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Addressing Climate Change-Driven Increased Hydrological Variability in Environmental Assessments for Hydropower Projects – a Scoping Study

A scoping study conducted for the World Bank by Vattenfall Power Consultant AB, Sweden

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Executive Summary

The report scopes the existing body of knowledge in the areas relevant to a climate change-driven increased hydrological variability. It starts out by reviewing the framework for modelling future climate, including the need for downscaling the global models to the regional and possibly even the local level. It discusses the difficulties in transferring climate-model outputs into hydrological models. The report concludes that scaling (bias-correction) methods are to be preferred to the so called delta-approach when hydrological variability is concerned.

A review of available literature on the context of hydrological variability, a changing climate and hydropower/reservoir operation, together with personal contacts with researchers and operators in the field, reveals that comparatively little has yet been done. What is done is strongly focussed on resource-strong organisations and countries in the western world, plus South Africa. The main conclusions possible to make, based on the reviewed material, is that: a) most hydropower/reservoir operators do not see climate change as a particularly serious threat. The existing hydrological variability is more of a concern, and the financially relevant planning horizons are short enough that with variability being much larger than predicted changes, these latter do not seem decisive for planning and; b) that where studies focussing on the reservoir storage component have been implemented, the insecurities in modelling results are considerable. Different global climate models often contradict each other, although there is increasing agreement in the results from such models. Models also have difficulties with predicting the seasonal distribution of rainfall, a key determinant for operational adaptation in reservoir management.

A look at operational responses to increased hydrological variability has resulted in a simplified recommended approach (to be elaborated upon before it is used) expressed as a 8-point approach. The approach deals with the practical use of existing information and easily accessible modelling tools, but focuses on adaptive management. With all the uncertainties involved, this should come as a surprise to no one. But, it is important to emphasise that adaptive management means constant attention to new signals that conditions are changing. A very strong focus on adaptive management in the face of potential increased hydrologic variation is of the utmost importance.

The environmental-assessment implications of increased hydrological variability will necessarily be very complex. The related impacts on land use, vegetation, ecosystems, agriculture etc., will likely exacerbate direct primary impacts on river hydrology. It is likely that such im-

pacts, many of which will take place also without climate change, will be more important to the ability of the environment to render ecosystem services than the climate-change impact itself. Strategic-level studies (such as Strategic Environmental Assessments and Cumulative Impact Assessments) will be very important tools. The strategic level of analysis will allow a scenario-based inclusion of increased hydrological variability into the overall impact assessment of future hydropower development (or in energy system master plans).

An important aspect to keep in mind is that all predictions of socio-environmental systems' responses to introduced stresses (such as new dams) are inherently uncertain, probably a lot more so than even the uncertainties involved in predicting future climate.

The report ends with recommendations for priority research. Issues mentioned include: statistical techniques for separating climate-change impacts from natural variability; improvements in regional climate models with a stronger focus on prediction in the short to medium term and; the inclusion of land-use and ecosystem expertise in the prediction of hydrological impacts on hydropower and reservoirs.

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Abbreviations

CIA = Cumulative Impact Assessment

GCM = Global Climate Model

EA = Environmental Assessment

IHV = Increased Hydrological Variability

RCM = Regional Climate Model

SEA = Strategic Environmental Assessment

The assignment

This assignment has been conducted by a group of four people, under the team leadership of Bernt Rydgren, Vattenfall Power Consultant, Sweden. The other team members have been: Marthinus Basson, BKS, South Africa, Phil Graham of the Rossby Centre at the Swedish Meteorological and Hydrological Institute and Dag Wisaeus of Vattenfall Power Consultant, Sweden. The assignment has been a scoping study, based on desk reviews of available science as well as personal contacts with a limited number of water resources managers and researchers in the field.

The assignment's goal was to provide a preliminary overview of the current knowledge base, looking at questions such as: What is the status of hydrological modelling in building on climate-change research? How do hydropower operators presently respond to hydrological variability, and do they see a need for further action in light of predicted climate change? How is hydrological variability included in hydropower environmental assessments? Will a possible climate change-induced increased hydrological variability demand new methods to be applied in the environmental assessment process? How will it affect hydropower project planning and economics?

Introduction

Marked changes in the global climate have been observed over recent decades. These are attributable to both natural and human factors that act upon the climate. Natural drivers include e.g. changes in solar radiation, gases and particles from volcanic eruptions, possibly changes in the earth's magnetic field. Because of these, global climate is known to have oscillated over the millennia between cold and hot periods, with accompanying changes in precipitation over parts of the world.

Recent observations, however, show that global temperatures are now rising at a substantially higher rate than can be observed or derived from past records. This is largely attributable to human impacts such as the release of greenhouse gases into the atmosphere and changes in land surface properties. As a result of the changes in temperature, rainfall patterns and river runoff are also changing – causing concern about the impacts of these and the rate of change.

In the most recent reports from the Intergovernmental Panel on Climate Change (IPCC), it was stated that "warming of the climate is unequivocal" and that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." (IPCC, 2007a). Some uncertainty remains, partly due to the lack of data from developing countries, for various processes and steps within the analyses, but the latest IPCC assessment provides even stronger evidence that anthropogenic climate change is a factor that the world society must address now and in coming generations.

A warming climate generally increases activity within the hydrological cycle as evaporation processes are enhanced and more moisture is made available for circulation in the atmosphere. This can result in changes to both magnitude and frequency of precipitation patterns. Such changes will not be evenly distributed around the globe and effects will vary considerably between regions. Regarding hydrology and water resources, such changes to the hydrological cycle will potentially affect local conditions in ways that deviate from past climate records. Engineering designs, such as hydropower installations, are typically based on past climate conditions and are, therefore, subjects to impacts from changes in the climate, both in terms of its long-term averages and its variability.

Long term trends from 1900 to 2005 have been observed in the amount of precipitation over many large regions (ibid). Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Long term trends have not been observed for the other large regions that have also been assessed.

The 4th IPCC assessment draws some conclusions that are especially relevant to the issue at hand here, e.g.: 1) It is regarded as very likely that the proportion of total rainfall coming from heavy rainfall events will increase over most areas during the 21st century and; 2) It is likely that the land area affected by drought will increase during the 21st century. These predictions are made with the uncertainties mentioned above.

By mid-century, annual average river runoff and water availability are projected to increase by 10-40% at high latitudes and in some wet tropical areas, and decrease by 10-30% over some dry regions at mid-latitudes and in the dry tropics (IPCC, 2007b).

Increased runoff and earlier spring peak discharge have already been observed in many glacier- and snow-fed rivers, as a result of a warming climate.

Hydrological variability is a natural phenomenon, and an important aspect of the hydrological regime. And like the general hydrological regime, it is highly different in different places.

Furthermore, by its very nature, variability is very difficult to predict, even in the short term. When one adds human interventions to the picture, predictability decreases even further. Issues such as land use, vegetation changes and direct human water use for domestic, agricultural and industrial purposes can have strong local impacts.

Rivers that are already the subjects of competition over water use are also often highly variable in their flow, and thus more susceptible to increases in variability than others, from a human-use perspective.

Common elements and emerging trends in hydrological research and modelling

Climate modelling

Looking forward toward future climates requires using state-of-the-art modelling tools to represent climate processes. Global climate models (e.g. Figure 1) are used to resolve the large-scale global circulation patterns that define climate. They originate from the global models used to make numerical weather predictions on a daily basis. However, it must be kept in mind that these models do not make weather forecasts, but rather an analysis of long-term climate conditions. In other words, they are not capable of saying what the weather will be for a specific day in a specific year, but rather what the statistical characteristics of the weather will likely be; based on projected changes/trends of key driving input parameters (such as temperature).

Due to their global extent, long climatological time periods and constraints in available computing power, global models have a coarse horizontal resolution. To get more detail at regional and local scales, downscaling techniques are used. Both dynamical and statistical methods are used, as described below.

