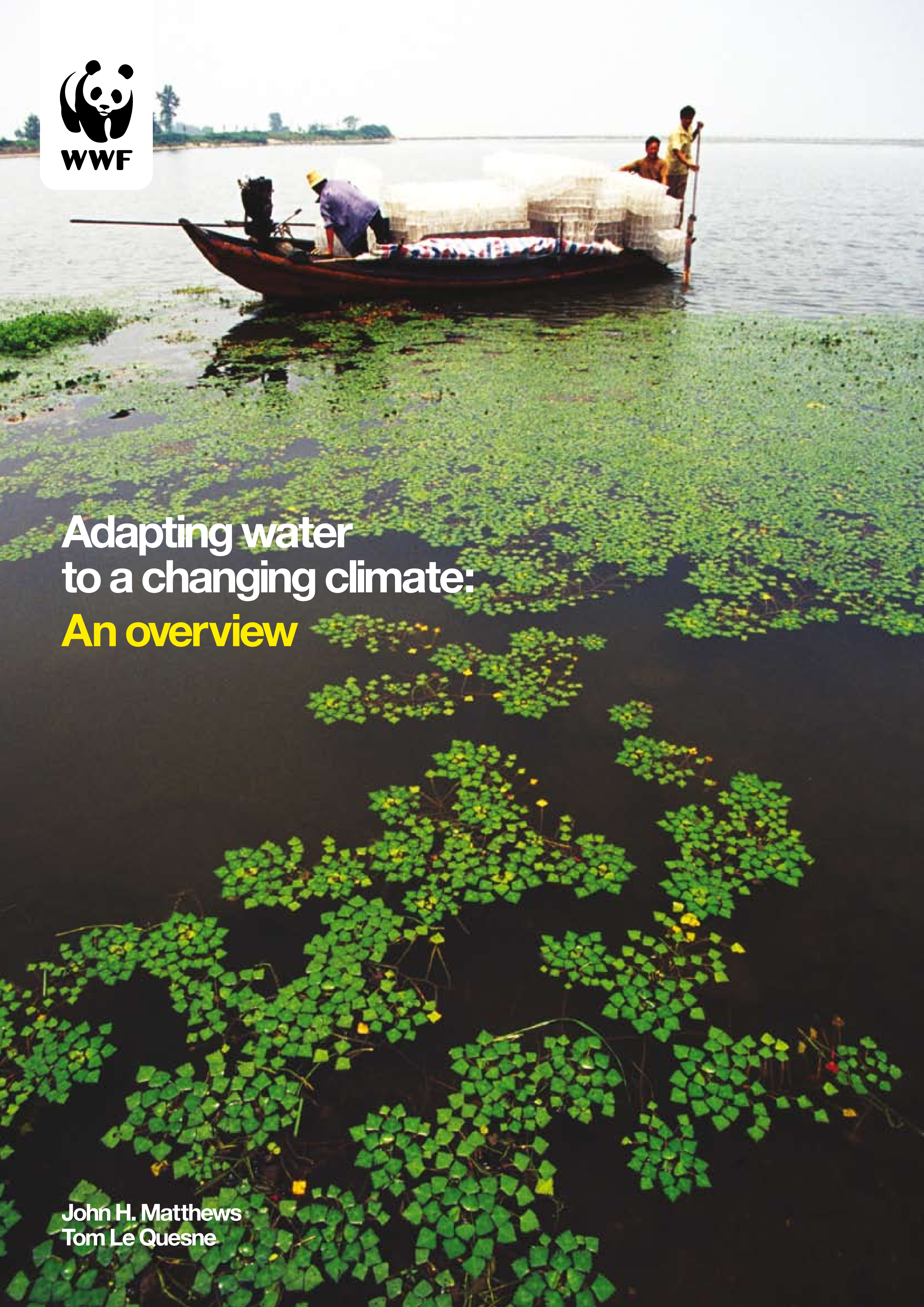

Adapting water to a changing climate: An overview

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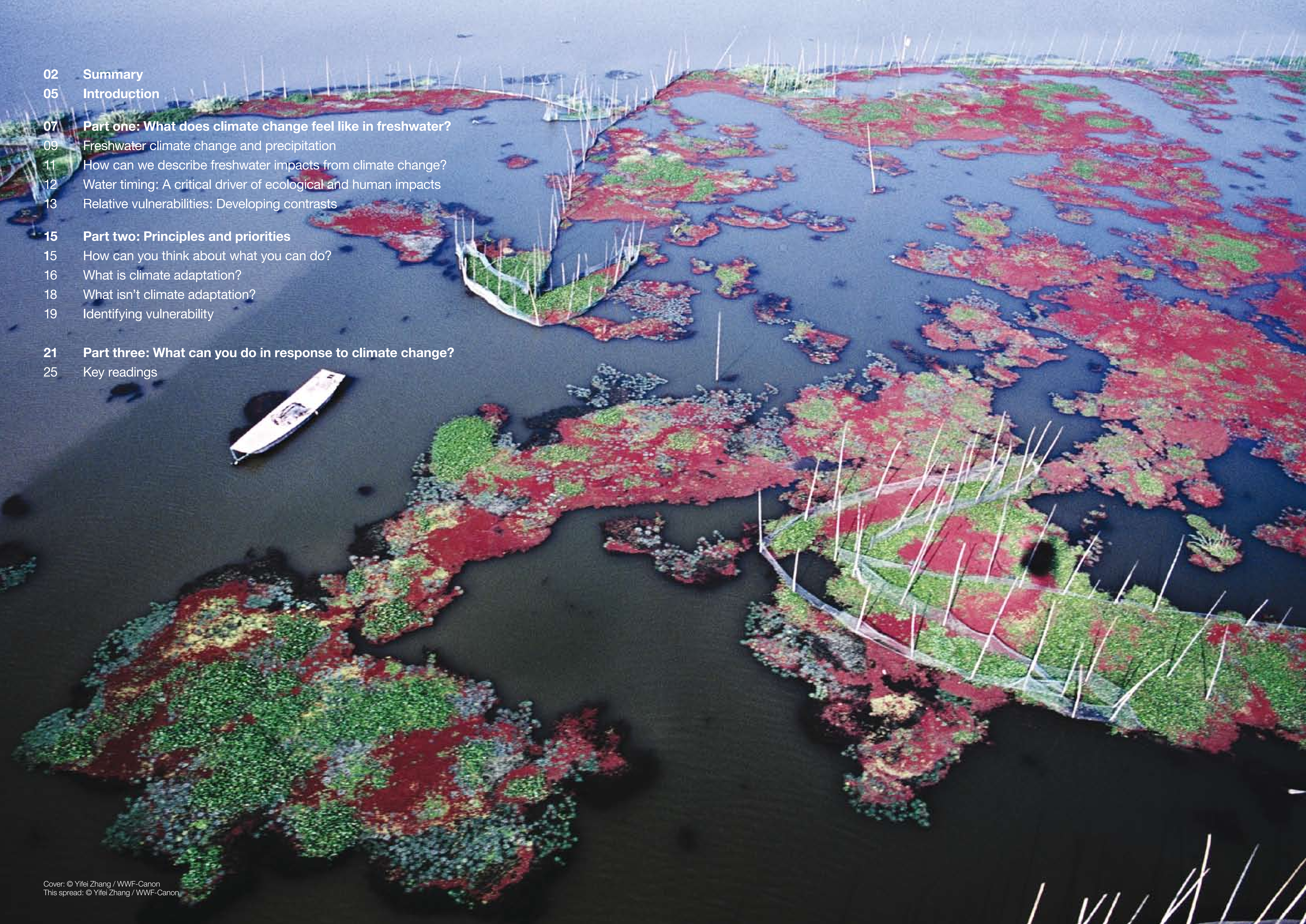

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SUMMARY

Withdrawals of water, construction of dams and other infrastructure, pollution, land-use shifts, invasive species, and habitat modification and destruction have altered and degraded many rivers, lakes, and wetlands over the past century. In recent decades, however, anthropogenic climate change has also begun to alter freshwater ecosystems, and this force will strengthen for many decades.

For freshwater ecosystems, trends in precipitation patterns will be a far more important aspect of climate change than air temperature. Climate change may occur:

- 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 climate "plateau" is followed by a period of rapid change before leading to some new plateau.

All three patterns have been seen in recent decades.

Climate impacts on lakes, wetlands, and rivers differ fundamentally from climate 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 the encompassing terrestrial 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 uncertainty.

However, uncertainty should not be an excuse for inaction. Impacts of climate change on freshwater ecosystems can be characterised by shifts in water quality, water quantity and water timing. Globally, water timing is likely to be the most important type of impact for both humans and other species since it affects both water quantity and quality. However, it is also the most difficult variable for models to predict with high confidence. As a result, water policy should not be focused only on data described at the annual level but also on a seasonal or monthly resolution, and should account for fundamental uncertainty.

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 types and rate of climate change. Thus, vulnerability to significant hydrological impacts should be carefully assessed, as well as the adaptation potential of the human and natural systems dependent on a particular set of hydrological conditions. Existing water infrastructure should be carefully managed to facilitate social and ecological adaptation.

Developing a climate adaptation strategy 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 stance of institutional learning and flexibility in the face of climate uncertainty. We propose seven elements of an adaptive water strategy:

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.
2. **Create flexible allocation systems and agreements:** Allocation and water rights systems are required that can protect social, environmental, 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 already experiencing stress. 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 systems, and within them 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.
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 appropriate risk reduction strategies.
7. **Support climate-aware government and development planning:** Many government economic and social planning decisions include assumptions about the future availability of water, and these decisions must take into account potential climate shifts if significant social and economic risks are to be avoided.

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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 is found — liquid, frozen, or vapour. Before our eyes, climate change is creating freshwater winners and losers among individuals, economies, whole societies, and of course ecosystems and species.

