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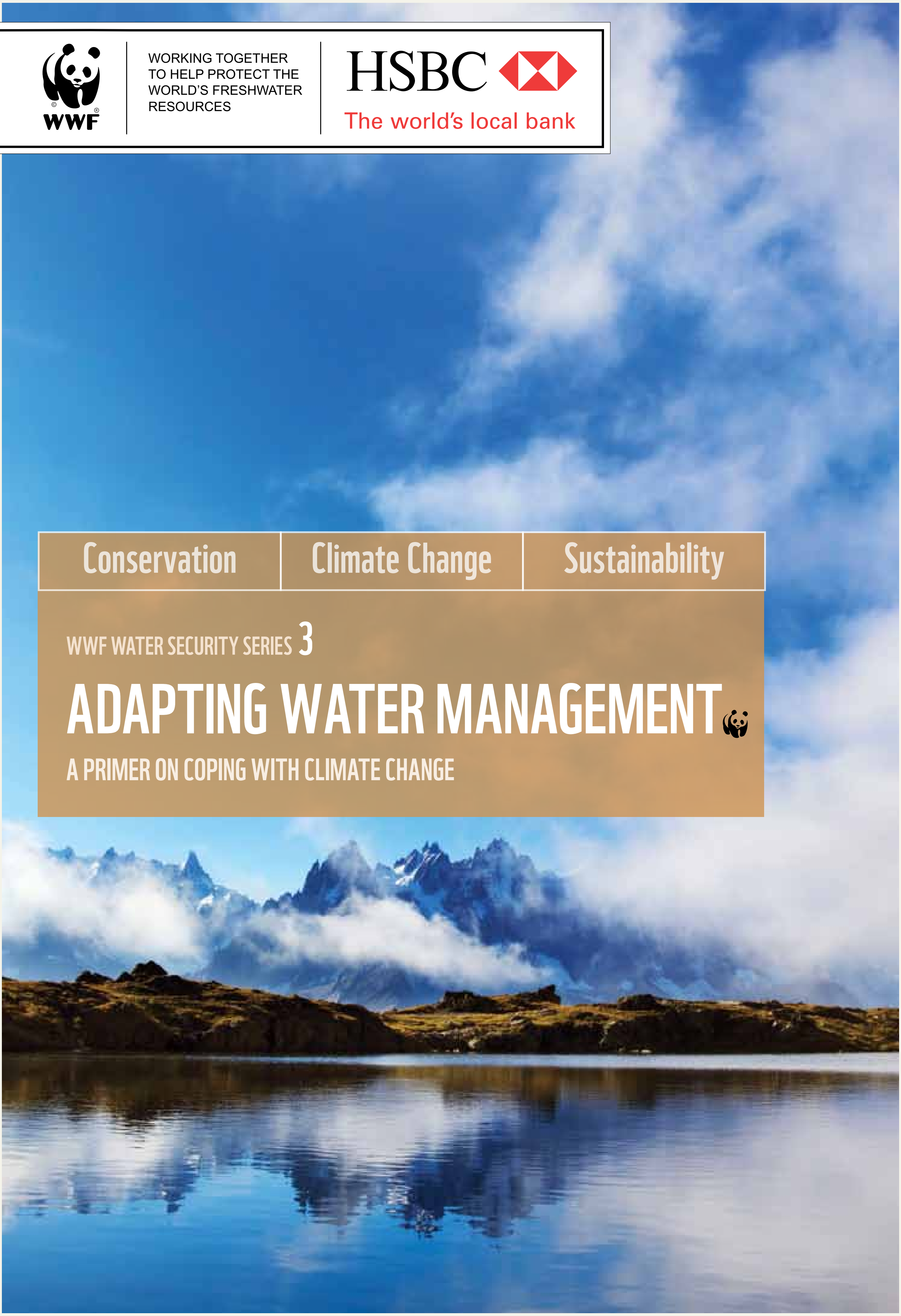

Conservation | Climate Change | Sustainability

WWF WATER SECURITY SERIES 3

# ADAPTING WATER MANAGEMENT

## A PRIMER ON COPING WITH CLIMATE CHANGE

WWF's Water Security Series sets out key concepts in water management in the context of the need for environmental sustainability. The series builds on lessons from WWF's work around the globe, and on state-of-the-art thinking from external experts. Each primer in the Water Security Series will address specific aspects of water management, with an initial focus on the inter-related issues of water scarcity, climate change, infrastructure and risk.

## Understanding Water Security

As an international network, WWF addresses global threats to people and nature such as climate change, the peril to endangered species and habitats, and the unsustainable consumption of the world's natural resources. We do this by influencing how governments, businesses and people think, learn and act in relation to the world around us, and by working with local communities to improve their livelihoods and the environment upon which we all depend.

Alongside climate change, the existing and projected scarcity of clean water is likely to be one of the key challenges facing the world in the 21st Century. This is not just WWF's view: many world leaders, including successive UN Secretaries General, have said as much in recent years. Influential voices in the global economy are increasingly talking about water-related risk as an emerging threat to businesses.

If we manage water badly, nature also suffers from a lack of water security. Indeed, the evidence is that freshwater biodiversity is already suffering acutely from over-abstraction of water, from pollution of rivers, lakes and groundwater and from poorly-planned water infrastructure. WWF's Living Planet Report shows that declines in freshwater biodiversity are probably the steepest amongst all habitat types.

As the global population grows and demand for food and energy increases, the pressure on freshwater ecosystems will intensify. To add to this, the main effects of climate change are likely to be felt through changes to the hydrological cycle.

WWF has been working for many years in many parts of the world to improve water management. Ensuring water security remains one of our key priorities.


## Acknowledgements

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The authors would like to acknowledge the series editors: Dave Tickner, Tom Le Quesne, and Mica Ruiz.

March 2009



John H. Matthews, Tom Le Quesne

# CONTENTS

# Summary:


Withdrawals of water, the construction of dams and other hard infrastructure, pollution, land-use shifts, invasive species, and habitat modification and destruction have degraded many rivers, lakes and wetlands. In recent decades anthropogenic climate change has also begun to alter freshwater ecosystems, and this force will continue to strengthen for the foreseeable future. For freshwater ecosystems, shifts in precipitation and evaporation patterns will be a far more important aspect of climate change than air temperature alone. Climate change may be manifested in different ways, all of which have been observed in recent decades in different parts of the world:

- Gradually, through a slow shift in the mean of some climate variable;
- Through increases in the frequency or intensity of extreme weather events such as floods or droughts – an increase in climate variability;
- Through sudden state-level changes, where a period of climate stability is followed by a period of rapid change before leading to some new stable period.

Climate change impacts on lakes, wetlands and rivers differ fundamentally from effects on other biomes such as forests or coral reefs because: (a) most bodies of freshwater are being used by humans and have not existed in a "wild" state for long periods of time; (b) management of freshwater ecosystems must include their connected terrestrial, estuarine, and marine biomes, since they contribute substantially to freshwater health; and (c) the elements of climate that are most relevant to freshwater are subject to high temporal and spatial uncertainty.

The impacts of climate change on freshwater ecosystems can be characterised by shifts in water quality (e.g., pollutants, temperature, dissolved oxygen), water quantity, and water timing (normal flood and dry periods). Globally, water timing is likely to be the most important impact for both humans and other species since it directly affects both water quantity and quality and because humans and other species often exhibit behavior that depends on predictable changes in flow. Unfortunately, it may also be the most difficult variable for models to predict with high confidence. As a result, water policy should focus on changes at sub-annual resolution, such as seasonally or monthly. Moreover, uncertainty should not be an excuse for inaction. Indeed, the process of reducing uncertainty must become a guide for action.

The assessment of vulnerability to negative effects from climate change should distinguish between 'impacts assessment', which attempts to project future biophysical and ecological changes in a deterministic manner, and 'vulnerability assessment', which attempts to combine an assessment of future suites of change with an assessment of the resilience of ecosystems and management institutions. Due to the high levels of uncertainty in models of future hydrology, assessing vulnerability must focus as much on adaptive capacity as climate-model downscaling. It may be useful to think about future vulnerability in terms of potential 'stories' about emerging climates rather than definitive scenarios.

Freshwater ecosystems differ in their relative vulnerability to climate change. For instance, large rivers will respond less rapidly than small streams exposed to the same extent, type, and rate of climate change. Similarly, some societies and institutions will be better adapted to change, and therefore less vulnerable to negative impacts.