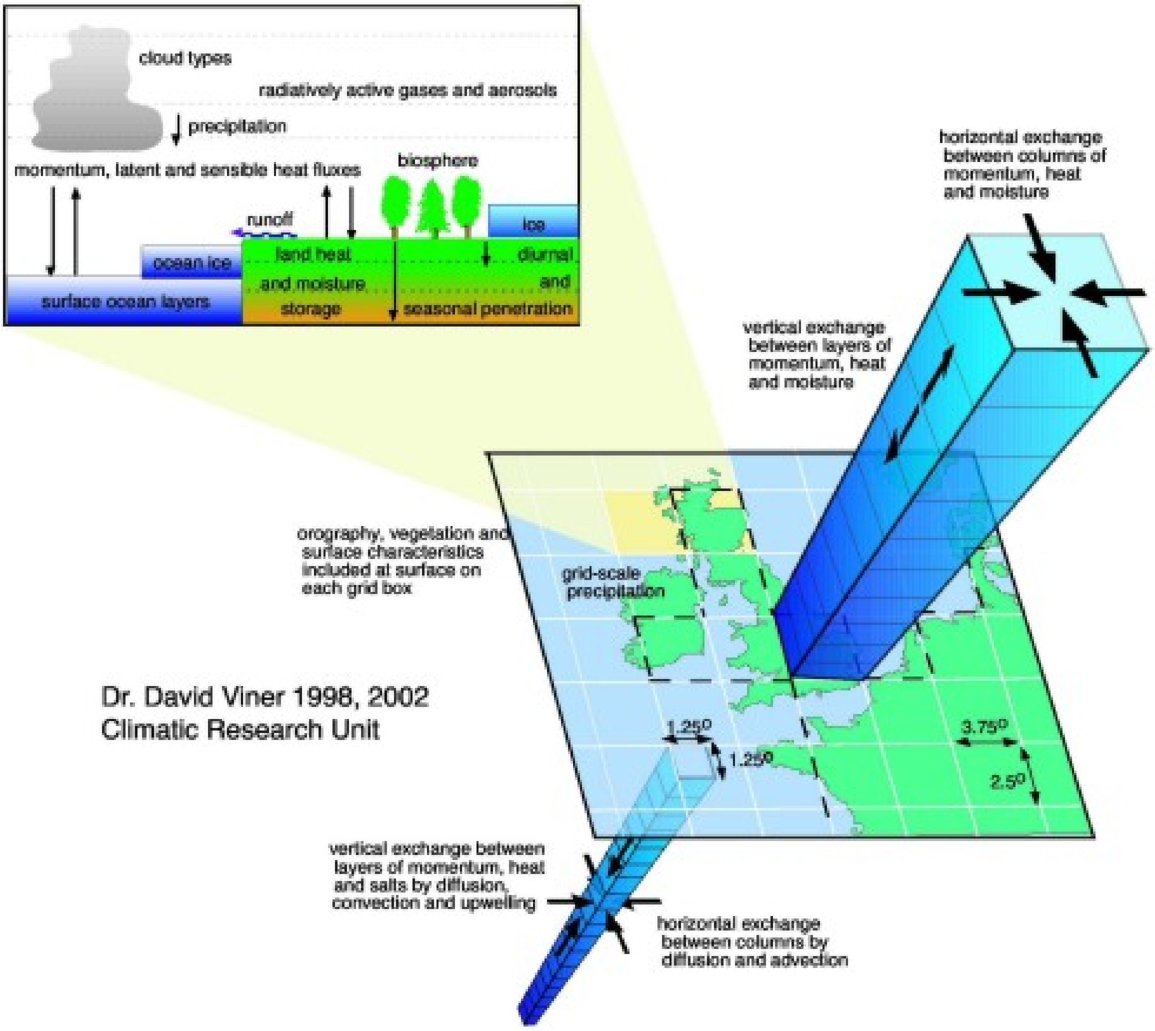

Figure 1. Schematic of the typical structure for global climate models. (From http://www.ipcc-data.org/ddc_gcm_guide.html)

Global climate models

Global climate models are also known as general circulation models (the acronym GCM is used in both meanings and the two terms are used interchangeably in this text). These models aim to represent all the physical processes of the atmosphere, land surface and oceans which are thought to be important for determining the evolution of climate. They operate on time scales extending from tens to hundreds of years. As mentioned above, this is computationally demanding and constrains the resolution that can be used in the models. GCMs are set up as a grid system that covers the earth's surface, extending both upwards and downwards in a series of layers that represent atmospheric and oceanographic processes, respectively (Figure 1). The horizontal resolution of GCMs tends to be some 300 km in the atmosphere and often about 150 km in the oceans. This is sufficient for the models to reproduce the major atmospheric and oceanic circulation patterns and trends for climatological variables over continental scales.

There are many different GCMs used worldwide. Although there are similarities between them, they do not produce exactly the same results from a given set of inputs. Different results from different models are one source of uncertainty in climate research. The quality of the models is judged by how well they can represent the present climate. When several models of relatively good quality agree on a particular result, then the results can be judged as robust. It is such robust results that have been used by the IPCC to both attribute global warming to anthropogenic climate change and to produce future projections of climate change. It is also important to identify where models do not agree and thus where uncertainty is higher.

Regional Downscaling

There are two primary categories of methods used for downscaling GCM outputs to regional or local scales, statistical and dynamical, as described below. Both methods have their own merits, and their respective strengths and weaknesses have been discussed in the scientific community for some time. As of late, researchers are realizing that using the strengths of both methods could be beneficial for some applications (e.g. Engen-Skaugen, 2007). In the current IPCC assessment, results from both statistical and dynamical downscaling methods are included for summarising regional climate projections (Christensen et al., 2007).

Statistical downscaling

Statistical downscaling (also called empirical downscaling) is a way to infer local information from coarse scale information by constructing empirical statistical links between large scale results and local conditions (e.g. Hanssen-Bauer et al., 2005; Wilby et al., 1999; e.g. Zorita and von Storch, 1999). Such statistical links are used to develop detailed local climate scenarios based upon output from GCMs. Statistical downscaling involves analysis of local scale observed variables (predictands) and large-scale atmospheric variables (predictors), establishing derived relationships between the two, and applying them to GCM outputs. An example of statistical downscaling would be the use of mean sea level pressure as a predictor for predicting precipitation, a predictand.

Some advantages of using statistical downscaling are that it can be done at relatively little cost and effort. Normal personal computers can be used and many GCM simulations can be analysed with relatively little effort. Furthermore, as the method is based on transfer functions, there is no need for detailed knowledge of physical processes.

An important requirement for statistical downscaling is availability of long and homogeneous observations of the meteorological variables in question (typically temperature, precipitation and wind). Ideally, some 30-40 years of observations are recommended. Shorter periods can be used but then there is the risk that they do not adequately cover the range of expected weather situations for the local area. An important assumption for such statistical methods is that the relationship between predictors and predictands is valid outside the calibration period (i.e. into the future climate).

Dynamical downscaling

Dynamical downscaling is the process of downscaling from global scales to regional or local scales using regional climate models (RCMs). This typically consists of applying a coupled atmosphere-land surface model to a limited area of the globe at scales considerably finer than those used for GCMs. Examples are shown in Figure 2. Horizontal scales are typically some tens of kilometres versus hundreds of kilometres for GCMs. Like statistical downscaling, dynamical downscaling requires driving inputs from a global model. However, dynamical downscaling differs from statistical downscaling in that it includes explicit representation of physical processes for every grid square included in its domain.

The models applied are based on the same type of physical descriptions used in GCMs, but in addition to finer resolutions (both horizontally and vertically) may be more detailed in some aspects (e.g. land surface interactions). Critical variables from GCM simulations define driving inputs at the boundaries of the RCM domain.