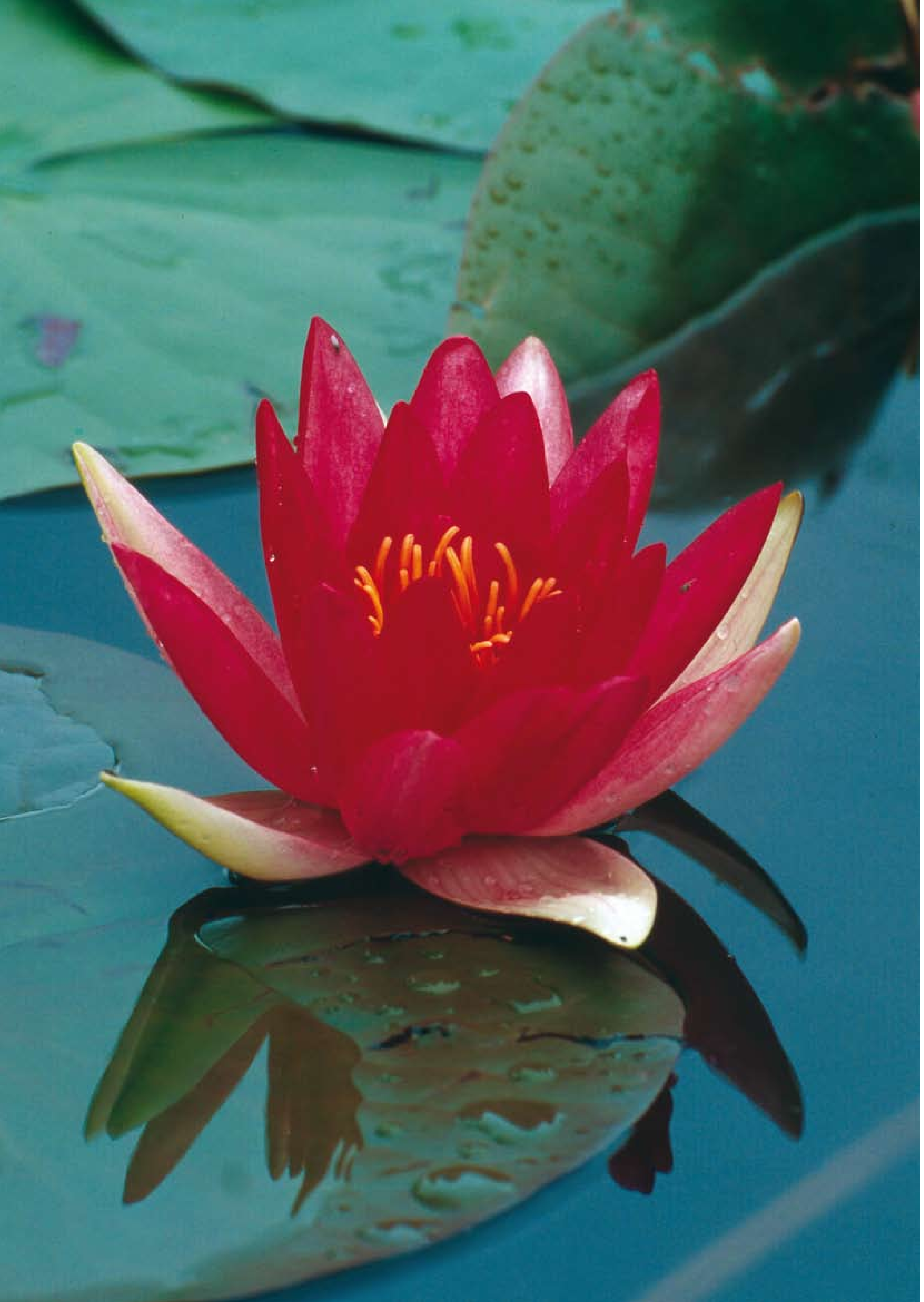
Water management of large bodies of water has been one of the great themes of the nineteenth and twentieth centuries worldwide, and many of the largest construction projects in human history have been attempts to consume, control, allocate, and regulate water, including the construction of tens of thousands of dams and components of irrigation infrastructure. However, extensive industrial and agricultural pollution and the conversion of wetlands to "productive" land have had dire impacts on the many aquatic and terrestrial species that rely on freshwater resources. One study of 344 freshwater temperate and tropical species suggested population declines of about 30% between 1970 and 2003 alone[1]. Freshwater ecosystems now see species extinction rates comparable to tropical rainforests[2].

Climate adaptation is the process of adjusting to novel climate regimes, such as reducing water consumption to compensate for reduced precipitation rates, shifting the location of an industry away from an increasingly drought-prone area to a region that will be receiving higher flows, or altering urban stream morphology to allow for larger and more frequent floods. Perhaps the greatest threat from climate change on freshwater ecosystems is the interaction between relatively "traditional" problems such as overabstraction or habitat fragmentation combined with climate-driven shifts. WWF is committed to the concept of flexibility as a response in itself to climate change: while we often have 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, and so we must develop resilience to negative climate impacts such as extreme weather events. In other cases, there may even be limits to adaptation and resilience that forces very difficult choices upon us.

