species chemistry and transport and heat transport.

FEFLOW is a powerful hydrological model for

- Regional groundwater management
- Groundwater/surface water interaction
- Saltwater intrusion
- Seepage through dams and levees
- Mine water management
- Groundwater management in construction and tunnelling projects
- Land use and climate change scenarios
- Groundwater remediation and natural attenuation
- Geothermal energy (deep and near surface; both open--and closed-loop systems)

For more information:

http://www.mikebydhi.com/Products/GroundWaterAndPorousMedia/FEFLOW.aspx

How can DHI tools help?

MIKE SHE

MIKE SHE is a fully integrated catchment modelling tool that represents the major processes in the hydrological cycle and includes process models for evapotranspiration, snowmelt, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modelling study, the availability of field data and the modeller's choices. Grid-based and sub-basin-based representations of the variability in the meteorological forcing or the catchment characteristics can be selected.

MIKE SHE is a powerful hydrological model for

- Integrated catchment hydrology
- Nutrient fate and management
- Conjunctive use and management of surface water and groundwater
- Irrigation and drought management
- Wetland management and restoration
- Environmental river flows
- Floodplain management
- Groundwater induced flooding
- Land use and climate change impacts on both surface water and groundwater
- Groundwater remediation

For more information:

http://www.mikebydhi.com/Products/WaterResources/MIKESHE.aspx

How can DHI tools help?

How can DHI tools help?

DHI Decision Support Systems

DHI's Decision Support System (DSS) platform is a generic tool designed to assist technicians, engineers, planners, operators, negotiators and decision makers in the process of making sound and sustainable decisions and investments, in a wide range of fields including integrated water management. The tool is able to compile, modify, analyse and present observations and model data in such a manner that this information can be readily used for making objective and transparent decisions. It can be linked to mathematical models, including MIKE by DHI to address a wide range of applications such as flood protection, reservoir design and operations, irrigation water requirements, groundwater impacts and the environment.

The key capabilities of the DSS platform:

- A comprehensive database for time-series, spatial data (GIS) and scenarios (models).
- Meta-data for describing data and facilities for tracing and auditing purposes.
- A web interface (web client) designed for dissemination of selected information over the internet.
- A suite of tools for processing, analysing and visualizing GIS and time-series data.
- A Scenario Manager that links to model tools (e.g. MIKE by DHI) and provides facilities for safe storage, execution and maintenance of scenarios.
- Generic optimisation tools for reservoir operation given certain downstream objectives (e.g. minimize irrigation water deficits, maximize hydropower production, and minimize downstream flood damage).
- Ensemble modelling tools to derive include probabilities and uncertainties in model predictions.
- A Script Manager that allows users to build their own scripts and tools
- An Indicator Manager that allows the user to develop their indicators for management and decision making
- Multi-criteria-analysis to support transparent and objective decision making and to facilitate stakeholder involvement.
- Cost-Benefit-Analysis to assess the economic feasibility of different investments (scenarios).

For more information:

http://www.dhigroup.com/SolutionSoftware/Platform.aspx

DHI Climate Change DSS

The DHI climate change DSS is designed to generate and visualize climate change data to support climate change assessments and decision-making. This DSS tool provides an atlas or data repository for climate information, allowing the user to view and display information concerning current and future climate scenarios, climate impacts and climate adaptation effects and some analysis tools such as data exchange, downscaling, and the ability to make comparisons for scenarios and uncertainty analyses.

The key capabilities of the Climate change DSS platform:

- Atlas or map-based repository for the storage and presentation of climate change information
- Web-based forum for data-sharing and decision making
- Document storage and retrieval
- Simple visualisation and statistical analysis tools
- View and display information concerning current and future climate scenarios
- Comparison and evaluation of results from modelling tools such as competing adaptation measures
- Downscaling from Global and Regional Climate models.

How can DHI tools help?

DHI tools

Glossary

References

Appendix

How can DHI tools help?

MIKE 3

MIKE 3 is a 3-dimensional modelling system for the simulation of flows, water levels, sediment transport and water quality for deep stratified lakes, reservoirs and/or stratified estuaries. Provided with a set of climate change forcing data and input of changed river inflows and nutrient loadings, this system can help model ecosystem changes in areas where stratification plays a vital role.

Typical MIKE 3 applications:

- Assessment of hydrographic conditions for design, construction and operation of structures and plants in stratified waters
- Ecological modelling including optimisation of aquaculture systems
- Lake hydrodynamics and ecology
- Coastal and estuary restoration projects

For more information:

http://www.mikebydhi.com/Products/CoastAndSea/MIKE3.aspx

How can DHI tools help?

ECOLAB

ECO Lab is a flexible numerical laboratory for ecological modelling. Within ECO Lab a set of different models already exists that can help solving some ecological and environmental issues related to climate change, however, new ecological models can also be developed to describe any ecosystem- or environmental system.