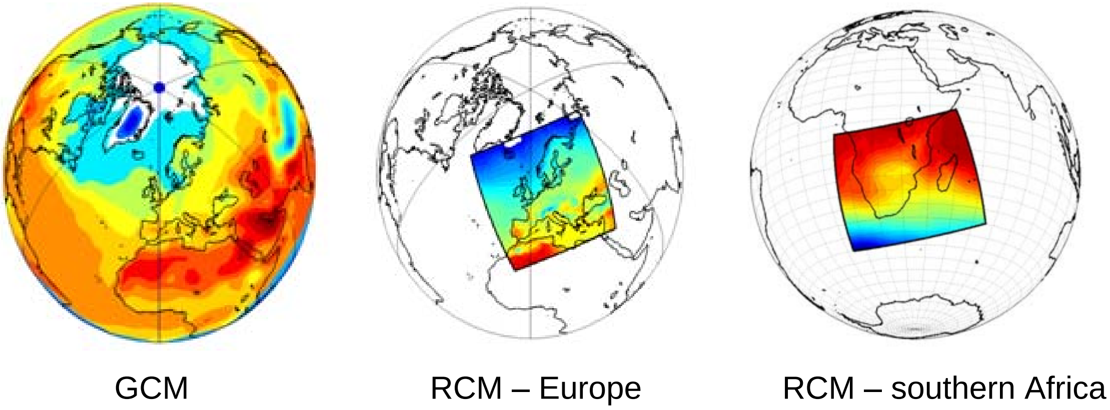

Figure 2. Examples of RCM domains for dynamical regional downscaling.

Regional climate modelling has been developed and used for dynamical downscaling of GCM results over the past 15-20 years. Since their introduction, the spatial and temporal resolution of RCMs has become finer and the level of output detail has increased considerably (e.g. Christensen et al., 2007; Giorgi and Mearns, 1999; Jones et al., 1997). As RCMs are physically based models, they include the full range of physical processes that interact in climate evolution. Thus they have the ability to provide a larger array of variables than statistical downscaling. They are not dependent on observed variables and can thus be used in regions that have no or only sparse observational records.

A disadvantage of RCMs is that they require substantial computing and data storage resources. This limits the number of different scenarios that can be evaluated. It also limits their use to more developed countries that can devote adequate funds and manpower to such applications. This is obvious by the much larger number of RCM studies performed in the northern hemisphere.

Creating future projections of climate change

In projecting future anthropogenic climate change, scenarios to estimate the plausible evolution of greenhouse gas concentrations over time are needed. Efforts are made to include all significant greenhouse gases, but this is usually expressed in terms of CO_2 equivalent. Early estimates simply assumed a constant increase in GHGs with time. A commonly used one is referred to as the “business as usual” (BaU) scenario, which assumed a 1% increase of equivalent CO_2 concentration per year after 1990.

The currently used emissions scenarios are representations of the future development of greenhouse gases (GHGs) and aerosols, based on internally consistent sets of assumptions about demographic, socio-economic, and technological changes in the future. The emissions scenarios from the IPCC Special Report on Emission Scenarios (SRES; Nakićenović et al., 2000) were built around four narrative storylines, A1, A2, B1 and B2, each based on different assumptions about the factors that drive the development of human society in the 21st century. Several more detailed scenarios were formulated within each storyline. Six of these, referred to as A1FI, A1T, A1B, A2, B1 and B2, were chosen by the IPCC as illustrative benchmark scenarios. In general terms, the world described by the A storylines strives after personal wealth rather than environmental quality. In the B storylines, more sustainable development is pursued.

Hydrological Modelling

Hydrological models are used to assess impacts of projected climate change on regional or local hydrological regimes. These vary in complexity and detail due to the applications at hand, availability of observational inputs and ambition level of the particular study being conducted. For hydropower applications, hydrological modelling results often serve as inputs to further models or analyses that look in more detail at aspects such as reservoir operations, power yields, hydraulic structures, sedimentation and dam safety.

Why hydrological models are needed

Although both RCMs and GCMs include representation of hydrology, they generally do not resolve the hydrological cycle at a level of detail that is suitable for hydrological applications (Bergström et al., 2001). For instance, they typically lack sufficient representation of snow storage in mountain terrain, and lake and river flow routing routines. They are also subject to systematic biases, particularly for precipitation, the primary variable that dominates in most hydrological regimes (Varis et al., 2004). For these reasons hydrological models are used to interpret future climate projections from climate models. However, different transfer methods to interface climate models with hydrological models also have an impact on assessing hydrological change.

Box 1. *Both regional and global climate models include representation of hydrology, but generally do not resolve the hydrological cycle in a satisfactory manner. They typically lack sufficient representation of snow storage in mountain terrain, and lake and river flow routing routines. They are also subject to syste-matic errors, particularly for precipitation, the primary variable that dominates in most hydrological regimes.*

Transferring the climate change signal to hydrological models

Transferring the signal of climate change from climate models to hydrological models is not a straightforward process. In a perfect world one would simply use outputs from climate models as inputs to hydrological models, but as mentioned above meteorological variables from climate models are often subject to systematic biases.

Due to climate model biases, many studies of the hydrological response to climate change to date have resorted to the practice of adding the change in climate to an observational database that is then used as input to hydrological models to represent the future climate (Andréasson et al., 2004; Bergström et al., 2001; Kilsby et al., 1999; Lettenmaier et al., 1999; Middelkoop et al., 2001; Sælthun et al., 1998; Schulze R.E., 2005). The first graph in Figure 3 shows a schematic of this common approach for impacts modelling. It has been referred to as the delta change approach (Hay et al., 2000), and variations of this approach have been the de facto standard in climate change impacts modelling for some time. According to Arnell (1998) this requires two important assumptions. One is that the base condition represents a stable climate both for the present and for a future without climate change. Secondly, the atmospheric model scenarios represent just the signal of climate change, ignoring multi-decadal variability. However, the longer the time period of climate model simulations, the more multi decadal variability is smoothed out.

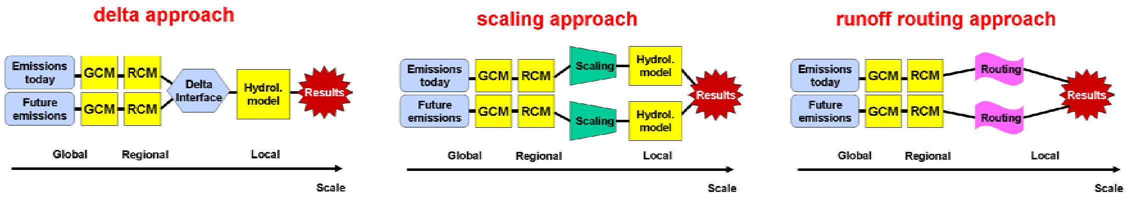

Figure 3. Approaches for transferring the climate change signal to hydrological models.

A major disadvantage of the delta change approach is that representation of extremes from future climate scenarios effectively gets filtered out in the transfer process. The delta change extremes are simply the extremes from present climate observations that have either been enhanced or dampened according to the delta factors. For this reason, researchers have recently been investigating more direct methods for representing the future climate in assessments of the hydrological response to climate change. This employs applying some form of scaling to RCM outputs to try to correct for biases before transfer to hydrological models (second graph in Figure 3). Some refer to this as bias correction. Such methods also have limitations, which can be severe, but they are more consistent with the RCMs and provide additional answers that are missing in the delta change approach (Arnell et al., 2003; Graham et al., 2007a; Lenderink et al., 2007).

Yet another approach is to use runoff results directly from climate models (Figure 3). This applies primarily to RCMs, where horizontal model scales are becoming finer and are approaching scales more representative of large-scale hydrological processes. RCM model runoff output is in the form of runoff generation, which is the instantaneous excess water per model grid square, without any translation or transformation for groundwater, lake and channel storage, or transport time. As such, this runoff value is difficult to compare to observations and it does not provide flow rates in rivers. River routing schemes can be used to route climate model runoff (mm day^{-1}) to river discharge (m^{3}s^{-1}) (Graham et al., 2007b; Hagemann and Dümenil, 1999; Hagemann and Jacob, 2007; Lohmann et al., 1996); this mainly affects timing and seasonal distribution. However, since this approach makes no corrections to runoff volumes, water balance biases from the climate models greatly influence the results.