This guide is intended as a primer of some of the basic issues surrounding freshwater from a climate change perspective, as well as a set of policy and resource management recommendations where the issues suggest a position that WWF would anticipate taking on key topics.

[1] WWF, 2006. *Living Planet Report 2006.* WWF International, Gland, Switzerland, 44pp.

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



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PART ONE: WHAT DOES CLIMATE CHANGE FEEL LIKE IN FRESHWATER?

Much of the journalism about anthropogenic climate change describes impacts that are difficult to imagine: statements describing an increase of some amount in global mean annual air temperature over a given period of time, such as "projected increases of up to 6°C by 2100" do not easily register with human experience. People do not perceive weather or climate in annual increments—particularly not derived aspects of climate like mean annual air temperature or concepts such as "global climate." Like most species, we experience weather as both a local and a daily or seasonal phenomenon, and we are often most conscious of climate itself through weather extremes from our sense of local "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 most 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.

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, and much of the surface water available in rivers and lakes in California derives from the slow melt of the winter snowpack in the Sierra Nevada. The snowpack itself acts like a frozen reservoir keeping river flows relatively even and reliable across the year.

In a sense, the successful economic development and investment of the state 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) mean that these assumptions no longer hold. 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 of 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), pp. 12422-12427.

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As individuals, it is difficult to experience "climate" much less "climate change"; we experience weather — a hot humid day, a tropical storm, or a cold snowy spring. Thus, it may be 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]. Today it is raining and feels very warm, but over the past 100 years in a given place these conditions (heavy precipitation, and a high of 32°C) may be very near the mean or "average weather" for this time of year, or they may be quite different and far from a century's definition of "normal." Even subtle, hard to perceive impacts from climate change can be quite significant, however, in altering key hydrological qualities and impacting 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. 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 shift can be characterised by three patterns that vary by locality and temporal scale, though in many places all three 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 summer monsoons are typical of this type of change. Statistically, such shifts are reflected by the gradual movement in the mean of some climate variable of interest. Most climate models have a tendency to characterise climate change as a slow shift in mean.

The second pattern is an increase in climate variability — the extremes of weather, oscillating about some relatively stationary mean. For precipitation, some regions are seeing more frequent and more severe flooding as well as droughts. Weather extremes such as very hot days, very strong tropical storms, or intense precipitation events appear to play important ecological roles in shaping where species are found (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 is seeing a period of stable or slow-changing climate ("state 1"), 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 periods of major regime shift often follow this pattern, with sudden change occurring once a threshold level or tipping point has been reached. 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 be ecological catastrophes.

Shifts in climate altering freshwater systems 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 extreme weather events such as severe droughts. Making worldwide generalisations about how economies and wild species will experience freshwater shifts is 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 hydrology.

[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).

Freshwater climate change and precipitation

Most freshwater is derived from precipitation. And in most parts of the world, numerous aspects of precipitation are changing, such as the amount of annual or seasonal precipitation, the timing of precipitation, the "normal" form of precipitation (such as shifting from snow to 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 what can happen where and when: economies, livelihoods, ecosystems, and 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. But almost invariably 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 downward. 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. Like bank accounts, lakes, rivers, groundwater, and glaciers can become "overdrawn" beyond their capacity to renew their reserves (outflows), or their rate of new "deposits" (inflows) from climate-driven changes in precipitation can slow or increase. In other words, climate shifts in precipitation matter to humans because, ultimately, we depend upon precipitation, directly and indirectly. And these shifts also matter to freshwater ecosystems, wild species that rely on freshwater, agriculture, and many other elements of human economies.

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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 stepwise since the 1960s about 10–20%, though even small changes in precipitation can lead to very large shifts in runoff, with river inflows dropping in response up to 40–60%. 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 has 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.

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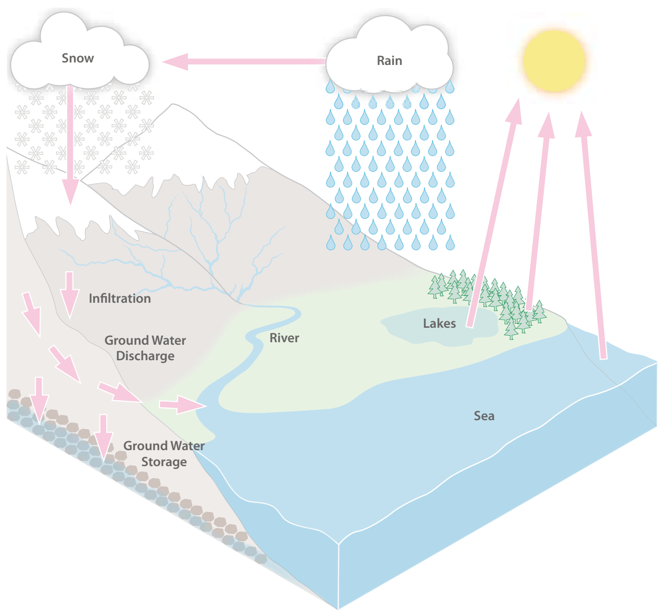
In the Pacific northwest of the USA, summer water temperatures are increasing at a rapid rate, impacting salmonid populations and migration patterns, with several species likely to become locally or regionally extinct within decades[6]. According to a US Forest Service statement,

> "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 habitat loss would be most severe in Oregon and Idaho with potential losses exceeding 40% by 2090[7]."