When analysing ecosystems for climate change impacts one should keep in mind that large scale changes in ecosystems and ecosystem functional groups are rarely address by ecosystem models. The change may be related to morphological changes as well as changed in biological structure e.g. significant changes in balance between functional groups of flora and fauna. It is important to evaluate whether such change may be seen as a consequence of the climate changes over the time periods that is used for the assessment. Expert guidance and/or advice for the specific ecosystem could be needed.

Typical ECO Lab applications:

- Water quality and ecological studies related to rivers, wetlands, lakes, reservoirs, estuaries, coastal waters and the sea
- Spatial predictions of any ecosystem response
- Simple and complex water quality studies
- Impact and remediation studies
- Planning and permitting studies
- Water quality forecast

For more information:

http://mikebydhi.com/Products/ECOLab.aspx

How can DHI tools help?

Glossary

DHI tools

Glossary

References

Appendix

Anomalies — The standard definition being "Something that deviates from what is standard, normal, or expected"

When referring to climate model output datasets:

Anomalies are the changes in that variable from a reference value – so projections might be presented as the change in temperature relative to a baseline climatology which might be 1971-2000 for example, rather than the absolute value.

AR4 — *4th Assessment Report* of the Intergovernmental Panel on Climate Change. The fourth in a series of reports from IPCC. The largest and most detailed summarry of the climate change situation, it is made up of 4 principal sections: The physical science basis; Impacts, Adaptation and Vulnerability; Mitigation of Climate Change; The Synthesis Report.

AR5 — *5th Assessment Report* of the Intergovernmental Panel on Climate Change. Due to be published in 2014

CDF — Cumulative Distribution Function

The cumulative form of a probability density function describing the statistical character of a variable.

Climatologies — When referring to climate model output datasets:

Climatologies are average variables over a long period – they may be 30 year or 20 year average of January rainfall for a period centred around 2085 for example.

Copula — A three dimensional distribution function which can be used to describe the probability of two types of events occurring concurrently.

CMIP3 — *Coupled Model Intercomparison Project 3.*

CMIP5 — *Coupled Model Intercomparison Project 5*.

Latest global climate modelling project which will be used to write the IPCCs upcoming 5th Assessment Report.

CORDEX — Co-Ordinated Regional climate Downscaling Experiment

CORDEX is a framework aimed at improving coordination of international efforts in regional climate downscaling research. The website will host output datasets from RCMs across the globe.

Downscaling — In numerical modelling, Downscaling is a process which takes outputs from a model and adds information at spatial or temporal resolutions smaller than the grid scale or time step of the model.

ECMWF — European Centre for Medium-range Weather Forecasts

Based in Reading, UK, is an independent intergovernmental organisation supported by 35 states, providing operational medium- and extended-range forecasts and a state-of-the-art super-computing facility for scientific research.

Glossary

Emission scenario	Scenarios of emissions of greenhouse gases
ENSEMBLES Ensemble	1. ENSEMBLES Name of the European project to collect various GCM/RCM climate model runs. Database of results stored on their website for research. 2. Ensemble: A collection of runs for the same time period but suing different models to enable comparisons of results
EVA	Extreme Value Analysis Statistical analysis of the largest events in a record to characterise the nature of these extremes and the probability of their occurrence in any year.
Feedback mechanisms	Mechanisms in the climate system where a change leads to an effect which in turn amplifies (positive feedback) or diminsishes (negative feedback) the original change. An example of positive feedback mechanism is: Increased temperatures melt ice, the reduction in ice cover means the surface is less reflective (lower albedo) which means less heat will be reflected and warming will be accelerated (amplifying the original change), which in turn will lead to more ice melting etc.
GCM	*Global Climate Model / General Circulation Model* Coupled ocean and atmosphere numerical models used to predict changes in climate under various atmospheric CO^2 scenarios.
Geoengineering	Refers to all the large-scale engineering ideas for physical intervention in the climate system to try to counteract the effects of global warming. E.g. reducing incoming sunlight by placing mirrors in space.
GEV	*General Extreme Value distribution.* One of many distributions that can be used to describe the statistical character of extremes. It comes in 3 forms depending of the value of the shape parameter.
IPCC	*Intergovernmental Panel on Climate Change.* A scientific body of the United Nations, international leaders for the assessment of climate change, hosted by WMO.
Isostatic movement	Describes the upward or downward movement of a tectonic plate relative to areas around it, caused by changed in weight (density or thickness). Changes in weight distribution were caused by melting of glaciers after the last glacial maximum. Areas previously glaciated will be rebounding and other areas may be subsiding as part of a see-saw effect.
ITCZ	Inter-Tropical Convergence Zone The zone of upper air convergence which lies over the area of maximum solar radiation (moving northward and southward of the equator with the seasons). Intense heating leads to convection and heavy rainfall in the tropics.
L-moments	Moments (statistics) used to describe a dataset which are based on linear (giving the L) combinations of the ordered data