The partitioning of precipitation into evapotranspiration and runoff is critical for realistic representation of the hydrological cycle. Graham et al. (2007b) investigated the hydrological performance of 13 RCM control simulations over the Baltic Sea basin with a simple comparison of the partitioning of annual RCM precipitation into evapotranspiration and total runoff generation. They found that the majority of RCMs investigated tended to underestimate the partitioning of precipitation into runoff. This is likely due to a general overestimation of evapotranspiration in the basin. Runoff routing schemes from climate models must thus be used with caution. They are best used when expressed as percent change in river discharge and can only serve to provide indication of trends. Until further improvements are made in climate models, their use for detailed water resources studies is limited.

In addition to precipitation and temperature, evapotranspiration is a critical component of the water balance. There is a large amount of uncertainty associated with evapotranspiration and projected future climates (Bergström et al. 2001). Hydrological studies typically include calculation of their own estimates of evapotranspiration, both for the present climate and for future climates. This has shown to produce reasonable estimates for present climates as calibration can be performed against observations of river flow. However, using the same calibrated evapotranspiration methods for the future can be suspect, particularly for temperature based methods. For this reason, delta change techniques have come into use for estimating evapotranspiration as well (Andréasson et al., 2004; Graham, 2004; Lenderink et al., 2007). There are various ways to perform such estimates, but a main objective is that the annual percent change in evapotranspiration matches the annual percent change as simulated by climate models, while preserving the water balance in the hydrological simulations. Deterministic rainfall-runoff simulation models could offer the more robust solution for converting rainfall output from GCMs to streamflow.

Uncertainties in hydrological applications

There is a long chain of uncertainties associated with assessment of impacts to hydrological systems and water resources. The most prevalent originate from the GHG emissions scenarios, the GCMs, statistical downscaling, dynamical downscaling (RCMs), methods for transferring the climate change signal to hydrological models and from the hydrological models. Added to this are uncertainties and scarcity in available observations, used for both calibrating and verifying models.

According to several studies, uncertainty from different GCMs is the largest contributor, followed by the emissions scenarios (Andréasson et al., 2004; Graham et al., 2007; Prudhomme and Davies, 2007). Of particular importance for hydrological modelling is the uncertainty in precipitation from climate models (Arnell, 2004; Döll et al., 2003). Uncertainty from the hydrological models themselves is considered to be relatively small in this context (Jha et al., 2004; Wilby, 2005). According to Jenkins and Lowe (2003), climate model uncertainties play the largest role in projections of the near future, while uncertainty of the GHG emissions scenarios becomes increasingly important over longer time horizons.

Hydrological studies have shown that biases in precipitation from climate models make it difficult to directly use meteorological outputs in hydrological and water resources oriented applications. Evapotranspiration is also a source of much uncertainty, both in climate models and hydrological models. The combination of biases in meteorological variables and the need for high resolution has to date precluded using the actual hydrological components from climate models for detailed assessment of hydrological impacts. Continued work to improve the hydrological processes in both global and climate models, including river routing techniques, is needed. Such development, together with finer resolution, as mentioned above, would serve to enhance the quality and utility of climate model simulations, particularly if it leads to better representation of extreme hydrological events. Recognising that biases may be around for some time to come, hydrological development should also focus on improved methods to filter out biases without misrepresenting the climate change signal coming from climate models.

Where is the Science headed?

Due to the complexities involved, climate science and associated impacts assessment is continuously evolving. Better understanding of the processes coupled to technological advances keep development moving forward. Much has been accomplished since the original IPCC assessments, and further improvements in coming years are expected.

Climate modelling

Global climate models play a central role in projecting future anthropogenic climate change, both by providing estimates of change on large horizontal scales and by providing the large-scale information needed by various downscaling methods. Further improvement of these models is directed toward better representation of sub-grid scale phenomena that are particularly important for the response of climate to external forcing (e.g. cloud processes, radiative transfer, convection, small-scale mixing in the atmosphere and the ocean, as well as the exchange of heat, water and momentum between the atmosphere and the other components of the climate system). Regional climate models also need improvements for representing sub-grid scale processes, even with their finer resolutions.

In the next five to ten years, the horizontal resolution of GCMs will likely come close to that of today's regional models. RCMs will then be approaching resolutions of only a few kilometres. Even at such scales, however, many phenomena remain unresolved, including individual clouds. Success in improving global and regional climate models must focus not only on modelling per se but also on collecting and making widely available detailed observations that will help to guide the development of the models, particularly as resolutions improve.

Climate models should also evolve to include other processes than those of the more "traditional" physical climate system. Complex interaction and feedback processes involving the biogeochemical cycles makes it necessary to introduce other model components to the climate models. Examples of such components are, among others: fully coupled models of atmospheric chemistry, aerosol models, interactive vegetation models, models describing the carbon cycle, and models including marine chemistry.

Despite efforts put into improving climate models, it is likely that the projections from different models will continue to differ for many years to come, particularly on regional scales. Better ways to deal with these differences are needed instead of assuming that all models give equally likely projections. Some steps toward weighting projections according to model quality have been taken (e.g. Giorgi, 2005; Giorgi and Mearns, 2003; Murphy et al., 2004), but as yet there is only limited understanding of which aspects of the present-day climate simulations matter most for simulation of projected climate changes. It is also important to evaluate the possibility that the behaviour of the real climate system might fall outside the range of conventional model results (e.g. Allen and Ingram, 2002; e.g. Stainforth et al., 2005).

Both statistical and dynamical downscaling have shown added value over global models for assessing regional climate, although they may show differing results. Comparison of future scenarios downscaled by the two approaches may form an additional basis for assessing uncertainties associated with the downscaling. Both approaches have advantages and disadvantages due to the nature of the methods used. While dynamical downscaling may have problems with biases, statistical downscaling avoids this problem as it is a data based method. However, being physically based, dynamical methods realistically simulate non-linear effects and other dynamical features, whereas statistical methods often lack the full range of true variability. Choice of approach depends both on the questions to be addressed, and on availability of adequate inputs and resources (e.g. observations, computing power, skilled scientists). An advantage of the statistical approach is that it can deal with local scales, including site scale. In the interim before the resolution of RCMs is considerably improved, it provides an alternative way to create local climate change scenarios needed for many impact studies.

Future applications to hydropower

Regarding hydropower, any improvements in interpretation techniques for hydrological models and related analyses would be a welcome development. As mentioned above, more accurate estimates of both precipitation and evapotranspiration, as well as possible changes in seasonality and variability, are needed. Toward this end, methods that scrutinise and make use of climate model changes in the statistical distribution of both precipitation and temperature should be pursued and utilised.

Concluding remarks on hydrological modelling

- Downscaling from GCMs is a necessity, although it is not possible to say which of the two predominant methods should be used for a specific location. The choice between statistical and dynamical downscaling should depend on availability and quality of observational records and the local performance of statistical methods contra availability and performance of RCM model results.
- From a modelling accuracy-point-of-view, the use of continuous transient simulations should be preferred over time-slice simulations and in particular more emphasis should be placed on the near future.
- Use of multiple GCMs should be made and where feasible multiple emissions scenarios.
- Delta-approach methods may be sufficient for assessing mean responses, but should not be relied upon for assessing extreme events.
- Use of scaling methods should be preferred where extreme events are to be evaluated, as such methods have much better potential to include changes in variability.
- Estimating evapotranspiration for future climates is a critical step in hydrological assessment and should be addressed with care.
- Greater confidence needs to be achieved with regards to possible future changes in the volume, seasonality and variability of runoff, as well as the associated time scales.

Finally, there is no way to avoid uncertainty in assessing impacts of climate change. It exists through all steps in the chain of assessment and will continue to be a broad issue for some time to come. It is important to keep this in mind. To help cope with some of the uncertainty, ways are needed for hydropower owners to assess climate change in terms of an adaptive risk management (see further in the sections below). What are the expected consequences and what level of risk is acceptable? Hopefully, climate science will be able to help with this in the coming future by providing more quantitative estimates of the likelihood of certain levels of change (e.g. ENSEMBLES-Project, 2004-2009). However, this will still take some time in coming, and will still only be in terms of conditional likelihood (i.e. given a certain emissions scenario). Establishing which pathway world development will take and thus the future levels of CO_2 is an even more open issue.