# Summary

Developing a strategy to help social and ecological systems adapt to climate change that encompasses all of these concerns for freshwater resources is difficult but should include two components: Firstly, a commitment to lower greenhouse gas emissions to slow the rate of climate change in the future. Secondly, an active approach to institutional learning and flexibility in the face of climate and impact uncertainty. We propose eight elements to an adaptive water strategy:

1. **Develop institutional capacity:** The development of strong institutional capacity, adaptive and effective governance, and the ability to successfully implement sound adaptation policies should be regarded as the single most important task in facilitating successful adaptation to climate change in freshwater. In the water sector, these institutions are typically weak and seldom well-placed to cope with climate-driven impacts
2. **Create flexible allocation systems and agreements:** Systems of water allocation and water rights are required that are sufficiently flexible to protect social, environment, and essential economic interests under conditions of varying water availability.
3. **Reduce external non-climate pressures:** The impacts of climate change will be significantly exacerbated in systems that already experience stress from other factors, such as over-abstraction, poorly planned infrastructure, or exotic species invasions. Reducing these pressures is key to facilitating adaptation.
4. **Help species, human communities and economies move their ranges:** Species may need to move both between and within ecosystems as conditions in headwaters or lower reaches become unviable because of climate change. Equally, economic activities may need to shift.
5. **Think carefully about water infrastructure development and management:** Short-term gains from building new irrigation, hydropower, or flood control measures that are based on recent climate history may actually limit future options for climate adaptation, resulting in maladaptation. Assumptions of hydrological stationarity in planning and management decisions should be questioned.
6. **Institute sustainable flood management policies:** There is an increasing risk that flood defences based on historic precipitation patterns will be overwhelmed. Sustainable flood management looks to reduce flood risk by understanding how floods move through catchments and developing climate-appropriate risk reduction strategies, such as accommodation rather than defense.
7. **Support climate-aware government and development planning:** Many government economic and social planning decisions include assumptions about the future availability of water and freshwater-derived ecosystem services, and these decisions must take into account potential climate shifts if significant social, and economic risks are to be avoided.
8. **Improve monitoring and responsiveness capacity:** Finding our way through the uncertainties in predictions of climate impacts means that we must become more attuned to shifts in ecological, hydrologic and social aspects in our systems as they occur. We must make sure that the results of monitoring processes are embedded within our management, planning, and design processes.

# Introduction:

**Anthropogenic climate change, popularly known as global warming, is already altering freshwater ecosystems almost everywhere on earth: where water is found, how much water is there, and in what form it exists – liquid, frozen, or vapour. Before our eyes, climate change is creating freshwater winners and losers among individuals, economies, whole societies and nations, and of course among species and ecosystems.**

Climate change has profound implications for managing freshwater resources and the people and species dependent on those resources, but water management long predates any awareness of anthropogenic climate change. Indeed, large-scale water management has been one of the great themes of the nineteenth and twentieth centuries worldwide. Many of the largest construction projects in human history have been attempts to consume, control, allocate, and regulate water, perhaps most notably the construction of tens of thousands of dams and irrigation infrastructure. Moreover, extensive industrial and domestic consumption and discharge, pollution and the conversion of perhaps half of all wetlands globally to "productive" uses have had dire impacts on the many aquatic and terrestrial species that rely on freshwater resources.[1]

One study of 344 freshwater temperate and tropical species suggested population declines of about 30% between 1970 and 2003 alone. Freshwater ecosystems now experience rates of species extinction as high as or higher than in any other biome.[2]

Climate adaptation is the process of adjusting to and anticipating emerging climate regimes – avoiding risk and facilitating change. Examples include reducing water consumption to compensate for lower precipitation rates, shifting the location of an industry away from an increasingly drought-prone area to a wetter region, or altering urban stream morphology to compensate for larger and more frequent floods. Perhaps the greatest threat to freshwater ecosystems from climate change is the interaction between relatively "traditional" problems such as over-abstraction or habitat fragmentation with climate-driven shifts, such as more frequent droughts.

WWF is committed to the concept of flexibility as a response in itself to climate change: while there may be a range of predictions for future climate conditions, the uncertainties around those predictions are typically high and may require some time to finalise plans and approaches. In some cases, we may not have the option to move people, species, and industries, so we must encourage and develop resilience to negative climate impacts such as extreme weather events. In other cases, there may even be limits to adaptation, resilience, and sustainability that force very difficult choices upon us.

This primer is intended as a guide to some of the basic issues surrounding water management from a climate change perspective.

1 WWF, 2008. *Living Planet Report* 2008. WWF international, Gland, Switzerland, 8 pp

2 Ricciardi A., and Rasmussen J.B. 1999. (Extinction rates of North American freshwater fauna. Conservation Biology 13: 1220–22)

# PART A: What does climate change feel like in freshwater?

PART A:

# What does climate change feel like in freshwater?

Much of the journalism covering anthropogenic climate change describes impacts that are difficult to imagine: “projected increases in mean air temperature by up to 6°C by 2100” do not easily register with human experience and are not useful as the basis for sound policy.

People do not perceive climate per se. Like most species, we experience weather, and we experience weather as both a local and a daily or seasonal phenomenon. We are often most conscious of climate itself through weather extremes that contrast with our sense of “normal” climate: very hard rains, long and severe droughts, and extremely hot or cold days.

Moreover, the term “global warming” suggests that air temperature is the most important or most altered aspect of climate. But anthropogenic climate change is altering all aspects of climate, and air temperature alone is probably not even the most important aspect of climate for living things on the planet. Indeed, precipitation is often a far more restrictive part of local climate than air temperature, historically limiting where people can engage in many industrial or agricultural activities and where you find particular wild species – even non-aquatic species. And precipitation is the source of almost all surface freshwater on earth.


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**Freshwater climate change impacts are not always identified as being related to either anthropogenic climate change or tofreshwater. The western U.S. state of California is famous for its wine industry, but trends in the snowpack of the Sierra Nevada are reducing summer and fall water availability for agriculture and cities. Some observers suggest that reduced water supplies and increased climate variability are likely to result in the California wine industry effectively shifting northwards to the U.S. states of Oregon and Washington and the Canadian province of British Columbia. Most consumers are likely to experience this shift as a change in the industry's priorities rather than as a product of the changes in regional precipitation regime.**

## The end of the Californian wine industry?

In the USA, the state of California has seen significant changes in mean winter temperatures and the accumulation of snowfall in the mountains of the Sierra Nevada. Precipitation is very seasonal across most of the region, with long dry summers and cold wet winters. Much of the surface water in rivers and lakes in California derives from the slow melt of the mountain snowpack, which acts like a frozen reservoir keeping flows relatively even and reliable throughout the year.

The economic development of California has assumed that these conditions would remain the same into the foreseeable future. But these conditions are changing. The combination of a rapidly growing economy and population (greater demands) with a declining snowpack (diminishing supplies) means this assumption no longer holds. Californians may not experience the shifts in climate that are occurring at high elevations in winter, but they are experiencing the ecological effects of those shifts: pressure from local governments to change yard and garden plants from thirsty grasses to plants that can survive long periods without watering, a world-famous wine industry that seems likely to shift north into the states of Oregon and Washington to survive; more frequent and more serious wildfires; and even serious discussion about building desalinisation plants for southern parts of the state.

All of these impacts are a result of trends in California's climate that are likely to continue and strengthen in coming decades, even with major reductions in greenhouse gas emissions.[3]

3 Hayhoe, K., et al. 2004. Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences.* "101*(34)*". 12422-27

PART A:

# Freshwater climate change and precipitation

Most surface freshwater is derived from precipitation. Across the planet, numerous aspects of precipitation are changing, such as the amount of annual or seasonal precipitation; the seasonal timing of precipitation; the "normal" form of precipitation (such as snow versus rain); the intensity of precipitation events (how much per unit of time); the frequency and severity of extreme events like droughts and floods; and the net accumulation or loss of water in places like glaciers and the poles. Moreover, all of these aspects of precipitation are expected to continue to shift over the coming century. In some regions, these shifts will lead to dramatic impacts on regionally "normal" aspects of life, such as economic activities; the presence of disease vectors; local livelihoods; characteristic qualities of ecosystems (fire regime, onset of spring); and the mixture of "typical" species.

Why should we think about precipitation and climate change? After all, most humans consume water that is derived from reservoirs, lakes, rivers, and (in the case of boreholes and wells) groundwater. Almost invariably, however, such water derives from precipitation. Lakes and rivers, for instance, catch recent precipitation in the form of surface runoff, and most groundwater is "recharged" by surface precipitation that percolates through rock and soil.