Glossary

DHI tools
Glossary
References
Appendix

NARCCAP	The US RCM project
NCAR	*National Center for Atmospheric Research* A US centre hosting modelling information.
NCEP	National Centers for Environmental Protection A US group of centres working in weather prediction.
NetCDF	*Network Common Data Form.* The form in which large datasets are often stored. Requires specialist tools for processing.
PCMDI	*Program for Climate Model Diagnosis and Intercomparison* Hosting information about model imtercomparison projects CMIP3 and CMIP5
Penman-Montieth equation	A widely-used equation for modelling Evapotranspiration. Requiring many inputs such as daily mean temperature, wind speed, relative humidity, and solar radiation.
Predictand	The variable being predicted
PRUDENCE	A database of RCMs runs in Europe from 2004. The predecessor to ENSEMBLES.
RCM	*Regional Climate Model* Regional coupled ocean and atmosphere numerical models used to predict changes in climate under various atmospheric CO^2 scenarios. Smaller scale than global models. Use global models as boundary conditions.
RCP	*Representative Concentration Pathway*. A future scenario of atmospheric greenhouse gas concentration used to define possible futures in CMIP5 climate modelling.
Reanalysis data	Climate model data run with observed data to produce a gridded dataset of observations.
Synoptic	Synoptic scale meteorological events are large scale events with spatial horizontal scale of 1000s of kilometres.
SRES	*Special Report on Emissions Scenarios* IPCC report in 2008 outlining the emissions scenarios which were used in 4th Assessment Report modelling (CMIP3)
Stationarity	A property of a dataset which has a stable average value over time.

Glossary

References

[DHI tools](#)

[Glossary](#)

References

[Appendix](#)

Arnbjerg-Nielsen, K., 2008, Forventede ændringer i ekstremregn som følge af klimaændringer (In Danish: Anticipated changes in extreme rainfall due to climate change), Recommendation Paper No. 29, The Water Pollution Committee of The Society of Danish Engineers, Can be downloaded from http://ida.dk/svk/

Boukhris O., Willems P., 2008, Climate change impact on hydrological extremes along rivers in Belgium', FloodRisk 2008 Conference, 30 Sept. – 2 Oct. 2008, Oxford, UK In: Flood Risk Management: Research and Practice (Eds. Samuels et al.), Taylor & Francis Group, London, 1083-1091 (ISBN 978-0-415-48507-4)

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Christensen, J., Boberg, F., Christensen, O., Lucas-Picher, P., 2008, On the need for bias correction of regional climate change projections of temperature and precipitation, Geophys. Res. Lett., 35 (20), L20,709.

Christensen, J.H., Kjellström, E., Giorgi, F., Lenderink, G., Rummukainen, M., 2010, Weight assignment in regional climate models, Climate Research, 44, 179-194.

Church, J.A., J.M. Gregory, N.J. White, S.M. Platten, and J.X. Mitrovica. 2011. Understanding and projecting sea level change. Oceanography 24(2):130–143, http://dx.doi.org/10.5670/oceanog.2011.33.

DEFRA. 2005. Use of joint probability methods in flood management. A guide to best practice. RRD Technical Report FD2308/TR2

DEFRA. 2006. Flood and coastal defence appraisal guidance (FCDPAG3) Economic appraisal supplementary note to operating authorities – climate change impacts. Department for Environment, Food and Rural Affairs, London, 9pp.

Dégué, M., Rowell, D.P., Lüthi, D., Giorgi, F., Christensen, J.H., Rockel, B., Jacob, D., Kjellström, E., de Castro, M., van den Hurk, B., 2007, An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections, Climatic Change, 81, 53-70.

Dessai, S. and van de Sluijs, J., 2007, Uncertainty and Climate Change Adaptation -a Scoping Study. Netherlands Environmental Assessment Agency Report, Utrecht. Report NWS-E-2007-198.

DHI 2004(?). Flood Management: solutions and services.

DHI 2010. P. Glennie, G. J. Lloyd, H. Larsen, The Water-Energy Nexus: The water demands of renewable and non-renewable electricity sources, November 2010.

Döll, P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environmental Research Letters* 4 (2009) 035006 (12pp). IOP Science.

EC 2009. Climate Change and Water, Coasts and Marine Issues. Commission staff working document accompanying the White Paper: Adapting to climate change: Towards a European framework for action. COM(2009) 147 final. Brussels, 1.4.2009, SEC(2009) 386.

FAO 2008. Climate change, water and food security. Technical background document from the expert consultation held on 26-28 February 2008. Available at: www.fao.org/nr/water/docs/HLC08-FAOWater-E.pdf

References

Fowler, H.J., Blenkinsop, S. and Tebaldi, C., 2007, Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling, Int. J. Climatol., 27, 1547-1578.

Fung, C.F., Lopez, A. and New, M. (eds) 2011. Modelling the Impact of Climate Change on Water Resources. Wiley-Blackwell, UK.

Giorgi, F., Jones, C., Asrar, G., 2009, Addressing climate information needs at the regional level: The CORDEX framework, WMO Bulletin 2009, 58(3), 175-183.