Findings from a review of available published sources and direct contacts with hydropower operators and other interested organisations

The future cannot be expected to look like the past. At a first glance, this is a truism, and could easily make one a little uneasy with the lack of depth-analysis behind such a conclusion. But, if one considers how hydropower projects are planned, the statement above takes on very significant meaning. Both design, operational planning and financial evaluation of both new and existing schemes are largely based on hydrological time series from periods ranging from less than 10 to well over 50 years. A standard approach is to generate a design time series of say 40 years of (preferably) daily flows, based on existing historical data. These generated daily values will then be the basis of duration curves which can then easily be fed into a model for optimisation of design and operation. A typical outcome of such work is that the financial need for a certain “firm” generation at the plant (with some determined availability factor) will in turn determine the need for and size of reservoirs in the system.

Reservoirs will likely be one of the solutions suggested to counteract a possible future increased variability in run-off. At the same time they are also generally considered as problematic from a socio-environmental perspective. There is also general agreement that resettlement, mainly caused by the water impounded by reservoirs, is the largest problem issue in the planning and construction of new hydropower plants. It is also important to remember that reservoirs are no panacea. Hydropower, while not a consumptive use of water (except in cases of very high evaporation from reservoir surfaces) is far from the only legitimate user of the water resource, and many of the competing uses do not have the same regulation priorities as that of hydropower.

At the same time it is, however, equally clear that with an assumed increase in hydrological variability, the environmental-economics arguments of this issue will change somewhat. With increased variability, the value of reservoir capacity will increase as well. If the increase in variability is only within a given year (e.g. a more uneven seasonal distribution), the needed reservoir capacity will only have to reflect the difference between high-flow and low-flow periods. But, if the between-year variability were to increase, significantly larger storage capacity may be necessary in order to guarantee "firm" capacities at all times.

A fairly common opinion among the people we have consulted personally can be exemplified by the EEA (2007), page 50, where it, under the highly relevant headline: "Research needs for climate change and variability issues" is stated: "*Most water and flood risk planning horizons end before the 2050s, the point at which climate-driven changes in regional rainfall (and some river flows) are expected to emerge from natural variability."* This thinking permeates much of the responses we have had and e.g. G. Basson (personal comm., 2007) states that when climate models were applied to South African rainfall, predicted changes over the next 100 years were smaller than natural variability, making interpretation difficult. Katz and Brown (1992), quoted in Peel et al. (2005) came to the same conclusion. Further to such a natural science-based hesitance to treat the issue as urgent, is the financial angle. With traditional discounting applied to investment analysis, negligible value is put on income and/or expenditures incurred beyond 20-25 years into the future. And within such a time horizon, increased hydrological variability is simply not expected to be noticeable on top of historical variability.

It is important to note that the above differs somewhat from simple trend analysis as it applies to the entire hydrology, i.e. not just variability. Many hydropower projects in the planning stages around the world (notably on glacier-fed rivers) can count on expected increases in runoff over the financially important period of prediction. The comparatively simple relationship existing between increased temperatures and increased glacial melting (leading to the almost globally well-documented reduction of glacial mass) gives operators and planners a reason for medium-term optimism.

The above means that many hydropower operators have not yet started to attend specifically to climate-change issues. The explanations for this are obviously quite complex and varying, but the most important one seems to be that most financially strong, hence able to conduct research and/or methodological development, hydropower operators are from Europe, North America and the island of Tasmania in Australia, temperate regions which are generally not predicted to be as affected by anthropogenic climate change as subtropical and tropical regions will be (polar regions even more so, but the hydropower potential there is minimal). This means that the opinion discussed in the paragraph above makes sense to these operators, even if this might not be true world-wide. Indeed, in many cases, such as Scandinavia, people look at the predictions made by the latest IPCC report with a degree of understandable optimism – given that precipitation is predicted to increase, particularly in the winter season coupled with significantly warmer winter temperatures. This will actually reduce the need for reservoir storage and potentially increase the value of the installations. In the light of such future scenarios, the non-action is understandable. The only distinct hydropower exception to the rule-of-thumb from Box 2 below that we have identified is that of Harrison et al (2006), studying the Batoka Gorge project in southern Africa. There are several other water resources-orientated studies from e.g. South Africa, but these do not deal specifically with hydropower.

Box 2. *The most important reason for why hydropower operators have not yet acted strongly in response to warnings of impending climate change is that most financially strong (hence able to conduct research and/or methodological development), hydropower operators are from Europe, North America and Tasmania, temperate regions which are generally not predicted to be as affected by anthropogenic climate change as subtropical and tropical regions will be.*

Two comparatively wealthy regions of the world where climate change is predicted to put moderate to severe limitations on future hydropower generation are South Africa and Australia. Not surprisingly these are also the places from where the most relevant work can be found.

The information collated for this study shows a general awareness of climate change and some, but fairly low but growing concern about the potential impacts thereof. In several countries there are universities and other research institutions, utilities and government departments that are starting to assess the potential impacts of climate change and increased hydrological variability (IHV) on water resources and hydropower schemes. For the sake of practicality, we have chosen not to consider IHV in isolation – although IHV alone could have pronounced impacts – but it is affected by, and itself affects, many other aspects of the environment. A noteworthy observation is that no standard procedures or common approach could be found from the reports and responses. Instead, the studies vary considerably in terms of both methodology and detail.

Presently, EIA guidelines for hydropower projects around the world do not (in the experience of the authors of this report) include aspects of hydrological variability beyond that dealing with dam safety issues, i.e. extreme flood peaks. The most controversial issue regarding hydrological design in a hydropower EIA is often that of environmental flows. Environmental flows here stand for "water for ecosystems" (Korsgaard, 2006). This concept is also known by a suite of other names, e.g. ecological flows, compensation flows, minimum flows etc. This flow has historically been determined by rather crude mechanisms, typically as a percentage of long-term average monthly flows, or even of annual flow. This has frequently led to conflict between the plant owners and environmental pressure groups and authorities, as such prescriptive rules make no allowance for natural variability. During this decade, more sophisticated methods have been developed (e.g. ibid. and King et al., 2003), but the impact-assessment profession has been slow to pick up on these, mainly because the methods have been quite resource-intensive.

As stated above, the recent body of literature published on climate change impacts on hydrology generally focuses mostly on North America, Europe and Australasia. Although it is difficult to summarise findings globally, some robust statements can be made. For regions where much winter precipitation falls as snow, higher temperatures are expected to lead to changes in seasonality of river flows (Barnett et al., 2005). The effect is greatest at elevations where snowfall is marginal in today's climate (Jasper et al., 2004). Warming also leads to glacial retreat, which in the short term results in increased downstream river flow, but will eventually result in reduced river flow as glacial masses degrade. Observational evidence indicates that increased runoff and earlier spring peak flows are already occurring in many glacier and snow fed rivers (IPCC, 2007b). For warmer regions with little or no snowfall, changes in precipitation will play a larger role than changes in temperature. Studies from rain-dominated river basins tend to show increases in flow seasonality. A common response is higher flows in the peak flow season, and lower flows or an extended dry period in the low flow season (Arnell, 2003; Booij, 2005; Burlando and Rosso, 2002; Evans and Schreider, 2002; Menzel and Burger, 2002). In some cases, timing of the peaks or lows could be affected, such as with an earlier onset of the East Asian monsoon (Bueh et al., 2003).

In at least two cases, rather extensive studies have been performed that cover regional aspects of hydrological impacts. This pertains to the effects of climate change on water resources in the western United States (Barnett et al., 2004) and in the Nordic countries (Bergström et al., 2003; Bergström et al., 2007). In yet another study, impacts to hydropower over all of Europe were investigated (Lehner et al., 2005; Lehner et al., 2001, see below).