Frozen precipitation in high altitude areas and middle to high latitude regions can in effect become reservoirs of old, even ancient precipitation that helps feed lakes and rivers during droughts. But like steadily draining bank accounts, lakes, rivers, groundwater and snowpacks and glaciers can become "overdrawn" beyond their capacity to renew their reserves (outflows) or to balance their rate of "deposits" (inflows). In other words, climate shifts in precipitation matter to humans because we depend upon precipitation, whether we are aware of this dependence or not. And these shifts also matter to freshwater ecosystems – to the wild species that rely on freshwater, to agriculture, and to many other elements of human economies.

As individuals, we may find it difficult or impossible to directly perceive climate shifts in freshwater and precipitation. Climate is a statistically defined "norm" defined over some increment of time.[4] Even hard-to-perceive impacts from climate change can be quite significant, however, in altering key hydrological qualities and affecting species and economies.

Shifts in climate that alter freshwater ecosystems have profound socio-cultural, economic, and ecosystem implications. Globally, many lakes, rivers, and wetlands already feel the impact of climate change in terms of when they contain water, how much water they hold, and the qualities of that water, including its temperature. These impacts are likely to grow in strength in coming decades and will have important implications for the living things dependent on that water and for the economic activities that rely on freshwater resources.

Will climate shifts occur gradually or suddenly? The rate of climate change locally can be characterised by three patterns that vary by region and temporal scale, though in many places all three types of change are occurring simultaneously. First, gradual and persistent change has been observed widely. Slow increases in mean air temperature or a gradual advance in the arrival date of

4 Climate scientists are particularly loathe to attribute any specific weather event like a tropical cyclone or a very hot summer to climate change, since such individual events could theoretically occur in the absence of climate change. This is why they are more interested in how often such events occur, how severe they are, and how they alter "mean" weather conditions (i.e., climate).

summer monsoons are typical of this type of change. Statistically, such shifts involve a gradual movement in the long-term average (mean) of some climate variable of interest. Many climate models characterise most aspects of climate change as a slow shift in mean.

The second pattern is an increase in climate variability – a greater frequency in the extremes of weather that oscillate around some relatively stationary mean. For precipitation, some regions are seeing more frequent and more severe flooding as well as more droughts. Weather extremes such as very hot days, large tropical storms, or extremely intense precipitation events appear to play important ecological roles in shaping where species are found (i.e., range shifts).

For humans, they often drive reactive changes in policy, as when two so-called "500-year floods" occur within a decade. Many analyses of recent historic climate show significant shifts in climate variability and the occurrence of weather extremes.

The third pattern occurs when a period of stable or slow-changing climate ("state 1") is followed by a period of rapid climate shift, which leads into another climate plateau ("state 2"). Such sudden state-level changes are difficult to model, but the long-term climate record suggests that they do happen, with sudden change occurring once some climate threshold or tipping point has been exceeded. In recent decades, only a few events might qualify for this pattern, such as the sudden movement of a major ocean current or atmospheric jet stream. For humans and already stressed natural systems, major state-level changes will probably feel like ecological catastrophes.

Alterations in freshwater systems from climate change are not globally uniform. Some regions, for instance, have seen increases in the quantity of freshwater over recent decades, while others have seen precipitous declines in rain or in the frequency of severe droughts. Making worldwide generalisations about how economies and wild species will experience freshwater shifts is therefore not easy. But beginning to understand how climate change impacts lakes, rivers, and wetlands really means exploring the relationship between climate change and precipitation and how together these alter local hydrology.



**The discussion of climate impacts on humans is normally dominated by economic effects, but freshwater ecosystems also perform "cultural ecosystem services" that may be perceived as just as significant as industrial or livelihood impacts. Here, the drought-stricken Gambiri riverbed in northern India, part of the Ganges basin, holds the mounds of recent cremations awaiting the return of the river to wash the ashes downstream to the sacred mother Ganges. Disruption of this "service" by the Gambiri from the synergies of climate change and poor water management represent a profound religious crisis to Hindus in this basin.**

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**Australia has recently faced a series of severe droughts that have had serious economic impacts at regional, national, and global scales. These droughts may signal a shift for some parts of the continent to a new precipitation regime.**

## Australia: A long series of droughts or a new climate regime?

Although the impacts of climate shifts on freshwater ecosystems can be dramatic, in many cases they are not recognised as "freshwater problems" per se. For instance, parts of Australia have recently seen significantly more climate variability, particularly in the form of frequent and severe droughts. The Australian government's new Department of Climate Change reports that in some regions (especially eastern and southern Australia) rainfall has decreased gradually since the 1960s about 10–20%. Even small changes in precipitation can lead to very large shifts in runoff, with river flows dropping up to 40–60% in response. Projections show additional large decreases in mean annual precipitation by 2050. Perhaps most important, droughts are expected to become up to 20% more frequent by 2030[5]. Existing economic institutions are not designed to cope with common and severe droughts; the 2002–2003 drought alone is estimated to have cost about US$7.6 billion (in 2006 US$). The effects are not limited to Australia alone, of course. The resulting decline in Australia's grain production is widely thought to have exacerbated the global food crisis of 2008.

For residents of this area, the severity has led to major changes in water consumption and management, increases in wildfire severity (US$261 million in the Canberra fire of 2003, 2006 US$), and synergistic impacts, such as the loading of three of Canberra's four dams by sediment-filled runoff following the 2003 fire.

5 Pittock, B. 2003. Climate Change: *An Australian Guide to the Science and Potential Impacts,* Australian Greenhouse Office. http://www.greenhouse.gov.au/science/ guide/ index.html.

PART A:

# How can we describe freshwater impacts from climate change?

Freshwater impacts can be described in terms of three different but inter-related components: water quality, water quantity or volume, and water timing (sometimes called water seasonality, flow regime, hydroperiod, or hydropattern). A change in one of these three elements often leads to shifts in the others as well. Water quality refers to how appropriate a particular ecosystem's water is for some "use," whether biological or economic. Many fish species, for instance, have narrow habitat quality preferences for dissolved oxygen, water temperature, dissolved sediment, and pH. Humans generally avoid freshwater for drinking or cooking if it has excessive levels of dissolved minerals or has a very high or low pH.

Water quantity refers to the water volume of a given ecosystem, which is controlled through the balance of inflows (precipitation, runoff, groundwater seepage) and outflows (water abstractions, evapotranspiration, natural outflows). At a global scale, precipitation is tending to fall in fewer but more intense events, resulting in generally more precipitation. At local scales, there is wide variation. The most striking changes in water quantity often occur with precipitation extremes like floods and droughts; lake and wetland levels can also change radically as a result of even slight changes in the balance between precipitation and evaporation. The occurrence of precipitation extremes is expected to increase globally, as well as the severity of extreme events themselves.

Water timing or seasonality is the expected or average variation in water quantity over some period of time, usually reported as a single year. Most water bodies have a "normal" seasonal variation that in wetlands and lakes is called the hydroperiod and in rivers and streams is called flow regime; together, these terms are sometimes lumped together as hydropattern.

Many terrestrial and aquatic species are extremely sensitive to water timing. Natural selection has adapted (in an evolutionary sense) the behaviour, physiology and developmental processes of many aquatic organisms to particular water timing regimes, such as spawning during spring floods or accelerated metamorphosis from tadpole to adult frog in a rapidly drying wetland. Shifts in water timing mean that there may be detrimental mismatches between behaviour and the aquatic habitat. In turn, these shifts can affect fisheries stocks and industries that depend on seasonal water flows.

Controlling water timing has long been a priority of human water management. A flooded rice field is an attempt to change an ephemeral wetland or floodplain into a regulated ecosystem to optimise growth and yield. The tens of thousands of dams and irrigation canals across the planet today demonstrate the human desire to control variations in water levels that occur on a natural but irregular basis, to provide more reliable irrigation or hydropower. Dams and other types of infrastructure designed for flood control reflect a desire to reduce flow variability and extremes.