Gleckler, P.J., Taylor, K.E., Doutriaux, C., 2008, Performance metrics for climate models, J. Geophys. Res., 113, D06104, doi:10.1029/2007JD008972.

Grinsted, A., Moore, J.C. and Jevrejeva, S., 2009, Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD, Clim. Dyn., DOI 10.1007/s00382-008-0507-2.

Groves, D. G., Lempert, R., Knopman, D., Berry, S. 2008. Preparing for an Uncertain Future Climate in Inland Empire – Documented Briefing. DB-550-NSF, RAND, Santa Monica, CA, USA.

Gudmundsson, L., Tallaksen, L.M. & Stahl, K., 2011. Projected changes in future runoff variability - a multi model analysis using the A2 emission scenario. EU WATCH Project deliverable 4.3.1a, output from Work Block 4; task 4.3.1, 30 July 2011. http://www.eu-watch.org/publications/technical-reports

Hall, J. 2007. Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. Hydrological Processes 21(8): 1127-1129.

Hanel, M., Buishand, T.A., Ferro, C.A.T., 2009. A nonstationary index flood model for precipitation extremes in transient regional climate model simulations. J. Geophys. Res. 114, D15107. doi:10.1029/2009JD011712.

Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society, 90, 1095-1107.

Hawkins E, Sutton R (2010) The potential to narrow uncertainty in projections of regional precipitation change, Clim. Dyn., doi: 10.1007/s00382-010-0810-6.

Hennegriff, W., Kolokotronis, V., Weber, H., Bartels, H., 2011, Climate Change and Floods – Findings and Adaptation Strategies for Flood Protection, www.kliwa.de (accessed January 2012)

Horton, R., Herweijer, C., Rosenzweig, C., Liu, J., Gornitz, V., Ruane, A.C., 2008, Sea level rise projections for current generation CGCMs based on the semi-empirical method, Geophys. Res. Lett., 35, doi:10.1029/2007GL032486

Hunt, A. and Watkiss, P., 2011. Climate change impacts and adaptation in cities: a review of the literature. Climatic Change, 104 (1), pp. 13-49. http://dx.doi.org/10.1007/s10584-010-9975-6

IFPRI 2009. Climate change: Impact on agriculture and costs of adaptation. Food Policy Report. International Food Policy Research Institute. Gerald C. Nelson, Mark W. Rosegrant, Jawoo Koo, Richard Robertson, Timothy Sulser, Tingju Zhu, Claudia Ringler, Siwa Msangi, Amanda Palazzo, Miroslav Batka, Marilia Magalhaes, Rowena Valmonte-Santos, Mandy Ewing, and David Lee. Available at: http://www.ifpri.org/publication/climate-change-impact-agriculture-and-costs-adaptation

IPCC 2007a. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability. Section 3.4.3 Floods and droughts. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch3s3-4-3.html

IPCC 2007b. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability. Chapter 6: Coastal Systems and Low-Lying Areas. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch6.html

IPCC 2007c. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability. Chapter 3: Freshwater resources and their management. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch3.html

IPCC 2007d. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability. Section 3.2: Current sensitivity/

References

vulnerability. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch3s3-2.html

IPCC 2007e. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability. Section 3.4.1 Surface waters. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch3s3-4.html

IPCC 2008 Climate Change and Water. IPCC Technical Paper Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds.IPCC Secretariat, Geneva, 210 pp. June 2008

Japan Gov. 2010. Practical guidelines on strategic climate change adaptation planning – Flood Disasters. October 2010. www.mlit.go.jp/river/basic_info/english/climate.html

Jevrejeva, S., Moore, J.C., Grinsted, A., 2011, sea level projections to AD2500 with a new generation of climate change scenarios, Global and planetary Change, 80-81, 14-20.

JRC 2009. Climate change impact assessment on flood hazard. European Commission Joint Research Centre, Institute for Environment and Sustainability. http://floods.jrc.ec.europa.eu/climate-change-impact-assessment.html

Kay, A. L. and Davies, H.N., 2008, Calculating potential evaporation from climate model data: A source of uncertainty for hydrological climate change impacts, J. Hydrol., 358, 221– 239.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James, P., Smith, A., Wilby, R.L., 2007, A daily weather generator for use in climate change studies, Env. Model. Software, 22, 1705-1719.

Kopp, R., Simons, F., Mitrovica, J., Maloof, A., Oppenheimer, M., 2009, Probabilistic assessment of sea level during the last interglacial stage, Nature, 462, 863–867. (doi:10.1038/nature08686).

Lankao, P. R., 2008. Urban Areas and Climate Change: Review of Current Issues and Trends Issues Paper for the 2011 Global Report on Human Settlements. Institute for the Study of Society and Environment. National Center for Atmospheric Research, Boulder, Colorado.