For studies conducted in western USA, three river systems were in focus. These are the Columbia River, the Colorado River and the Sacramento/San Joaquin river system. All three used statistical downscaling from a single Global Climate Model (GCM) and the Columbia River study also included downscaling from an Regional Climate Model (RCM) for comparison. Regardless of the downscaling used "bias correction" techniques to account for systematic biases in the climate modelling were needed for all applications (Wood et al., 2004). The GCM model was described as having a low climate sensitivity compared to most other global climate models, which was thought to result in a "conservative estimate" of expected warming. They used a "business as usual" anthropogenic emissions scenario and investigated three future 30-year periods corresponding to 2010–2039, 2040–2069 and 2070–2098. Climate change projections for all three basins showed general warming and seasonal variations in precipitation as the century progressed, which led to reductions in the annual snowpack and general reductions in annual streamflow.

For the Columbia River, changes in annual average runoff volume were projected to be small (less than 5%), but seasonal changes were large. As a result, increased competition between water resources users was predicted. Future tradeoffs were defined as a choice between stored water for summer and autumn hydropower, or spring and summer releases to maintain instream flows for salmon, but not both. Furthermore, even though the two downscaling methods resulted in generally similar trends, the RCM showed greater spring warming and larger decreases in winter precipitation compared to statistical downscaling. This resulted in accelerated levels of change compared to a similar period for statistical downscaling (Payne et al., 2004).

For the Colorado River system, reservoirs levels were shown to decrease by more than 30%, with releases decreasing by as much as 17% by the mid 21st century. The greatest effects were evident for the lower Colorado River Basin. This was estimated to result in reductions in hydropower generation by as much as 40%. Furthermore, due to full allocation of the water resources in the Colorado system, virtually any reduction in precipitation is expected to lead to failure to meet demands (Christensen et al., 2004).

Results for the Sacramento/San Joaquin river system in central California also projected substantial failure in meeting basin-wide demands. Reduced reliability was shown for water supply deliveries, hydropower production and instream flows. Maintaining adequate levels of water quality is a driving force in water allocation for this multi-use basin. Although, a general degradation of supply was projected, the study also focused on identifying modified system operations as a means to mitigate and adapt to the projected impacts of climate change (Vanrheenen et al., 2004).

Results from a cooperative Nordic study resulted in identifying countrywide hydrological impacts from climate change projections (Beldring et al., 2006). They used dynamically downscaled results from a common set of RCM simulations. Two different GCMs were used to provide global boundary conditions for the RCM. Additionally, two IPCC anthropogenic emissions scenarios were used, SRES A2 and B2. All simulations represented the future period 2071-2100. A delta change approach was primarily used. In contrast to the results for the USA discussed above, these studies showed increases in future water availability, particularly for northernmost basins. In this region, climate models predominately show increasing temperatures coupled to increasing precipitation. Furthermore, seasonal variation of both temperature and precipitation changes are projected to be substantial. Winter changes are expected to be more pronounced for both. Summary findings from this work are that global warming will increase hydropower production in most of the areas studied (Bergström et al., 2007). Further shortening of the Nordic winter will make it less stable and lengthen the ablation season on glaciers and ice caps, resulting in more river flow year-round. The projected changes could have practical implications for the design and operation of many hydropower plants, especially from glaciated highland areas. The projected change in the annual rhythm of runoff will put more stress on spillways, as they will likely need to be operated more often, particularly as changes in the winter climate will generate more frequent inflows when reservoirs may be full. This could produce more frequent flooding problems and impact on downstream infrastructure.

Work in the Nordic countries has also looked at the impact of climate change on dam safety (Tuomenvirta et al., 2000). This is complex and involves revisiting guidelines for establishing maximum probable inflows to dams. It requires detailed assessment of changes in temperature, precipitation frequency and maximum snowpack in varying combinations to obtain worse case scenarios for individual dams. The work thus far has shown mixed results. Risks at some dams increases with projected climate change while it remains the similar to present conditions or even decreases at others. Results from Finnish studies show that even though there are large increases in design floods on most dams in the country, this leads to concerns for dam safety on only five to twelve dams, depending on what scenario is used (Veijalainen and Vehviläinen, 2006). A general conclusion from Swedish studies is that this is an issue that has to be seriously considered. A large range between results from different climate scenarios implies that uncertainty is great and the impacts are not self-evident. The critical factor is whether the most extreme floods are generated by rain or snowmelt. Therefore, careful investigation is justified for each specific dam (Andréasson et al., 2007).

Hydro Tasmania is the “western” hydropower operator that, based on our collated material, has paid the most attention to the issue of hydrological change as a result of climate change. It has conducted extensive research studies over many years, and many of the lessons learnt from these could be useful as guidance for others setting out to do similar work. Several quite significant findings have come out of their studies. One is that in spite of finding an increase in future rainfall, their modelling results indicate a concomitant *reduction* in turbinable runoffs. This is due to the increasing IHV, with a stronger seasonality in the rainfall/runoff patterns and hence a lack of storage capacities in upland run-of-river stations, meaning these are unable to use the increased flow in winter to spring. Another interesting finding is that in spite of the high level of sophistication of this work, the seasonal accuracy of model predictions are poor. McIntosh et al. (2005) report 25% to 75% underestimations of summer rainfall and around 100% overestimation of winter rainfall, as compared to actual observations. Given that climate models typically predict changes in the 0-25% range for most places on earth, the problems with these discrepancies are quite obvious. But, they conclude that one aspect (limitation) of models have to be kept in mind – that they can only represent statistical variability, not individual occurrences (ibid.). Hydro Tasmania has made several decision regarding management of their operations based on their findings. One is that they no longer use the entire flow record, at their disposal, in operational planning. As a result of the review of the historic record of inflows, there was a statistical change in inflows over the most recent 31 years compared to the entire record. The changes also reflected the general findings of the climate-change modelling, adding weight to the need for changing the inflows used for planning. Therefore they have decided to only use the most recent 31 years of record. A further result of their studies, given that most of their assets are at mid-life or end-of-life, is that Hydro Tasmania will take the findings into consideration when planning for the replacement/refitting of their installations. This proves the point made elsewhere in this paper that adaptive management will likely be the single most powerful response to climate-change at the disposal of hydropower operators.

Hughes and Mallory (2007), presents a South African approach to managing IHV, using duration curves and optimum water abstraction rates for various users in order to arrive at a socio-economically and environmentally acceptable distribution of the available resource. He concludes by saying that such an approach (or similar) is necessary for water resource management to be both equitable and sustainable, but also warns that enforcement needs will be high (prohibitive?) and water users might have problems accepting a commanding management approach.

Harrison et al. (2006) show that river runoff tends to amplify changes in precipitation patterns, meaning that the modelled changes in rainfall will likely have even greater impacts on the operation of hydropower plants in negatively affected regions. To add to this, energy-generation changes tend to be greater than the changes in runoff, causing a further multiplication effect. For example, Nash and Gleick (1993) estimated sensitivities up to 3.0 (a sensitivity of 3.0 means that 1% change in precipitation results in 3% change in generation) between hydropower generation and runoff in the Colorado Basin. The Harrison et al. study is somewhat unique in the material we have collated, since it actually analyses the impact of hydrological variability on the financial performance of hydropower. They found that the analysed (planned) plant they studied was strongly susceptible to climate change, and much more so to changes in precipitation than to changes in temperature. This finding is supported by e.g. Al-derwish and Al-Eryani, 1999, quoted in WCD, 2000. The reason is that evapotranspiration is limited by water availability. This does, however, have implications for how one looks at projects with large (as in large surface areas) storage reservoirs and those without, because of evaporation potentials. Harrison et al. warn that IHV may spell trouble for hydropower in a world where private investments are becoming increasingly important to growth in the power sector, making risk-averse thinking more prevalent.

Harrison and Whittington (2001), report a number of studies which have examined the impact of climate change on hydropower production, see box 3 below.