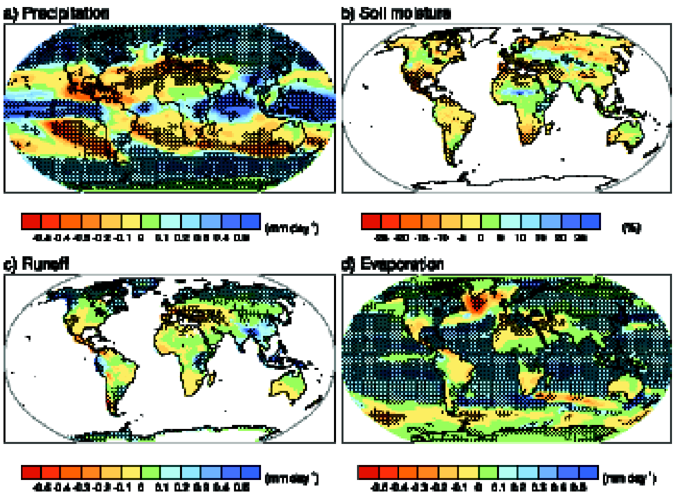
Unfortunately, many large-scale studies of freshwater climate impacts provide information only on total or average annual flow or runoff patterns. Such reporting ignores sub-annual seasonal variation in climate trends as well as how much variability exists between years. A small shift in evapotranspiration or precipitation, for instance, can change a historically low-water period into a season with frequent droughts, though at an annual resolution the net shift in inflows and outflows may seem insignificant.

# PART A:
## How can we describe freshwater impacts from climate change?

A preferable way of investigating the potential for seasonal impacts is through the use of annual hydrographs. Worldwide, shifts in water timing are likely to be the most widespread and important type of climate impact on freshwater systems.

Until now, efforts to manage water have typically assumed "stationarity" in the role of climate in hydropattern. That is, they have assumed that the historic record of seasonal variation is a good guide to the future. This assumption is probably much less valid today in the majority of freshwater ecosystems globally. Climate change is altering the seasonality of many water bodies even when the water quantity at an annual scale remains relatively unchanged. The timing of precipitation, for instance, is altering in many regions, shifting the timing of seasons of high and low precipitation as much as several weeks. And higher air temperatures in winter and spring mean that in many temperate regions there is more winter rain than snow (leading to greater frequencies of winter flooding), a smaller snowpack, an earlier spring melt, more summer evapotranspiration and less reliable summer flows. Higher air temperatures also cause increases in the rate of evaporation from lakes and reservoirs and, in higher latitudes and altitudes, decreases in the frequency and duration of lake ice cover.

The interaction between these elements is complex, and the ecosystem impacts are difficult to model and predict. For instance, in the Pacific Northwest of the USA, summer precipitation rates are dropping while summer water temperatures are increasing at a rapid rate, impacting salmonid population sizes and migration patterns, with several species likely to become locally or regionally extinct within decades.[6] According to a US Forest Service statement,




**Source: IPCC**

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations' scientific panel tasked with analysing climate change impacts on human and natural systems. The Fourth Assessment Report was published in 2007 (see Further Readings). Here, the IPCC shows agreement across 15 climate models for several freshwater variables. To indicate consistency of sign of change, regions are stippled where at least 80% of models agree on the sign of the mean change. Changes are annual means for one future climate-development scenario (SRES A1B) for the period 2080–2099 relative to 1980–1999. Soil moisture and runoff changes are shown at land points with valid data from at least ten models. [Based on WGI Figure 10.12].[7]

"Although the intensity of the effects will vary spatially, climate change will alter virtually all streams and rivers in the [Columbia] river basin. Current predictions suggest that temperature increases alone will render 2–7% of headwater trout habitat in the Pacific Northwest unsuitable by 2030, 5–20% by 2060, and 8–33% by 2090… Salmon

6 Independent Scientific Advisory Board. 2007. Climate change impacts on Columbia River Basin fish and wildlife. Northwest Power and Conservation Council. http://www.nwcouncil.org/library/isab/ISAB%202007-2%20Climate%20Change.pdf.

7 IPCC. 2007. *Climate Change 2007: Impacts, Adaptation, and Vulnerability.* M. Parry, O. Canziani, J. Palutikoff, P. van der Linden, C. Hanson (eds.). Cambridge University Press, Cambridge, UK.

# PART A:
## How can we describe freshwater impacts from climate change?

habitat loss would be most severe in Oregon and Idaho with potential losses exceeding 40% by 2090.[8]”

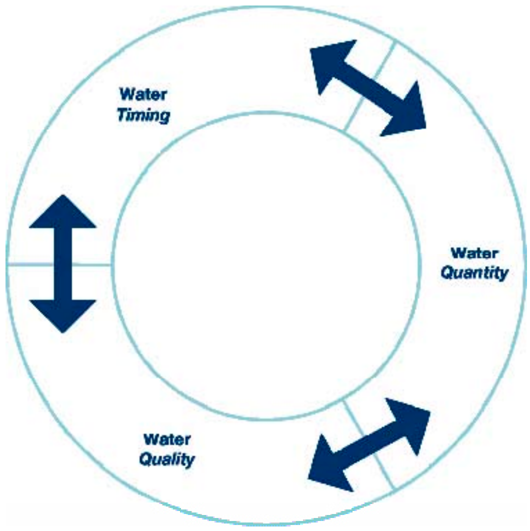
The interaction between warmer winter temperatures, increasing levels of nutrient pollution, and growing urban pressures among the large, shallow lakes of the central Yangtze basin of China is leading to near-permanent eutrophic conditions, even in the coldest months of the year.

In many arid and semi-arid regions, annual precipitation levels are decreasing, threatening the livelihoods of farmers and pastoralists and cities in regions like northeastern Brazil, southern Africa, and major population centres in northern Mexico and the southwestern USA.

In temperate and boreal regions, annual precipitation levels are generally increasing. Northern and western Europe in particular are projected to see significant increases in flood risk, with mean annual runoff rates increasing between 5–15% by the 2020s and 9–22% by the 2070s, with much of the change in precipitation coming during fall, winter, and spring and through more intense precipitation events. Paradoxically, the result will be both more floods and more droughts.

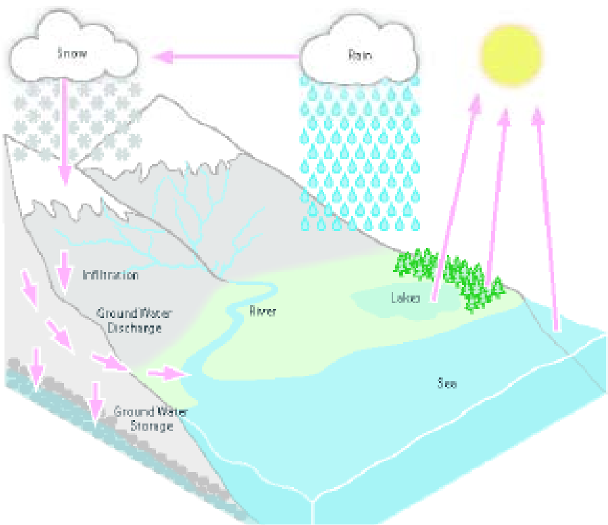
Developing appropriate responses to emerging and uncertain threats is a serious challenge for policymakers. As a UK government committee ruefully reported: “Under climate change, there will be both more water, and less.” Even at a regional level, good policy that is future-oriented, flexible, pro-active, and sustainable will be difficult to develop and will depend on clear conceptions of vulnerability and the uncertainty in forecasts from climate models.

8 http://www.fs.fed.us/ccrc/topics/salmon-trout.shtml.




**Water quality/quantity/timing**

All freshwater climate impacts can be described in terms of their effects on water quality (oligotrophic vs. eutrophic, pH, and so on), water quantity or volume, and water timing (the seasonality of normal water variation, such as a spring flood following high-altitude snowpack melt). These three types of impacts are deeply interconnected. A shift in water timing, for instance, could reduce or increase the intensity of “normal” dry-season low flows.




**The water cycle**

The water cycle is complex and multifaceted. Most of the freshwater accessible to humans and ecosystems is ultimately derived from precipitation, including surface water (lakes, wetlands, and rivers), frozen water sources (snowpacks, glaciers), and groundwater.