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.



The interaction between warmer winter temperatures and increasing levels of nutrient pollution and urban pressures along the large, shallow lakes in the rapidly developing central Yangtze basin of China is leading to near-permanent eutrophic conditions.

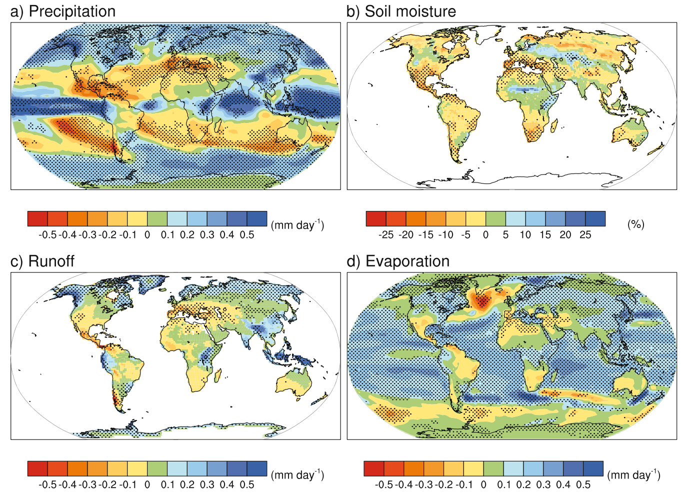
In many arid and semi-arid regions, annual precipitation levels are decreasing, threatening the livelihoods of farmers and pastoralists and cities in regions like northeastern Brazil, southern Africa, and major populations centres in northern Mexico and the southwestern USA.

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, more generally, through more intense precipitation events[8]. Paradoxically, the result will be both more floods and more droughts.

As a UK government committee ruefully reported: "Under climate change, there will be both more water, and less." These changes are expected to place particular stress on urban stormwater systems, not to mention low-lying structures in the expanding view of floodplains. The United Nations' Intergovernmental Panel on Climate Change (IPCC) has recently suggested that extensive shifts in climate adaptation strategy may be needed in northern and western Europe, including expanded floodplains, regions that can be filled or flooded during crises, and more effective flood forecasting systems. Southern and southeastern Europe is likely to see more extensive and severe droughts, placing intermediate flood and drought-prone regions such as central Europe in a difficult position for shifting precipitation regimes.

[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] http://www.fs.fed.us/ccrc/topics/salmon-trout.shtml.
[8] IPCC 2007.

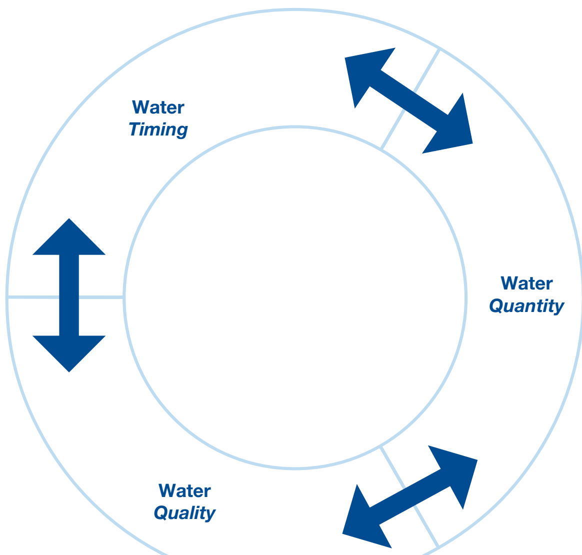
Source: IPCC
The Intergovernmental Panel on Climate Change (IPCC) is the United Nations' scientific panel tasked with analysing climate change impacts on human and natural systems. The Fourth Assessment Report was published in 2007 (see Key Readings). Here, the IPCC shows agreement across 15 climate models for several freshwater-relevant 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].



How can we describe freshwater impacts from climate change?

The human and ecological impacts on freshwater from climate change can be described in terms of three different components: water quality, water quantity or volume, and water timing (sometimes called water seasonality, flow regime, hydroperiod, or hydropattern). Often a change in one element 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, thermal tolerance, dissolved sediment, and pH. Humans generally avoid freshwater for drinking or cooking if it has high levels of dissolved minerals or has a very high or low pH.

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 a "normal" dry-season low flows.