In the Indus River basin, the uncertainties are greater than in the other basins depending on difficulties to simulate the impact of monsoonal seasonality on the precipitation in the highest and most glaciated parts of the Himalaya. Most scenarios predict increased precipitation and hydropower production in the Indus River. However, the reverse conclusion cannot be dismissed (Reibsame et al., 1995).

Box 3.

Region/River	Temperature	Precipitation	Production
Nile River	+4.7ºC	+22%	- 21%
Indus River	+4.7ºC	+20%	+19%
Colorado River	+2.0ºC	- 20%	- 40%
New Zealand	+2.0ºC	+10%	+12%

Arora and Boer (2001) studied simulated changes to the hydrological regimes of some of the world's biggest rivers. Some of their more noteworthy results were that the modelling results sometimes did not agree well with observed changes and, possibly more surprising, that the flood peaks actually were reduced in most cases.

An important modelling study is the EuroWasser study by Lehner et al. (2005). This study uses the WaterGap model to assess and compare gross hydropower potential and developed hydropower potential. Two different GCMs, the ECHAM4 and the HadCM3 were used but neither statistical nor dynamical downscaling were utilised. Instead the GCM results were simply interpolated to the same 50 km horizontal grid used for hydrological modelling. These were then used in a delta change approach based on a 30-year present day time series. Ten-year time slices from the GCMs represented future periods for the 2020s and the 2070s. Interestingly enough, the two models generate strongly disagreeing results. The ECHAM4 model shows a much more negative short-term scenario for countries such as e.g. Spain, the UK, Germany, Poland and Belarus but a more positive outcome in e.g. southern Italy, Greece and Scandinavia. Conversely, the long-term impacts are considerably more positive for the ECHAM4 model in places such as the Katalan part of Spain, Italy, Switzerland, Austria and much of the Balkans. There is long-term reasonable agreement between the two models in that Scandinavia and Russia will experience higher runoff in the distant future and most of the Iberian peninsula, east-central Europe (notably the Ukraine, Romania, Bulgaria, the Czech republic, Slovakia and Poland) and Turkey will experience considerable reductions in runoff volumes. Recent improvements (after the study was conducted) to the climate models would likely improve the picture in the Balkans somewhat. While the results are extremely difficult to interpret at the operational level (mainly due to the fact that the two climate models do not agree very well), this is an approach that, once better climate models are available, could assist the hydropower industry in its work with climate-change adaptation. The European wide assessment of impacts to hydropower by Lehner et al. (2005) was based on simulations from two GCMs. Both simulations used the same emissions scenario, "business as usual." The aim was to assess future hydropower potential on a country scale.

The fact that most predictions build on models is obviously a great problem. MacIntosh et al. (2005) provide a striking quote of unknown origin from a George Box; *"All models are wrong, but some are useful"*. In some cases the frantic debate that has come about regarding anthropogenic climate change and the results of, primarily GCMs, have also sometimes clouded the fact that there indeed exists, and has always existed, non-anthropogenic climate change. Mason (2006) presents such an example by showing how the historical levels of Lake Victoria, the subject of a very infected debate in the region, are not quite as easy to understand as the debate would have. Over-abstraction, the most commonly quoted reason in the debate, certainly plays a part, but a clear correlation with the sun-spot cycles coupled with a very strong increase in regional rainfall in the early 1960s are equally valid explanations. This increase is now falling off, back to levels normal during the pre-1960 period.

"Natural" oscillations in climate has been the subject of much study. One such study (Chiew et al., 2005) concluded that results were somewhat inconclusive, but that many of the studied catchments showed significant oscillations of either an 11-14 year period, or a 20-25 year period, or both. There were more such observations than what should have been expected from a random sample. A well-known, and old, regional example is that of Tyson and Dyer (1975) for South Africa. This work has been followed up by a vigorous, more recent, debate in South Africa (Alexander, 2005, 2007, Midgley and Underhill, 2007) over the existence of such an oscillation.

Furthermore, recently a number of studies have been released that put many of the GCM results into question. The renowned journal Science has several on-line studies showing e.g. that rainfall will increase at the same rate as the increasing temperature raises atmospheric water content, i.e. by about 6.5% per degree C. This is in sharp contrast to most GCMs, predicting about 1-3% increases in rainfall, per degree C. Another study based on sediment cores and drilling into coral reefs reveal that hurricane activity has gone down from the 18th century until today, in spite of a rather large increase in global temperature. This is somewhat counter-intuitive, given that hurricane activity is well documented to be almost entirely related to water temperatures above 27º C, something that logically must be more common in a warmer world.

For a thorough presentation of the predicted regional impacts of climate change, see IPCC, (2007b).

While this report was being finalised, a very interesting study by Byer and Yeomans (2007) was published. The authors have reviewed a number of hydropower EIAs in Canada, and found the following things to be generally true: climate change has not been adequately acknowledged or addressed in most EIAs; uncertainties about climate change have been addressed even less well; climate change is addressed inconsistently between similar types of project; and more recent EIAs are not necessarily better with respect to these concerns. They suggest three different ways to address these issues: scenario assessment; sensitivity analysis; and probabilistic analysis. They also discuss how these are appropriate in different situations, and conclude that context will decide which is preferable. They provide a table with preferred analytical approach as a result of two variables – the importance of the information generated and the quality of the quantitative data available for modelling. Generally speaking, the choice moves from sensitivity analysis at low levels of importance and quality of available data, through scenario as these increase/improve, to probabilistic at high importance and excellent quality data available.

Also just as the present report was being finalised, The Nordic Council of Ministers published a book entitled "Impacts of Climate Change on Renewable Energy Sources" (Fenger, 2007). Without having had the time to analyse their results in detail, the main conclusions are: 1) Using the HdAM3H and ECHAM4 models for Norway, Sweden, Finland, Iceland and Latvia., the modelled runoff results are very interesting. Not least the rather strong differences that the two models yield. Both models show strong increases in runoff for western Norway, but much more so for the ECHAM4 model. They also agree on both direction (dryer in the south, wetter in the north) and approximate magnitude for Sweden except the mountains where the ECHAM4 predicts much higher increases in runoff. For Finland, the results are similar (increased runoff), but with a stronger increase for the ECHAM4 model. Iceland is only studied by the HdAM3H model, which predicts small increases for most of the country but very large increases from glaciated areas (>1000 mm/year more than today's figures). In Latvia the results are contradictory. The HdAM3H predicts a drier future, and the ECHAM4 a wetter one. The sizes of the changes are, however, quite modest in comparison to the other countries. The hydrological modelling work is based on the report by Bergström et al. (2007) quoted elsewhere in this report; 2) The impacts on hydropower production will be positive in the app. 100-year scenario modelled. However, dam safety is an issue which will demand more attention due to “the new annual rhythm in runoff”; 3) Special mention is made regarding the glacial runoff which will increase strongly until about the middle of this century and then start decreasing due to decreased glacial-ice volumes, reaching today’s values around the year 2200.

Addressing increased hydrological variability in the planning and operation of hydropower

Planning for new hydropower plants

Hydropower planning normally considers periods of something like 15-50 years, most commonly 25-30. It is quite perceivable, and in fact likely, that impacts of climate change (and specifically IHV) could manifest themselves within that planning horizon. This is, however, true as it pertains to the absolute generation year-by-year, but as described above, due to the discounting in the financial analyses, it is rarely a concern with most planners at the moment. From a natural resource-management point of view this introduces a problem. Most hydropower installations, if properly maintained and refurbished, can have a technical life-span of 60-100 years, and yield significant economic advantages to the power sector long after their pay-off period is over. Failure to plan for a more distant future will then seem less than optimal. The debate on discount rates has been on-going for a very long time, with various authors introducing concepts such as *environmental discount rate*, which would then axiomatically be more relevant for i.e. ecosystem issues, and Pearce et al. (2006) argue that there is support for using discount rates that decline with time. In the Rescon study (Palmieri et al., 2003), annex B, a literature review concludes that a variety of approaches could be adopted to deal with the problem with long-lived resources. One such approach could be the setting aside of funds to address future (additional) socio-environmental costs if and when they occur. At reasonable intervals, based on comprehensive monitoring and (importantly) evaluation, one could then reset the “baseline” for damages and readdress the necessary size of such funds.