Lawrence, D. and Hisdal, H. 2011. Hydrological projections for flooding in Norway under a future climate. NVE Report 5-2011, Norwegian Water Resources and Energy Directorate, Oslo, 47 pp, ISBN 978-82-410-0753 -8.

Lawrence, D., Haddeland, I., 2011, Uncertainty in hydrological modelling of climate change impacts in four Norwegian catchments, Hydrology Research, 42, 6, 457–471.

Leander, R., Buishand, T.A., 2007, Resampling of regional climate model output for the simulation of extreme river flows, J. Hydrol., 332, 487-496.

Lempert, R. J. and Groves, D. G. 2010. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. Technological Forecasting and Social Change 77(6): 960-974.

LUC 2006. Adapting to climate change impacts—a good practice guide for sustainable communities. Defra, London. Land Use Consultants (LUC) in association with Oxford Brookes University, CAG Consultants and Gardiner & Theobold. http://www.london.gov.uk/lccp/publications/sustain_comm.jsp

Luo, J. (2010). *Grundwasser-Strömungsmodellierung zur Neubesessung der Trinkwasserschutzzone Wasserwerk Tegel.* Berlin: DHI-WASY.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M., Kjeldsen, T.R. (eds.), 2012, A review of applied methods in Europe for flood-frequency analysis in a changing environment, COST ACTION ES0901: European procedures for flood frequency estimation (FloodFreq).

References

Madsen, H., Sunyer, M., 2011, Estimation of changes in extreme precipitation from climate model projections, 34th IAHR World Congress - Balance and Uncertainty, 26 June - 1 July 2011, Brisbane, Australia.

Manning, M. R., J. Edmonds, S. Emori, A. Grubler, K. Hibbard, F. Joos, M. Kainuma, R. F. Keeling, T. Kram, A. C. Manning, M. Meinshausen, R. Moss, N. Nakicenovic, K. Riahi, S. K. Rose, S. Smith, R. Swart & D. P. van Vuuren. (2010) Misrepresentation of the IPCC CO2 emission scenarios. Nature Geoscience 3, 376 - 377.

Maraun, D., Wetterhall, F., Ireson, A.M., Chandler, R.E., Kendon, E.J., Widmann, M., Brienen, S., Rust, H.W., Sauter, T., Themeβl, M., Venema, V.K.C., Chun, K.P., Goodess, C.M., Jones, R.G., Onof, C., Vrac, M., Thiele-Eich, I., 2010, Precipitation downscaling under climate change. Recent developments to bridge the gap between dynamical models and the end user, Rev. Geophysics.

McCarl 2008. Adaptation Options for Agriculture, Forestry and Fisheries. A Report to the UNFCCC Secretariat Financial and Technical Support Division

MDGF 2011. Criteria for Identifying Climate Change Adaptation Options. MDG achievement fund, Cordillera, Philippines.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Monninkhoff, B. (2001). *ArcSIWA 1.1 - Berechnung der Grundwasserneubildung - Tutorial.* Berlin: DHI WASY.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. & Wilbanks, T.J. 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756 (11 February 2010)

Nicholls, R.J. 2011. Planning for the impacts of sea level rise. Oceanography 24(2):144–157, http://dx.doi.org/10.5670/oceanog.2011.34.

Nicholls, R.J., Hanson, S.E., Lowe, J.A., Warrick, R.A., Lu, X., Long, A.J. and Carter, T.R., 2011, Constructing Sea-Level Scenarios for Impact and Adaptation Assessment of Coastal Area: A Guidance Document. Supporting Material, Intergovernmental Panel on Climate Change Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), 47 pp.

Nicholls, R.J., Marinova, N., Lowe, J.A., Brown, S., Vellinga, P., de Gusmao, D., Hinkel, J., Tol, R.S.J., 2011, Seal-level rise and its possible impacts given a “beyond 4C world” in the twenty first century, Phil. Trans. R. Soc. A (2011) 369, 1–21, doi:10.1098/rsta.2010.0291

A. Olhoff and C. Schaer (2010). Screening Tools and Guidelines to Support the Mainstreaming of Climate Change Adaptation into Development Assistance – A Stocktaking Report. UNDP: New York.

NeWater 2009. FAQs. http://www.newater.info/index.php?pid=1056

OECD 2009. Integrating Climate Change Adaptation into Development Co-operation: Policy Guidance

Parson, E., V. Burkett, K. Fisher-Vanden, D. Keith, L. Mearns, H. Pitcher, C. Rosenzweig, M. Webster. 2007. *Global Change Scenarios: Their Development and Use*. Sub-report 2.1B of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, DC., USA, 106 pp.

PASCO 2011. Glacial Lake Outburst Flood (GLOF) Monitoring. http://www.pasco.co.jp/eng/solutions/monitoring/golf/

Pfeffer, W., Harper, J., O'Neel, S., 2008, Kinematic constraints on glacier contributions to 21st-century sea-level rise, Science, 321, 1340–1343. (doi:10.1126/science.1159099).