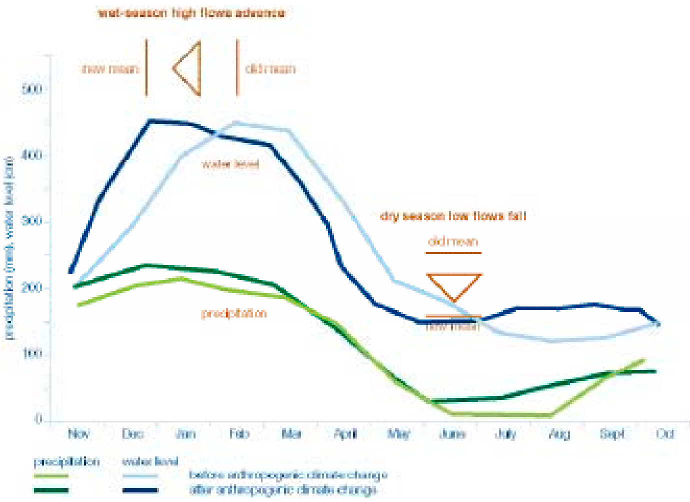
PART A:

# Relative vulnerabilities: Developing contrasts

The three types of impacts can be used to describe how climate will alter freshwater systems, but they do not describe how sensitive a particular system may be to any given shift in climate. Thus, assessing the vulnerability of a freshwater ecosystem or one of its components (such as the headwaters versus the floodplain) is often a key object of interest for resource managers. Here, vulnerability is meant to describe the sensitivity and resilience of an eco-hydrological system to shifts in its climate envelope. One useful means of expressing relative vulnerability is through contrasts between types of freshwater ecosystems or the uses of those ecosystems. The following list is by no means comprehensive. But these and other types of contrasts should serve to illustrate how we can begin to identify what kinds of freshwater systems are most vulnerable to changes in the local climate regime. This is likely to be particularly important in the context of the uncertainty associated with modeling future hydrological changes.

**Scale:** Large versus small. Generally speaking, large systems are buffered simply on the basis of having a greater base volume from climate impacts, particularly extreme weather events such as droughts or floods. Small systems will respond more rapidly and often in more serious ways (hypoxia, shifts from fresh to brackish or saline conditions, high sediment loads).

**Variability:** Permanent versus temporary. Species and economic behaviour dependent on freshwater resources that are normally temporary or ephemeral are more likely to be acclimatised to weather variability. Thus, species and livelihoods dependent on such systems – such as many aquatic macroinvertebrates, large migratory terrestrial vertebrates in eastern Africa, cattle ranchers – are likely to have higher inherent adaptive capacity. Species and people that depend primarily on "permanent" water resources, however, may be very vulnerable to unexpected deviations in water quantity, quality, and timing. They are less likely to have experienced or be adapted for extreme weather events.




Moving hydropatterns Most precipitation climate data are reported at an annual scale, but an annual resolution ignores important elements of water timing and flow seasonality. Thus, annual hydrographs that show "normal" variation in flow regime, hydroperiod, or hydropattern are far more informative when trying to understand how changes in the timing or form of precipitation will alter a given freshwater ecosystem. This sample hydrograph shows that even small shifts in precipitation timing can lead to very significant shifts in flow regime.

# PART A:
# Relative vulnerabilities: Developing contrasts

**Residence time:** Old water versus new water.
Most freshwater ultimately derives from precipitation, but systems vary substantially in the residence time of their waters. The Pantanal in South America and the Okavango delta in southern Africa, for instance, are both massive wetlands that receive pulses of water from direct, local/regional and highly seasonal precipitation ("new water"), but they are sustained through their respective dry seasons by the large reservoirs of groundwater that build up during the wet season ("old water," which fell weeks or months earlier). Indeed, groundwater is a critical source of water for humans in many regions globally, though the residence time – the effective age of the groundwater reflecting its recharge rate – is not well understood in most regions. This gap in knowledge could become an acute problem in groundwater-dependent areas with relatively short residence times or increasing large water demand.

In any case, systems fed by snowpack and groundwater should be fairly stable even if there are shifts in the timing of spring melts or monsoon seasonality compared to systems that depend primarily on new water, particularly in arid and semi-arid regions. Climate-sensitive systems will respond very rapidly to even small shifts in the timing, amount, intensity, and form of precipitation. Large lakes may also experience changes in water levels as a result of even slight shifts in the relative timing and balance between precipitation and evaporation.

# PART B:
# Principles and priorities

PART B:

# How can you think about what you can do?

The freshwater impacts of anthropogenic climate change will not be globally uniform or even universally negative; there will be winners and losers. Even when focusing on adverse effects, differences in vulnerability and the ability to respond to negative shifts require careful thought about how to plan and prioritise action. In this section, we discuss the special issues that apply to climate shifts on freshwater ecosystems and suggest the best means to start adapting to climate shifts.

Are there qualities about climate change impacts on freshwater that are special or unique relative to other types of ecosystems? Do the impacts on freshwater ecosystems require us to think in a way that is different than we might for marine or terrestrial ecosystems? We believe there are three aspects about freshwater climate change that are critical to keep in mind.

1. The aspects of climate change that most impact freshwater are associated with high uncertainty. The confidence surrounding predictions for air temperature has proven to be relatively high compared to many other climate variables. The historic precipitation record has large gaps, but has slowly come into better focus. On the other hand, the precipitation components of the circulation models that climate scientists use to predict future climate show much lower levels of confidence. Often, the strongest statements we can make about future climate relate to simple consistencies among the models themselves, such as, "Over the coming two decades, more than half of the models suggest we can expect more winter precipitation than currently." Worse, many circulation models do not have fine temporal or spatial resolution. There may be very little certainty about mid-March climate in a particular place in 10, 25, or 50 years.

   Finally, the extent and renewal processes of many natural "reservoirs" of water such as groundwater and snowpack present very large uncertainties. Groundwater recharge rates and capacities are often unknown and demands on them are poorly regulated; the temperature uncertainties that determine whether winter precipitation falls as snow or as rain are quite high; and there are immense difficulties in assessing whether accumulated snowpack or glaciers will dissipate through melting (as liquid water) or sublimate or evaporate directly into the air as water vapour. Some improvement can be expected in modelling capacity in coming years, but we are likely to always have lower confidence around the variables most important to freshwater. Managing under uncertainty is a defining characteristic of adaptation in freshwater.

**2.** Freshwater rarely exists in a human-free vacuum: Human settlements have often been located near freshwater resources, and people have been modifying, developing, and exploiting those resources for a very long time. There are regions (the Nile in Africa, the Tigris-Euphrates in greater Mesopotamia, Yemen, Asia Minor, and the Tibetan plateau rivers such as the Ganges, Mekong, and Yangtze) that have been embedded in a matrix of intense human use for millennia. Recent evidence suggests that some wetlands in eastern China were first altered for agriculture some 8,000 years ago. Definitions of use vary widely as well: an ecologist's aquatic macroinvertebrate community is a rancher's cattle tank. Thus, few bodies of water can be considered "pristine" or wild, and efforts to assist these ecosystems with the process of climate adaptation need to consider human and ecological communities together.

**3.** Freshwater ecosystems do not "end" at the water's edge: Many of the basic nutrients that determine the ecological health of freshwater ecosystems come from outside of freshwater systems – migratory salmon bring nitrogen from the open oceans to rivers and forests far inland, watershed runoff and groundwater discharges to rivers and lakes sustain their natural budgets of dissolved minerals, and the steady rain of leaves and branches from riparian vegetation provide much of the organic carbon in lakes and rivers. Even in relatively wet regions, surface water is a rich confluence between terrestrial and aquatic organisms. So changes that happen beyond the boundaries of the aquatic zone can have profound effects on freshwater ecosystems and vice versa.

PART B:

# What is climate adaptation?

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The Roman god Janus with his future- and past-oriented faces is a good analogy for how we should begin to incorporate climate trends into water resource management: aware of past impacts and ecosystem health, but not using the past as a deterministic guide for the future and the new climate regimes it contains.

There is a widespread concern among conservation and development professionals that climate adaptation represents such a fundamentally new way of envisioning our work that a complete shift in worldview is necessary. Is our toolkit for managing water infrastructure and aquatic species irrelevant? We believe that the overwhelming majority of the current theory and practice of conservation and development remains both relevant and useful and that the past is a helpful but not unerring guide to the future. We must maintain a mindfulness of climate uncertainty.

The Roman god Janus had a single head with two faces: one face saw the past and another looked to the future. Like Janus, we believe that water resource managers must be mindful and aware of climate history, but we must also look forward into the future to a new, uncertain, and shifting climate. We must accept that our knowledge of water resources captures only a particular moment in climate history. As a result, we must be humble about our ability to predict the future and thus become cautious in our management of resources for coming decades. Indeed, some of the most significant catastrophes surrounding water may derive from making important decisions reactively or under pressure, without time to reflect on the adaptive and maladaptive implications of those decisions for future resource managers.