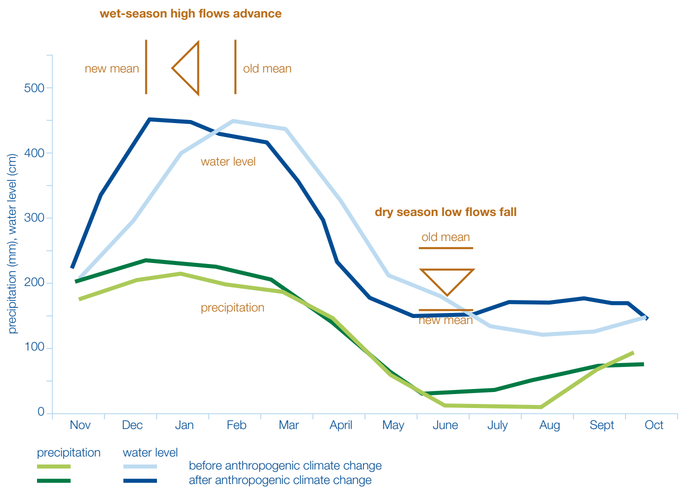


Water quantity refers to the water volume of a given ecosystem, which is controlled through the balance of inflows (precipitation, runoff, groundwater seepage) and outflows (water abstractions, evapotranspiration, natural outflows). At a global scale, precipitation is tending to fall in fewer but more intense events, resulting in generally more precipitation. The most striking changes in water quantity often occur with precipitation extremes like floods and droughts. The occurrence of precipitation extremes is expected to increase globally, as well as the severity of extreme events themselves. Tropical storms such as cyclones and hurricanes are also extreme weather events, but the climate science surrounding these is still highly uncertain, and we cannot yet determine how these will be altered in intensity and frequency in future decades.

Water timing or seasonality is the expected variation in water quantity over some period of time, usually one year. Most water bodies have a "normal" seasonal variation that in wetlands and lakes is called hydroperiod and in rivers and streams is called flow regime; together, such variation is sometimes lumped together as hydropattern. In temperate latitudes, the time of high water often coincides with spring followed by a low-water period near the end of summer, while in subtropical or tropical climates high water is more likely to be called a monsoon or rainy season and low water a dry season. Climate change is altering the seasonality of many water bodies even when the water quantity at an annual scale remains unchanged. The timing of precipitation, for instance, is altering in many regions, shifting often 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, and more evapotranspiration. The spring high water in many regions is thus occurring earlier and with a lower peak than previously.

Taken together, these three aspects of freshwater can fully describe the dynamic hydrological processes of freshwater systems. For instance, when the timing of the low-water period in the flow regime of a river or stream is extended — with a longer period of low-water conditions — the water quality of the system is significantly altered. Dissolved oxygen levels drop, nutrient concentrations rise, and algal blooms become more likely in the warmer water.

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.



Water timing: A critical driver of ecological and human impacts

Of the three categories of impacts, water timing is arguably the most important for ecosystems and human use since when you find water affects quantity and substantially impacts quality as well. Unfortunately, many large-scale studies of freshwater climate impacts report annual flow or runoff patterns, which ignores sub-annual seasonal variation in climate trends. A small shift in evapotranspiration or precipitation, for instance, can easily change a historically low-water period in flow regime into a period with much more frequent droughts, though at an annual resolution the net shift in inflows and outflows may seem insignificant. A preferable way of investigating the potential for seasonal impacts is through the use of annual hydrographs, which are the most common means of showing water timing. Worldwide, shifts in water timing are likely to be the most widespread and most important type of climate impact on freshwater systems.

Many terrestrial and aquatic species are extremely sensitive to water timing as well. 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 regime mean that there may be detrimental mismatches between behaviour and the aquatic habitat.

Controlling water timing has long been a priority of the human history of 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, and the tens of thousands of dams and irrigation canals across the planet today represent the desire to control variations in water levels that occur on a natural but irregular basis for more reliable irrigation or hydropower; as our confidence has grown, we have even created conditions for both purposes in regions where those activities had never been imagined before. In contrast, dams and other types of infrastructure designed for flood control reflect a desire to reduce flow variability and extremes.

Relative vulnerabilities: Developing contrasts

Together, these three types of impacts can be used to describe how climate will alter freshwater systems, but they do not describe how likely particular systems may respond rapidly or significantly to climate. Thus, assessing the vulnerability to a system or one of its components (such as the headwaters versus the floodplain) is often a key object of interest for resource managers. Indeed, some of the basic aspects of what constitutes relative system vulnerability in a particular landscape should be incorporated into the worldview of policymakers and many types of nontechnical staff engaged with water issues in conservation and development on a daily basis. One useful means of expressing vulnerability is through contrasts between types of water bodies, freshwater ecosystems, or uses of those ecosystems. The following list is by no means intended to be comprehensive. But these and other types of contrasts should serve as a means for illustrating how we can begin to identify what kinds of freshwater systems (or parts of a single system) are most vulnerable to changes in the local climate regime without the use of models or historical climate trend analyses.