In glacier-fed rivers the duration of peak-summer flows from the melting glaciers should be studied. If the increased flows, resulting from a warming climate, are estimated to last several decades, and the depreciation time of the hydropower plant is of the same (or shorter) order, it might be profitable to design the plant for the temporarily higher flow.

Hydropower plants located at higher altitudes have often been designed as run-of-river plants, since it has been assumed that snowfields and glaciers function as reservoirs (Phinney et al., 2005). Further downstream, where most of the precipitation falls as rain, large reservoirs have been constructed. They store the runoff on an inter-seasonal basis, and sometimes even between years. A consequence of climate change is that the importance of storage capacity will rise, depending on the decrease in glacier volumes and an expected increase of the incidence of extremes.

The approach outlined below, which can later be expanded upon, is provisionally proposed for consideration.

1. Do baseline planning assessments based on available solid information.
2. Conduct standard trend analysis for existing hydrological records. This is empirical evidence, and does not have a dependency on modelling.
3. Obtain detailed scenario projections for the particular region in question from global climate models (or regional models, if such are available, see above). All available outputs that could serve as input to next tier models (e.g. hydrological simulation models) are important.
4. *Option 1:* If sufficient outputs/inputs are available, generate runoff scenarios with deterministic hydrological models, which can account for non-linear dynamic responses. Focus on quantity (annual volumes), seasonal distribution and variability as the main outputs. Also assess potential changes in environmental flow requirements.
5. *Option 2:* If there are insufficient outputs from the climate models for input to deterministic hydrological models, and also as an alternative approach for control purposes, revert to the use of statistical models. The scaling of key variables, such as total precipitation, should be proportionate to the changes predicted by GCMs.

   Either calibrate a statistical model to observed rainfall sequences and then change key parameters such as the mean and coefficient of variability, to generate optional scenarios of possible rainfall sequences, as input to deterministic models.

   Or, calibrate a statistical model directly on observed runoff records, and change key variables to generate possible resulting runoff scenarios.
6. Use the outputs from options 1 and 2 above in simulation models, and apply probabilistic techniques, for assessing the impacts of the various flow scenarios on water re-

source systems and hydropower schemes. It is of paramount importance to include other, and often competing, water uses in these simulations. This will then allow an assessment of the impacts on hydropower plant and reservoir operating rules and, hence, on the potential for water yield and hydropower generation.

7. Perform normal economic and risk analyses.
8. Lastly, but maybe most importantly – adopt an adaptive-management approach with regular monitoring, evaluations and reviews, with possible redesign of the management programme, as found necessary. This needs to be based on a solid set of indicators.

Design changes may be required for aspects such as spillway capacities, outlet structures/works etc.

It is important to remember the complex responses that will inevitably occur to major changes in the hydrological regime. The amount and distribution of the flow is only one such parameter. Sediment transport, domestic and agricultural water withdrawals, environmental flow needs and many others will also be affected.

Operation of existing plants

Operational decisions cover much shorter time scales than planning – from minutes or hours to seasonal variations, and as a conservative longer-term view up to 5 years (for systems with large storages and long carry-over periods/long hydrologic memory).

Planning is typically done on green-field projects where the physical parameters are largely flexible, or for existing projects that need to be re-engineered.

Operating decisions are normally taken within the confines of fixed physical parameters and other operational constraints of the scheme.

The impacts of climate change/IHV are therefore unlikely to have a major influence during a specific operating horizon. However, it is bound to have an impact during several consecutive operating horizons, and it is therefore prudent that this be anticipated and provided for also from an operating perspective.

A similar approach as for planning can be followed, but within the constraints as applicable to an existing scheme. The outcome is more likely to have a bearing over the medium term to long term, and most probably not within e.g. one year. Part of the outcome could also be that some physical works/alterations may be required.

Issues relevant to EIAs in the hydropower industry

The most pressing need for inclusion of an assumed increased hydrological variability into hydropower EIAs seems to be the importance for the hydropower project of co-dependencies in the environment – notably land use, vegetation and ecology (which will all change if temperatures increase, and precipitation changes). The importance of the EIA predictions, primarily as they deal with ecosystem services of paramount importance to e.g. project-affected subsistence populations, will increase if climate-change-driven increased variability introduces negative stress on the carrying capacity of the environment. An environment already under such severe stress would then be forced to absorb the cumulative stress of the changes brought on by the hydropower project. Thus, normal impact prediction has to be augmented by predictions of the on-going climate shift.

The entire concept of climate change has the potential of increasing the differences in priorities and outlook between, on one hand the techno-economic experts, and on the other hand the socio-environmental experts. This would make the necessary co-operation harder, so this potential problem needs to be addressed in order to reduce this risk. In fact, even closer co-operation will be necessary, and could be facilitated by a better focus in early strategic studies, such as master plans etc.

The environmental assessment (EA) tools of Strategic Environmental Assessment (SEA) and Cumulative Impact Assessment or CIA (really a specialised form of SEA) are strategic-level instruments at policy, plan or programme level. At this level of EA practitioners frequently utilise scenarios for predictions and illustrations of expected outcomes given certain key assumptions. It is highly recommended that multi- and bi-lateral donors assist countries in the implementation of such scenario-based SEA/CIA studies for their entire electricity and/or hydropower sectors. Including the potential impacts of IHV into such studies would then give decision-makers a basis upon which to make decisions regarding the sensibilities and sensitivities involved in different development options.

It has been stated above, but it deserves mentioning again here, that a very strong focus on adaptive management in the face of potential IHV is of the utmost importance, even more so when considering the secondary and tertiary impacts concerned with land-use and vegetation changes on the hydrological regime.

All EAs study the complex interactions between bio-physical and socio-economic parameters. Ecosystems and their responses to change are extremely complex, and all impact assessments are therefore inherently uncertain. This uncertainty is probably considerably larger than the uncertainty associated with climate change.

Priority research

In terms of the hydrological modelling research needed to advance the prediction techniques to a point that actual hydropower planning will be feasible through the use of such models, the following priority foci (not necessarily in this order), should prove productive:

- Statistical techniques and improved simulation models for separating climate-change signals from natural variability.
- Better RCMs for prediction of climate change over reasonable financial-planning horizons. A stronger focus on scenarios for the 2015-2050 period, rather than 2070 or 2100 as is the case in most climate-change research. This would greatly facilitate the utilisation of research findings by hydropower operators, on time scales that are relevant also from an economic/financial point of view.
- The joining of regular hydrological trend analysis and climate-change modelling in providing useable design criteria for green-field hydropower developments.
- Well planned monitoring of key variables for assessing changes in climate that relate to streamflow. Specific focus should be given to improving the knowledge and confidence with respect to the relationships between climate change and streamflow.
- A focussed effort on actual hydropower implications of climate change has been initiated by CEA Technologies of Canada (CEA, 2007). This type of effort should be multiplied, so as to increase the geographic spread of the empirical evidence.
- A large research topic is the complex interactions of increased overall environmental stress which can be expected if hydrological variability increases, particularly where precipitation can be expected to decrease. One problem with running hydrological models based on precipitation changes arrived at through RCM runs is that the climate models do not model the land-use and vegetation changes resulting from potential climate change, changes that will likely be especially relevant in arid and semi-arid (i.e. already hydrologically very variable) environments. These changes in land use and vegetation, which will also be enhanced if population growth continues, could have a much greater impact on resulting runoff than the changes in (only) precipitation

would indicate. Alas, significantly better utilisation of land-use and ecosystem researchers are needed if the impact on large-scale hydropower is to be predicted.

- Appropriate coordination of activities in the above fields to enhance the overall value and applicability of the outcomes and to ensure the relevance thereof. A workshop to be attended by selected stakeholders and specialists could contribute to setting initial goals and directives in this regard.

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