References

DHI tools

Glossary

References

Appendix

Practical Action 2006(?). Web page. http://practicalaction.org/climatechange_nepalfloods

Rahmstorf, S., 2007, A semi-empirical approach to projecting future sea-level rise, Science 315, 368–370. (doi:10.1126/science.1135456).

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007, Climate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Richter, D. (1995). *Ergebnisse methodischer Untersuchungen zu Korrektur des systematischen Meßfehlers des Hellmann-Niederschlagsmessers.* Offenbach am Main: Berichte des Deutschen Wetterdienstes.

Rohling, E., Grant, K., Hemleben, C., Siddall, M., Hoogakker, B., Bolshaw, M., Kucera, M., 2008, High rates of sea-level rise during the last interglacial period, Nat. Geosci., 1, 38–42.(doi:10.1038/ngeo.2007.28).

Rugbjerg, M. and Johnsson, M., 2012, Climate change effects on marine design conditions in the North Sea, the Inner Danish Waters and the Baltic Sea, In preparation.

SenSTADT (2009) Berlin Senate Department for Urban Development; Model data to setup and verify recharge model, internal project data preperation, partly published in *Digitale Umweltatlas Berlin*: www.stadtentwicklung.berlin.de/umwelt/umweltatlas/index.shtml

Smith, M. and Barchiesi, S. (2009) Environment as infrastructure – resilience to climate change impacts on water through investments in nature. Perspectives Paper prepared for the 5th World Water Forum, Istanbul, Turkey.

Stone., D.A and Knutti, R. (2011) Weather and Climate. In Fung, C.F., Lopez, A. and New, M. (eds) 2011. Modelling the Impact of Climate Change on Water Resources. Wiley-Blackwell, UK. Chapter 2.

Sunyer, M.A., Madsen, H., Ang, P.H., 2012, A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change, Atm. Res.,103, 119-128.

UK Environment Agency. 2009. TE2100 Plan Consulation Document. http://www.environment-agency.gov.uk/research/library/consultations/106100.aspx

UNEP-Risø 2011. Technology Needs Assessment (TNA) Project, Guidebook series: Technologies for Climate Change Adaptation. Different sectors including: Water; Agriculture; Coastal Erosion and Flooding. Guidebooks available at: http://tech-action.org/guidebooks.htm

UNFCCC 2007. Detailed analysis by sector prepared for background paper. Mitigation and adaptation. Adaptation reports on: Natural ecosystems; Agriculture, forestry and fisheries; Water supply; Extreme events; Infrastructure; Coastal zone; and Human health. All reports available at: http://unfccc.int/cooperation_and_support/financial_mechanism/financial_mechanism_gef/items/4054.php

UNFCCC 2008. Climate change: Impacts, vulnerabilities and adaptation in developing countries. http://www.preventionweb.net/english/professional/publications/v.php?id=2759

van der Linden P., and J.F.B. Mitchell (eds.) 2009: ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK. 160pp.

Van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K. 2011. The representative concentration pathways: an overview. Climatic Change, 109 pp5-31.

Vellinga, P. et al., 2008, Exploring high-end climate change scenarios for flood protection of TheNetherlands. International Scientific Assessment carried out at request of the Delta Committee. Scientific report WR-2009-05. KNMI, Alterra, The Netherlands. See http://www.knmi.nl/bibliotheek/knmipubWR/WR2009-05.pdf .

Vermeer, M., Rahmstorf, S., 2009, Global sea level linked to global temperature. Proc. Natl. Acad. Sci. USA 106, 21 527–21 532. (doi:10.1073/pnas.0907765106).

VicGov 2011. Webpage: Allocation & trading: Water allocation framework: Environmental Water Reserve. State Government of Victoria, Department of Sustainability and Environment. Accessed Oct. 31 2011 http://www.water.vic.gov.au/allocation/water_allocation_framework/environmental_water_reserve

Vörösmarty, C., Green, P., Salisbury, J., Lammers, R. 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science* **289**, 284 (2000).

Waughray, D (ed.). 2011. Water security: the water-food-energy-climate nexus: the World Economic Forum Initiative. Island Press. http://www.weforum.org/reports/water-security-water-energy-food-climate-nexus

Webster M., Paltsev S., Parsons J., Reilly J., Jacoby H. 2008. Uncertainty in greenhouse emissions and costs of atmospheric stabilization. MIT Joint Program Report #165, Cambridge, MA, USA.

Willems P., 2011, Revision of urban drainage design rules based on extrapolation of design rainfall statistics, In: 12nd International Conference on Urban Drainage, Porto Alegre/Brazil, 10-15 September 2011, 8 p.

Willows, R.I. and Connell, R.K. (Eds.). 2003. Climate adaptation: Risk, uncertainty and decision-making. UKCIP Technical Report. UKCIP, Oxford.

World Bank (2009). Water and Climate Change: Understanding the risks and making climate smart investment decisions. Available at:

http://siteresources.worldbank.org/EXTNTFPSI/Resources/DPWaterClimateChangeweblarge.pdf

WWAP 2009. World Water Development Report 3, Part 1. World Water Assessment Programme.