Climate change by itself is nothing new; the earth's climate has passed through major shifts many thousands of times in the past. This period of climate change is not even the first climate shift humans have gone through, much less the majority of extant species. The most recent glacial period, for instance, ended only 12,000 years ago, and there have been significant global episodes of warming and cooling since then as well, long before the industrial age of human society. Under historically normal circumstances, species can adapt to shifts in climate, given sufficient time. The two most widely observed responses in wild species are range shifts (where you find a species and in what abundance) and phenological shifts (when or how fast a behaviour occurs, like migration, breeding, the rate of development, and so on). These two responses parallel human responses to climate and weather as well – a warmer climate might mean a longer growing season, with a farmer changing the selection of crops to varieties that are associated with a warmer, drier, or wetter climate (a range shift) or altering the agricultural calendar (phenological shifts).

# PART B:
## What is climate adaptation?

Many observers have argued that our current shift in climate is a threat to livelihoods, economies, and species because the rate of change in the climate is so rapid. By the standards of significant shifts in climate regime over the past few million years, however, this view is incorrect. Some glacial-interglacial transitions occurred over only a few decades. Instead, our current period of climate change is notably different from previous periods for three important reasons.

First, human-source greenhouse gas emissions are the primary forcing agents of global shifts. Second, humans have altered the landscape substantially by moving other species around (facilitating species invasions), fragmenting habitats, reducing environmental quality through pollution, overharvesting wild species, and so on. Very significantly, we've built a lot of "hard" infrastructure for water management, such as dams, wells, wastewater treatment plants, and irrigation systems. This infrastructure has often profoundly altered the aquatic landscape – including posing barriers that may prevent species from shifting their ranges – and it was typically built (and is managed) with many tacit assumptions about climate stability and stationarity. Third, the current level of warming has not been seen for many hundreds of thousands of years and, most likely, several million years. Thus, many extant species have no ecological or genetic experience with emerging climatic conditions.

The cumulative effect of these three factors is that natural and automatic climate adaptation is now more difficult than during previous climate shifts. We have reduced the ability of most organisms to easily respond to climate change. In many cases, we have instead created conditions that will result in less successful adaptation or even maladaptive and detrimental impacts on us and other species. The implications of exposing species to completely novel climate regimes cannot be determined. Of course, human societies are far more complex than 12,000 years ago, but this complexity may itself lead to both difficulties and opportunities in adapting to major climate shifts.

Given the high levels of uncertainty around freshwater resources and the amount of physical infrastructure built around certain ways of organising ourselves, we must be both socially and ecologically adaptive. That is, we must become capable of reorganising ourselves to meet new challenges and opportunities. Low-lying areas and estuaries, for instance, are likely to see significant sea-level rise, potentially inundating large cities and other settled areas. Many people will be on the move – a human range shift, in effect. And we must be able to re-absorb these people in new capacities and roles even when they cross ecological and national boundaries.

Moreover, when human populations remain physically in place, changes in behaviour are likely to be necessary. For instance, if precipitation trends show a decline, farmers should plant crops that are less water intensive or that can be irrigated more efficiently. Urban and industrial water consumption may need to be reduced.

Climate change, especially the impacts on freshwater ecosystems, is associated with medium to high levels of uncertainty. Projections and modelling may only justify low confidence in predicted impacts, so institutions that govern water usage and management should focus on the process of decision making as an adaptation process in itself. For instance, the southwestern USA and northern Mexico are projected to become much drier than the recent past, while the northeastern USA and southeastern Canada are projected to become much wetter. There are no high-confidence projections on where the line between reduced and increased precipitation will fall, so institutions that manage water across a broad swath of the central USA should manage their water resources as if they expect both more and less water, as well as institute a process of "updating" their institutions with the latest regional climate science. To view the situation from a slightly different perspective, their climate adaptation strategy should be to not rule out a range of adaptation scenarios until climate trends become clearer and more certain. This flexibility and ability to respond is at the core of climate adaptation.



**Climate impacts on freshwater species are complex, multifaceted, and difficult to predict. Salmonids in western North America appear to be shifting their ranges between basins (moving from one river system to another) and within basins (from warmer downstream regions to cooler high-elevation tributaries). These responses may be direct physiological shifts (individual fish avoiding higher temperatures), indirect responses (fish are tracking range shifts in competing, predatory, and prey species), or some combination of these factors. In migratory organisms such as salmon, the timing of migration itself may also be changing, representing a phenological response to climate change.**

PART B:

# What isn't climate adaptation?

There are two risky aspects of not adapting effectively. First is the risk of simple ignorance – of not asking if our policies and actions will continue to be relevant and effective given what is happening and what is likely to happen.

We are now living in a period in which (for most regions of the world) the realised impacts of climate change are relatively small compared to the potential and predicted impacts for the rest of the century and beyond. Thus, we have hints of the shape of things to come as well as some modelling that provides estimates of upper and lower bounds for a series of new climates we will be passing through. Even given the levels of uncertainty associated with an assessment of future impacts, we often have some means of sorting relative likelihoods. Thus, we should enable an ongoing process of considering the climate relevance of our behaviour and plans.

The second risk of not adapting well is potentially more serious: the threat that our actions will be maladaptive and will significantly constrain our options in the future. Because the climate will be changing for decades even under our best attempts to control greenhouse gas emissions, some of our actions now may actually limit our ability to adapt to future climate conditions. For example, some communities or nations may respond to more frequent floods by building dykes that channelise rivers or by designing high-capacity stormwater systems to reduce threats in urban areas. Without careful consideration, these responses may only transfer the problem of extreme precipitation events downstream and reduce water quality for people and species. Investing in increased water storage volume may encourage societies to become profligate in water use exactly at the time that they need to adapt to greater variability in water supply. And investments in large "hard" infrastructure projects to address changes in flooding patterns or water supply may be far less cost-effective than finding ways to work with natural systems ("soft" infrastructure) or demand reduction to achieve the same benefits.

The Colorado River has been a source of contentious regional an international water management for over a century, but to date the arrangements assembled to allocate water within the USA and between the USA and Mexico have largely ignored the climate-driven shifts in the eco-hydrology of the Colorado River basin.



## The Colorado River Compact: Long-term planning gone awry?

The Colorado River of the arid southwestern USA has been a major source of water across a vast region. The first river Compact was negotiated in 1922 and allocated water resources based on only a few decades of flow and precipitation data. It also reflected an era of planning that assumed that water that actually reached the estuary and ocean had been "wasted," lost from the growing cities of the region and the rapid growth of highly profitable agriculture irrigating a desert.

Although there were many inequities in the original Compact, and the climate history determining acceptable flows was based on flawed and limited data, the Compact served more or less intact until the negotiation of a new interim agreement in December 2007 intended to serve until 2026. The negotiators of this Compact faced a very different set of needs and demands across the region from the previous century, but climate models of changing water availability and timing were not included, presumably because they were associated with high uncertainty and presented difficult choices. Instead, they focused their efforts only on updating the recent climate history and flow record for the Colorado.

The most up to date climate models show that this region is very likely to enter a period of severe drought not seen for many centuries (nor reflected in existing hydrological data). The new Compact may already be irrelevant and maladaptive, endangered by the threats of serious drought leading to stakeholder lawsuits, interstate conflict, and the need to develop a third climate-aware compact soon.

PART B:

# Identifying vulnerability and embracing uncertainty

Many efforts to develop a climate adaptation strategy focus on assessing the eco-hydrological and economic sensitivity and vulnerability of a given system to shifts in climate. Much technical attention focuses on identifying ecosystem-level responses to specific climate elements, such as a drop in late-summer precipitation or a rise in minimum winter temperatures. As a result, most vulnerability assessments are categorized as identifying specific climate shifts and developing system responses.

There is something to be said for the usefulness of this approach. Given sufficient financial and scientific resources, a formal vulnerability assessment of potential and realised impacts on a system of interest that summarises the state of knowledge at a given time. Formal assessments have the advantage that they can focus on specific issues, can quantify (or least bound) the levels of climate uncertainty and confidence, and can be updated and re-evaluated as more knowledge becomes available. They should become an important instrument of planning and encapsulate the best available data. Ideally, they should also identify climate opportunities as well as risks, distinguish between potential and realised impacts, and identify where climate adaptation is already occurring for ecosystems, species, societies, and economies.

However, an approach that emphasizes the deterministic application of physical and ecological modeling alone may limit the "problem" of anthropogenic climate change to simply developing a list of impacts and responses – what may be called "impacts thinking". We advocate a contrasting process-oriented approach – "vulnerability thinking" – that promotes flexibility, long-term planning and monitoring, and adaptive management.