Scale: Large versus small. Generally speaking, large systems are buffered simply on the basis of high 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 acclimated to weather variability, and thus consumers and residents dependent on such systems — such as many aquatic macroinvertebrates, large migratory terrestrial vertebrates in eastern Africa, cattle ranchers — are more likely to have high inherent adaptive capacity. Species and people that depend primarily on normally permanent water resources, however, may be very vulnerable to deviations in water quantity, quality, and timing. They are less likely to have experienced or be adapted for extreme weather events.

Residence time: Old water versus new water. Most freshwater ultimately derives from precipitation, but systems vary substantially in their 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 a major pulse of water originally from direct, local, and highly seasonal precipitation ("new water"), but they are sustained through their respective dry seasons by the large reservoirs of groundwater that are built up during the wet season ("old water," which fell weeks or months earlier). Lakes and rivers fed by snowmelt or glacial flows are similarly buffered with old water. Even if there are shifts in the timing of spring melts or monsoon seasonality, these systems should be fairly resilient. However, many systems worldwide depend primarily on new water, particularly in arid and semi-arid regions. And these systems will be respond very rapidly to even small shifts in the timing, amount, intensity, and form of precipitation.

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PART TWO: PRINCIPLES AND PRIORITIES

The freshwater impacts of anthropogenic climate change will not be uniform globally or even all negative; there will be winners and losers everywhere. 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 developing a climate adaptation program.

How can you think about what you can do?

How can we begin to think of freshwater climate change in a way that is both accurate and comprehensive? Or to put the same question in another way, do the effects and impacts on freshwater ecosystems from anthropogenic climate change require us to think in a way that is different than we might for marine or terrestrial ecosystems?

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 a relatively high compared to many other climate variables. The historic precipitation record, in contrast, has slowly come into better focus, but precipitation components of the circulation models that are the means climate scientists use to predict our future climate show much lower levels of confidence. Often, the strongest statements we can make about future trends are about simple directionality, such as "Over the coming two decades, we expect more winter precipitation." 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 25 or 50 years. Finally, many natural "reservoirs" of water such as groundwater and accumulated snow present very large uncertainties: groundwater recharge rates and capacities are often unknown and poorly regulated, while the temperature uncertainties that surround winter precipitation falling as snow versus rain are quite high, not to mention the difficulty modelling the relative importance of accumulated snow melting as liquid water versus sublimating or evaporating 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 and, more generally, at anything more fine than a regional or monthly scale of resolution. Managing under uncertainty is therefore a defining characteristic of adaptation in freshwater.
2. **Freshwater rarely exists in a human-free vacuum:** Human settlements historically have often been located based on their proximity to freshwater resources, and people have been modifying, developing, and often exploiting intensively those resources for a very long time. There are regions (the Nile in Africa, the Tigris-Euphrates in greater Mesopotamia, many of the rivers derived from the Tibetan plateau such as the Ganges, the Mekong, and the 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. Perhaps more prosaically, a rancher's small cattle tank is an ecologist's aquatic macroinvertebrate community. Thus, few bodies of water can be considered "pristine" or wild, and efforts to assist these ecosystems with the process of climate adaptation should consider both people and the ecological communities together.

Left: © WWF-UK
Right: © Yifei Zhang / WWF-Canon

3. **Freshwater ecosystems do not "end" at the water's edge:** All but the very largest freshwater systems are small and relatively isolated from one another. Indeed, 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 far inland, and the steady rain of leaves and branches from riparian vegetation are the source of much of the organic carbon in lakes and rivers. And even in mesic regions, surface water is a rich confluence between terrestrial and aquatic organisms. Water is literally an oasis of life, even when the water itself is not in what might be thought as short supply. But this aspect of water is best seen in boreal, arid, and semi-arid regions of the world where so many bodies of water are ephemeral or temporary — seasonal pulses that last only a few weeks or months but that teem with active life as long as liquid water remains.

What is climate adaptation?

There is a widespread concern in the fields of conservation and development that climate change somehow represents such a fundamentally new way of envisioning our work, and that a complete shift in worldview is necessary. In other words, many people fear that the water infrastructure and management toolkit that has been evolved over the past century is now irrelevant. We believe this view is inaccurate. Instead, given the three statements above, we propose that climate-aware freshwater conservation and development represent the same (and very well outfitted) toolkit for water management with an awareness that what we have seen in the past is a helpful but not a definitive or unerring guide to the future. We must do much of what we practice now, but with a climatic mindfulness.

Like the Roman god Janus with one face seeing the path behind and another face watching the path ahead, 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. This sense of water resources existing in a particular moment in time implies we must be humble about our knowledge and 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 the future.

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 climatic shift that humans have gone through, much less most extant species. The most recent glacial period, for instance, ended only 12,000 years ago. Climate adaptation is the process of adjusting behaviour and range as a function of major changes in climate, and most species under historically normal circumstances can adapt to shifts in climate. 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 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).