Yang, W., Andréasson, J., Graham, L.P., Olsson, J., Rosberg, J., Wetterhall, F., 2010, Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies, Hydrol. Res., 41(3-4), 211-229.

Zhang, X., F. W. Zwiers, et al. 2007. Detection of human influence on twentieth-century precipitation trends. Nature 448(7152): 461-U464.

Appendix - Climate model data

Table A1. Overview of Global Climate models used in CMIP3 (which formed the basis for IPCC's Fourth Assessment Report). Superscript numbers refer to models that share either the same atmosphere and/or ocean model component. Full details of the models can be found here: http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

Model	Modelling group
BCC-CM1	Beijing Climate Center, China
BCCR-BCM2.0[1]	Bjerknes Centre for Climate Research, Norway
CCSM3	National Center for Atmospheric Research, USA
CGCM3.1(T47)[2]	Canadian Centre for Climate Modelling & Analysis, Canada
CGCM3.1(T63)[2]	Canadian Centre for Climate Modelling & Analysis, Canada
CNRM-CM3[1]	Météo-France / Centre National de Recherches Météorologiques, France
CSIRO-Mk3.0	CSIRO Atmospheric Research, Australia
CSIRO-Mk3.5	CSIRO Atmospheric Research, Australia
ECHAM5/MPI-OM[3]	Max Planck Institute for Meteorology, Germany
ECHO-G[3]	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group, Germany and Korea
FGOALS-g1.0	LASG / Institute of Atmospheric Physics, China
GFDL-CM2.0[4]	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA
GFDL-CM2.1[4]	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA
GISS-AOM[5]	NASA / Goddard Institute for Space Studies, USA
GISS-EH[5]	NASA / Goddard Institute for Space Studies, USA
GISS-ER[5]	NASA / Goddard Institute for Space Studies, USA
INGV-SXG	Instituto Nazionale di Geofisica e Vulcanologia, Italy
INM-CM3.0	Institute for Numerical Mathematics, Russia
IPSL-CM4	Institut Pierre Simon Laplace, France
MIROC3.2(hires)[6]	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan
MIROC3.2 (medres)[6]	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies and Frontier Research Center for Global Change (JAMSTEC), Japan
MRI-CGCM2.3.2	Meteorological Research Institute, Japan
PCM	National Center for Atmospheric Research, USA
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research / Met Office, UK
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research / Met Office, UK

Appendix - Climate model data

Table A2. Overview of data archives with available Regional Climate Model projections.

Database/ Project	**Region**	**Date populated**	**Data download website**	**Period**
CORDEX	Global coverage	Under development	http://cordex.dmi.dk/joomla/	
ENSEMBLES	Europe and Africa	2009	http://ensemblesrt3.dmi.dk/	Transient, from 1951 to 2050 or 2100
PRUDENCE	Europe	2004	http://prudence.dmi.dk/	30-year time slices: 1961-1990 and 2071-2100
NARCCAP	North America	2007	http://www.earthsystemgrid.org/project/NARCCAP.html	

Table A3: List of available RCM projections from the PRUDENCE project.

Model	**Modelling group**	**Driving GCMs**	**SRES scenarios**
CNRM	Centre National de Recherches Meteorologiques, France	ARPEGE	A2, B2
DMI-HIRHAM	Danish Meteorological Institute, Denmark	HadAM3H, ECHAM4	A2, B2
ETH-CHRM	Swiss Federal Institute of Technology, Switzerland	HadAM3H	A2
GKSS-CLM	Institute of Coastal Research, Helmoltz-Zentrum-Geesthacht, Germany	HadAM3H	A2
HC-HadRM3	Met Office, Hadley Centre for Climate Prediction and Research, UK	HadAM3H	A2, B2
ICTP-RegCM	International Centre for Theoretical Physics, Italy	HadAM3H	A2, B2
KNMI-RACMO	Royal Netherlands Meteorological Institute, The Netherlands	HadAM3H	A2
MPI-REMO	Max-Planck Institute for Meteorology, Germany	HadAM3H	A2
METNO-HIRHAM	Norwegian Meteorological Institute, Norway	HadAM3H	A2
SMHI-RCAO	Swedish Meteorological and Hydrological Institute, Sweden	HadAM3H, ECHAM4	A2, B2
UCM-PROMES	Univesidad de Castilla La Mancha, Spain	HadAM3H	A2

Appendix - Climate model data

DHI tools
Glossary
References
Appendix

Table A4: List of available RCM projections from the ENSEMBLES project for Europe. Superscript indicates Model No. shown in Figure 4.5.3. All RCM/GCM combinations are based on the SRES A1B scenario.