Climate shifts already have been or will soon be significant enough to warrant a reconsideration of how most human institutions function in relation to the ecosystems in which they are embedded. The ability of these institutions to respond successfully will determine the extent to which climate change does or does not have damaging social and ecological impacts. Many current vulnerability assessments do not focus on this. Given that the confidence in specific shifts occurring in a particular place by a particular time period is generally low, the physical and ecological modeling approach may lead to a false confidence in the set of potential impacts and responses. In truth, a comprehensive impacts assessment may be able to reduce the uncertainty around evapotranspiration rates or the frequency of extreme weather events, but it will not often be able to provide a single clear set of management recommendations. This is the uncertainty gap.

We believe that a freshwater vulnerability assessment needs to embrace two related elements at its core that supplement physical and ecological modeling. Firstly, it must embrace uncertainty in moving towards recommended responses. This may require an approach that considers future uncertainty through the development of emerging climate stories with contrasting qualitative qualities rather than quantitative, deterministic, and assiduously downscaled scenarios. Secondly, it must assess the resilience of both ecological and institutional systems. It is this resilience that will ultimately determine how well systems are able to respond, and where impacts will occur: in other words, where there is vulnerability.

Vulnerability assessment should become a continuous, normal process rather than a single episodic event. Thus, one of the outcomes of assessing vulnerability should be an emphasis on developing institutional processes and methods to (a) reduce the areas of uncertainties uncovered by a vulnerability assessment, and (b) identifying gaps within the institution itself that inhibit climate-aware flexibility. By embracing uncertainty in climate projections, we can alter our water management institutions in order to resolve those uncertainties. These two tasks are the core of 'adaptation thinking' as an extension of 'impacts thinking'.

### How should we prioritize impacts by relative certainty?

Concepts of vulnerability should be informally incorporated into all aspects of water resource planning even in the absence of a formal vulnerability assessment. An effective schema for capturing the state of knowledge and degree of uncertainty is through a series of focus questions:

**What do we know is happening to the system in question already?** For instance, a historic trend analysis over recent decades may reveal that peak river flows are declining in height and occurring earlier in spring. This is a known, verifiable impact. At the same time, we might also know that infrastructure development has had a significant impact on the connectivity of wild species and a concomitant reduction in livelihood activities oriented towards fishing.

**What do we know will happen to the system?** Rising temperatures will accelerate and further alter spring flow regime. Higher temperatures will also increase the water demands of existing crops and, coupled with further urban development, increase demands on freshwater systems.

**What do we think with reasonable confidence is going to happen?** Precipitation patterns are likely to shift; lower low flows may lead to hyper-eutrophic conditions, significantly increasing water treatment costs. Developing scenarios of potential suites of impacts, even unlikely but catastrophic ones, can be useful for this set of issues. For instance, most climate models project gradual, persistent shifts in climate, but the climate record suggests that many large regime changes occur in a stepwise matter – periods of relative stability separated by a rapid transition. Sudden state-level change occurring over a period of one or two decades would present quite a different type of change from gradual, slow shifts.

# PART C:
# What can you do in response to climate change?

# PART C:
## What can you do in response to climate change?

We have two very general suggestions for supporting climate adaptation initiatives. The first should apply even if no other action is taken: support climate mitigation efforts to reduce the rate of emissions of greenhouse gases. This suggestion simply reflects the need to reduce the rate of climate change to give species and human societies more time to adapt. However, the earth is now committed to changes in the climate for decades to come even if all greenhouse gas emissions were to cease immediately. Ideally, then, we must consider more specific climate adaptation policies.

The second general climate adaptation suggestion is to maintain flexibility in order to avoid prematurely limiting future actions. In practice, this is a difficult rule to follow; sometimes decisions are forced and time-sensitive, or other priorities supersede adaptive strategies. In truth, rarely are decisions in development and conservation made with high confidence and perfect knowledge under any circumstances. However, flexibility implies that water management systems contain redundancies; that institutions are capable of monitoring important ecosystem and social indicator variables; that institutions can learn and adjust their policies in response to new information; and that decision-making is both decentralised (occurring at scales that are relevant to microclimate conditions) and coordinated (so that one region of a basin is not working against another).

This second suggestion underlies many of the eight elements of freshwater climate adaptation that follow. This list of recommendations is certainly not comprehensive, and not all elements will apply in every case. There are also important interactions between the different elements. But they should serve to describe in a general way how freshwater climate adaptation is both similar to and differs from both current water management approaches and adaptation in other biomes.

### 1. Develop institutional capacity

The development of strong institutional capacity should be regarded as the single most important task in facilitating successful adaptation to climate change in freshwater. The actions required to successfully adapt to climate impacts on freshwater systems depend on the existence of adequate institutional capacity. The functions that will be required of water management institutions include the control and monitoring of legal and illegal water use, the monitoring and assessment of ongoing physical and biophysical changes in freshwater systems, the control and enforcement of pollution prevention, and the regulation of water infrastructure development and operation.

None of these tasks is straightforward, and each requires significant technical, financial, and social capacities at different scales, from strong and well-governed national water ministries, through regional departments and basin councils, to local river basin offices and water user associations. In all of these cases, these institutions need to discharge their functions independently and in the absence of undue interference, corruption, or local capture. Clearly, effective governance is an underlying theme in developing capacity.

The contemporary reality is very far from this. In the vast majority of the world, water management institutions are weak, under-resourced, and subject to influence by powerful vested interests. Unless and until significantly more resources are devoted to the development and support of strong water management institutions, considered and controlled adaptation to climate change will be difficult at best.

### 2. Create flexible allocation systems and agreements

The most profound impacts of climate change on freshwater will be through changes in precipitation. In many cases, this will reduce the amount of water available, either in total across the year or at particular critical periods. If ecosystems and important social and economic water uses are to be protected, it is necessary for patterns of water use to adapt to any such annual or seasonal changes in water availability.

In all but the rarest circumstances, water use globally is governed by allocation or water rights systems that govern who is allowed to take water from a system, when, and in what quantities. An allocation system therefore either explicitly or implicitly determines how much water is or is not retained for ecosystems. Allocation systems can take many forms, including formal systems based on national water laws, informal and traditional systems, or a combination of these types.[9] The type of allocation system, and in particular whether it is flexible enough to be able to respond to changes in water availability, will be central to expressing societal responses to climate change.

Many allocation systems already have mechanisms for coping with existing levels of variability in water availability. For example, differing water users and water uses can be recognised as holding distinct priorities: when water availability is reduced, then water use by lower priority users is curtailed to protect higher priority uses. In an ideal situation, basic social and environmental needs for water will be of the highest priority, followed by essential economic activities (for example, cooling water for power stations). Mechanisms should also be in place to allow the remaining water to be allocated or reallocated for appropriate economic activities. The presence of a water allocation system that protects essential environmental flows and social needs while permitting flexibility in economic use of water helps to respond to climate-driven changes in water availability. In many cases, the expectations for water availability must themselves be flexible, whether on a seasonal (dry season versus wet season) or on an episodic basis (mean conditions versus droughts).

In reality, flexible systems exist in few places at the moment. More often, under conditions of water scarcity, water is allocated not to social and environmental priorities but rather to a particular sub-set of water users who may, for example, hold the longest standing water rights, as is the case in parts of the USA. In many contexts, water is simply allocated – legally or illegally – to the most politically powerful groups, or appropriated by upstream over downstream users.

Similar issues apply to water treaties between provinces, states, or nations. Typically, such treaties allocate water between basins based on assumptions of water availability drawn from historical precipitation patterns. If the amount of water available changes while the provisions of treaties remain fixed, this may lead to over-withdrawals of water impacting on ecosystems or social water needs. In some cases, political unrest and conflict may even result.

9 Le Quesne T., et al. 2007. *Allocating scarce water: A primer on water allocation, water rights and water markets.* WWF-UK, Godalming, UK.

### 3. Reduce external non-climate pressures

Freshwater ecosystems and species have long faced serious threats that are unrelated to anthropogenic climate change, such as water pollution, exotic invasive species, overfishing, and negative impacts from land-use shifts such as clearcutting riparian forests. The presence of so many nonclimate pressures is one of the most novel components of this era of climate change. Past climate shifts did not coincide with such threats (and certainly not all of them at once), and these external pressures reduce the natural adaptive capacity of wild and human systems. In many cases, we believe that reducing non-climate pressures means doing what we already know we must and should be doing, but with more urgency and efficacy.

For instance, nutrient pollution is a problem worldwide. Many freshwater ecosystems have historically been limited in their "productivity" (the abundance and mass of organisms living in these systems) by scarce nutrients. For algae and plants, nutrients such as phosphorous and nitrogen have limited their relative biomass. These "oligotrophic" systems typically have clear water in contrast to "eutrophic" systems that tend to have a high abundance of plants and algae, which can even choke out other types of organisms and alter the whole biogeochemistry of the water body.

For most human purposes, eutrophic conditions are associated with low water quality. With the advent of cheap chemical fertilisers and the large concentration of humans (and their sewage) near freshwater ecosystems, however, many oligotrophic systems enter eutrophic conditions more frequently and longer than in the past. Warmer air and water temperatures exacerbate the problem. Damage to ecosystems occurs precisely because of the combined effects of pollution and changing water temperatures. Management of agricultural runoff and effective sewage treatment can help reduce concentrated nutrient inflows and improve water quality substantially, increasing climate-adaptive capacity for these ecosystems.

## 4. Help species, human communities, and economies move their ranges

For most species, exploiting landscape connectivity via range shifts is a critical strategy in responding to climate change. For instance, a particular species may breed in very specific areas that may be unpolluted and retain good habitat quality. With changing temperature and precipitation regimes, however, that species may be forced to move to higher, cooler altitudes, or downstream if headwaters become more ephemeral. Thinking of connectivity in climate-aware terms requires ensuring that whole components of a system are relatively unpolluted and do not have significant physical barriers to movement. These movements may be made by individuals (within-generation movements), for example moving to cooler portions of the same water body such as deeper water, or moving upstream towards headwaters. Or they may occur over the lifetime of several individuals (trans-generational movements), such as through the process of colonising new aquatic habitats.

Humans too responded to past climate shifts by altering where activities occurred – such as fishers shifting to larger, more permanent bodies of water with increasingly reliable fish stocks. In some cases, policymakers and resource managers may need to work with local communities or livelihood groups to extend their adaptive capacity by assisting with the process of altering the ranges or timings of their behaviours.

## 5. Think carefully about water infrastructure development and management

New irrigation, hydropower, or flood control measures that are designed on the basis of recent climate history and the assumption that a given hydrological system is "stationary" may not deliver the expected services over their lifetime. Uncertainty about future hydrology, a key parameter of infrastructure feasibility, is emerging as a great challenge in infrastructure planning and engineering. Current flows in a river may be much larger than the future average, for example, as extreme precipitation events increase in frequency, threatening the very safety of the structure. Or they may decline and collapse as snowpack and glaciers in a headwaters region sublimate to the atmosphere instead of melting into the basin. A hydropower station based on the past century's record of flows may soon be over or under-designed.

By building the "wrong" structures now or by not modifying existing structures, we may actually limit our future options for climate adaptation. Planners need to think both about how climate change will shape the "supply" of water in terms of future river flows (and shifts in their mean and variability) as well as the demand for water services. Can energy demands be reduced through increased efficiency rather than increased generation? Can crop selection be shifted to less thirsty varieties? Some climate impacts may not be direct or intuitive. For instance, upstream agricultural areas may need to abstract more water to cope with increased evapotranspiration, which means that this water is not available for downstream dams. Indeed, evaporation from reservoir surfaces already consumes some 10–20% of total runoff in many arid basins such as the Nile, Colorado and Zambezi, and will almost certainly increase further. By creating an apparent increase in security of supply, increased infrastructure may result in increased water-consuming activities, making societies more vulnerable to future hydrological variabillity, not less.

Ideally, water infrastructure should become a tool in facilitating adaptation for both wild species and human communities. Water infrastructure and its management must be considered strategically, over climate-relevant temporal and whole-basin spatial scales. Considering the size of the financial investments embodied in large infrastructure development, the negative impacts on ecosystems and local communities often associated with that development, and the climate uncertainties that challenge designers, planners would do well to make conservative estimates of supply and aggressive estimates of demands.

### 6. Institute sustainable flood management policies

Climate change is likely to result in an increase in extreme weather events. In many parts of the world, this is likely to result in an increase in flood risk. In the context of changing precipitation patterns, the construction of hard engineering defences alone is likely to be insufficient, and may on occasion exacerbate the problem: there is an increasing risk that defences based on historic precipitation patterns will be overwhelmed, leading to very significant damage.

Sustainable flood management takes an integrated approach. It looks to reduce flood risk by understanding how floods move through catchments, developing risk reduction strategies that include schemes to retain water on uplands, and using floodplains and washlands to alleviate flood peaks. Alongside these measures, sustainable flood management looks to ensure that human communities are as resilient as possible to flood risk, such as avoiding the location of new development in high flood risk areas and ensuring that any vulnerable communities are able to recover from flooding events.

### 7. Support climate-aware government and development planning

Many government economic and social planning decisions include assumptions about future availability of water. Most significantly, agricultural development strategies presuppose particularly water availability or climatic conditions. Similarly, the development of industrial locations and plans for future growth in urban centres depend on assumptions about the availability of water, whether in an absolute annual-scale level of availability, the availability of water during certain seasons, or the frequency of flooding and droughts as climate variability increases. If assessments of changing water availability are not taken into account in this planning, there are very serious risks of significant adverse social and economic consequences if insufficient water is available to support the intended social or economic activity.

### 8. Improve monitoring and responsiveness capacity

Vulnerability assessments ideally capture the most accurate state of knowledge of realized and potential climate change impacts on a human or natural system of interest. Ideally, these assessments also state the limits of that knowledge and point out where uncertainty remains. A key implication behind such "bounded uncertainty" is developing institutional processes to detect trends, encompass areas of limited knowledge, and determine appropriate institutional responses. Ideally, these mechanisms mean that assessing vulnerability and rapidly distributing that knowledge becomes embodied within planning and management institutions as a normal, everyday process.

In practical terms, improving monitoring means identifying hydrological, ecological, and/or social variables that can serve as early-warning indicators of shifts in important traits in system of interest. These changes may be short-term impacts such as droughts, or they may be more complex, such as a shift in the mean number of heat-stress days for an endangered coldwater fish species. Certain flow rates or key species densities may be triggers that lead to direct intervention or changes in planning or design policies, such as the need to revisit a basin-wide environmental flows assessment process. Scenario planning for responses to high-stress situations such as sudden flood events before they occur is also critical, so that sound reactions can be developed and negotiated with minimal conflict.

# Further reading

Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp.

This volume represents the state of IPCC findings on climate impacts as of 2007 and is quite comprehensive in its discussion of cross-cutting and regional issues regarding climate impacts. Adaptation strategy is less well covered. While one chapter focuses on freshwater resources (updated below), many sections are directly relevant to freshwater ecosystems and resource management. This volume is far superior to the *Summary for Policymakers* that is more generally referenced.
http://www.ipcc.ch/ipccreports/ar4-wg2.htm)

Intergovernmental Panel on Climate Change. 2008. *Climate Change and Water.* Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds. Technical Paper IV of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210pp.

This document, published in mid 2008, is a significantly updated and more detailed version of the 2007 freshwater resources chapter from Working Group 2.
http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf

Stern, N.H. 2007. *The Economics of Climate Change: The Stern Review.* 2007. Cambridge University Press, Cambridge, UK. 692pp.

The Stern Review represents one of the most creditable and widely respected attempts to date to quantify economic impacts of current and projected climate change impacts.
http://www.dcc.gov.uk/activities/stern.htm

Hansen, L.J., J.L. Biringer, and J.R. Hoffman. 2003. *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.* Island Press: Washington, DC.

*Buying Time* was the first book-length treatment to move beyond climate impacts to develop strategies for assessing vulnerability and implementing a climate adaptation plan. It remains an important core reading.
http://assets.panda.org/downloads/buyingtime_unfe.pdf

The Cooperative Program on Water and Climate has an excellent set of water-related resources, including its own publications as well as links to those produced by other organisations. The latter section is annotated and updated regularly.
http://www.waterandclimate.org/index.php

# WWF's Freshwater Programme in numbers

100% RECYCLED

## 10

WWF is one of 10 organisations which has established the Alliance for Water Stewardship to establish an international certification programme for water managers and users

## 35%

the Freshwater Living Planet Index (a global measure of more than 700 vertebrate animals) declined by 35% between 1970 and 2007

## 100 MILLION

WWF has helped establish over 100 million hectares of freshwater protected areas in the last 10 years

## 12

our global freshwater priorities are the rivers and lakes in 12 critical places across 5 continents

**Why we are here**
To stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature.

wwf.org.uk

HSBC
The world's local bank

The HSBC Climate Partnership is a 5 year global partnership between HSBC, The Climate Group, Earthwatch Institute, The Smithsonian Tropical Research Institute and WWF to reduce the impacts of climate change for people, forests, water and cities. For more information visit **hsbc.com/climatepartnership**