Model	Modelling group	Driving GCMs
C4I-RCA3[1]	Community Climate Change Consortium for Ireland	HadCM3Q16
CHMI-ALADIN[2]	Czech Hydrometeorological Institute, Czech Republic	N/A
CNRM-ALADIN[3]	Centre National de Recherches Meteorolo-giques, France	ARPEGE
DMI-HIRHAM[4]	Danish Meteorological Institute, Denmark	ARPEGE, ECHAM5, BCM
ETH-CLM[5]	Swiss Federal Institute of Technology, Switzer-land	HadCM3Q0
ICTP-RegCM[6]	International Centre for Theoretical Physics, Italy	ECHAM5
KNMI-RACMO[7]	Royal Netherlands Meteorological Institute, The Netherlands	ECHAM5, MIROC
METNO-HIRHAM[8]	Norwegian Meteorological Institute, Norway	BCM, HadCM3Q0
HC-HadRM[9,10,11]	Met Office, Hadley Centre for Climate Predic-tion and Research, UK	HadCM3Q0, HadCM3Q3, HadCM3Q16
MPI-REMO[12]	Max-Planck Institute for Meteorology, Germany	ECHAM5
OURANOS-CRCM[13]	Consortium on Regional Climatology and Adap-tation to Climate Change, Canada	CGCM3
SMHI-RCA[14]	Swedish Meteorological and Hydrological Insti-tute, Sweden	ECHAM5, BCM, HadCM3Q3
UCM-PROMES[15]	Univesidad de Castilla La Mancha, Spain	HadCM3Q0
GKSS-CLM	Institute of Coastal Research, Helmoltz-Zentrum -Geesthacht, Germany	IPSL
VMGO-RRCM	Voeikov Main Geophysical Observatory, Russia	HadCM3Q0

Appendix - Climate model data

Table A5: List of available RCM projections from the ENSEMBLES project for Africa. All RCM/GCM combinations are based on the SRES A1B scenario.

Model	Modelling group	Driving GCMs
CHMI-ALADIN	Czech Hydrometeorological Institute, Czech Republic	ECHAM5
DMI-HIRHAM	Danish Meteorological Institute, Denmark	ECHAM5
ICTP-RegCM	International Centre for Theoretical Physics, Italy	ECHAM5
INM-RCA	Instituto Nacional de Meteorologia, Spain	HadCM3Q0
KNMI-RACMO	Royal Netherlands Meteorological Institute, The Netherlands	ECHAM5
METNO-HIRHAM	Norwegian Meteorological Institute, Norway	HadCM3Q0
HC-HadRM	Met Office, Hadley Centre for Climate Prediction and Research, UK	HadCM3Q0
MPI-REMO	Max-Planck Institute for Meteorology, Germany	ECHAM5
SMHI-RCA	Swedish Meteorological and Hydrological Institute, Sweden	HadCM3Q0
UCLM-PROMES	Univesidad de Castilla La Mancha, Spain	HadCM3Q0
GKSS-CLM	Institute of Coastal Research, Helmoltz-Zentrum-Geesthacht, Germany	ECHAM5

Appendix - Climate model data

Table A6: List of RCM projections available as part of the NARCCAP project. All RCM/GCM scenarios are based on the SRES A2 scenario

Model	Modelling group	Driving GCMs
CRCM	OURANOS/UQAM, Canada	CCSM, CGCM3
ECPC	UC San Diego/Sripps, USA	GFDL, HADCM3
HRM3	Hadley Centre, UK	GFDL, HadCM3
MM5	Iowa State University, USA	HADCM3, CCSM
RCM3	UC Santa Cruz, USA	CGCM3, GFDL
WRF	Pacific Northwest National Laboratory, USA	CCSM, CGCM3

Table A7: List of RCM GCM combinations which were completed as part of the ENSEMBLES project.

ENSEMBLES GCM-RCM Matrix 8/6/2010

Global model / Regional inst.	METO-HC Standard	METO-HC Low sens.	METO-HC Hi sens.	MPIMET Standard	MPIMET Ens.m. 1	MPIMET Ens.m. 2	IPSL	CNRM	NERSC	MIROC	CGCM3	Total number
METO-HC	2100	2100*	2100*	2100 (late 2010)								4
MPIMET				2100			2050*					2
CNRM								2100				1
DMI				2100*				2100	2100*			3
ETH	2100											1
KNMI				2100* 2100	2100*	2100*				2100*		1+4
ICTP				2100								1
SMHI		2100*		2100* 2100*					2100			3+1
UCLM	2050											1
C4I			2100*		2050 (A2)*							2
GKSS							2050*					1
METNO	2050*								2050*			1
CHMI								2050* (12/2009)				1
OURANOS**											2050*	1
VMGO**	2050*											1
Total (1951-2050)	5	2	2	7+2	0+1	0+1	2	3	3	0+1	1	25+5

Red: Online now; *: non-contractual runs; **:affiliated partners without obligations; underscore: 50km resolution; (in parantheses): Expected date. For partner acronym explanations, see the participant list. NOTE that all partners also did an ERA-40 driven analysis 1951(1961)-2000

Appendix - Climate model data