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 a few decades, whereas the current rate of change — while not slow — is not unusually fast either. Instead, our current period of climate change is notably different from previous periods for three important reasons. First, industrial 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 of wild species, and so on. Third, the current level of warming has not been seen for many hundreds of thousands of years and, potentially, several million years. Thus, many extant species have no ecological experience with climatic conditions we are now entering.

The cumulative effect of these three factors is that range shifts and phenological changes are now more difficult than during previous climate shifts. We have reduced the ability of most organisms (including ourselves) to easily respond to climate change. We have instead promoted maladaptive responses to climate change that will result in less successful or even 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, and this complexity may itself lead to both difficulties and opportunities in adapting to major climate changes.

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, 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 — in the midst of 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. Even 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, 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 and local trend analysis. To view the situation from a slightly different perspective, their climate adaptation strategy should be to not rule out any adaptation potential until climate trends become clearer and more certain.

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What isn't climate adaptation?

The risks of not adapting have two aspects. 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. Thus, we have hints of the shape of things to come and 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, there should be little excuse for not formally going through a process of considering the climate relevance of our behaviour and plans.

The second risk of not adapting is potentially more serious: the threat that our actions actually represent maladaptation and will actively constrain our behaviour in the future. Because climate will be changing for decades even under our best attempts to control greenhouse gas emissions, some of our actions may actually limit our ability to adapt to future climate conditions. Building dykes that channelise flooding rivers rather than creating more extensive "natural" floodplains to buffer high water and capture sediment, high-capacity stormwater systems to reduce threats in urban areas, and emergency reservoir bodies is likely to transfer the problem of extreme precipitation events downstream or, worse, destroy or cripple local infrastructure and economies and reduce water quality for people and species. Investing in storage may encourage societies to become profligate in water use exactly at the time that they need to adapt to less security of water supply. On the other hand, infrastructure can conceivably become a powerful tool in managing climate adaptation. Given that the future holds a strong likelihood of having many elements of our water infrastructure stressed simultaneously, limiting financial and personnel resources during critical periods, conservative planning and reevaluation will pay great dividends.

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 for many decades. 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 (or reflected in existing hydrological data). The new Compact may already be irrelevant and maladaptive, endangered by the threats of serious drought, stakeholder lawsuits, inter-state conflict, and the need to develop a third climate-aware compact soon.

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Identifying vulnerability

Climate vulnerability refers to the potential for adverse impacts from climate regime shifts on human and natural systems. Given sufficient financial and scientific resources, a formal vulnerability assessment (sometimes called a VA) of potential and realised impacts on a system of interest that summarises the state of knowledge at a given time is often warranted and justifiable. 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 reevaluated as more knowledge becomes available. They should become the instruments 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.

Concepts of vulnerability should be informally incorporated into all aspects of water resource planning even in the absence of a formal VA. In either case, one effective means of 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.

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PART THREE: WHAT CAN YOU DO IN RESPONSE TO CLIMATE CHANGE?

We provide two very general suggestions for supporting climate adaptation initiatives. The first should apply in any case, 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 global 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 climate adaptation policies.

In regard to those policies, the second climate adaptation suggestion is to maintain flexibility 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 seven elements of freshwater climate adaptation that follow.

The following list of climate adaptation 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 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 many different actions that will be required in order to successfully adapt to the impact of a changing climate on freshwater systems all fundamentally depend on the existence of adequate institutional capacity. The functions that will be required of 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 monitoring, 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 capacity. These capacities are required simultaneously at a number of 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.

The contemporary reality is very far from successfully implementing such policies. 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 impact of climate change on freshwater will be through changes in the levels of precipitation and run-off. In many cases, this will reduce the amount of water available for human use and ecosystems, 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 is governed by an allocation or water rights system that governs who is allowed to take water from a system, when, and in what quantities. This 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, traditional systems, or a combination of these[9]. These allocation systems, and in particular whether they are or are not flexible enough to be able to respond to changes in water availability, will be central to societal capabilities to respond to climate change.

Many allocation systems already have mechanisms for coping with existing variability in water availability. For example, differing water users and water uses can be recognised as holding different 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 to appropriate economic activities. The presence of a water allocation system of this form that protects essential environmental flows and social needs while permitting flexibility in economic use of water helps water use 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, such a flexible system exists 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 water users. Where this continues to be the case, it will be these groups who continue to use water under circumstances of climate-driven reductions in availability, leading to significant social and environmental costs.

Precisely analogous conditions obtain with respect to the terms of water treaties between provinces, states or nations. Typically, these 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, and often conflict between the treaty parties.

[9] Le Quesne T., et al.2007 Allocating Scarce Water: A primer on water allocation, water rights and water markets., WWF-UK, Godalming.

3. Reduce external non-climate pressures

Reduce external non-climate pressures, including water pollution, exotic invasive species, overfishing, and negative impacts from land-use changes such as clear-cutting riparian forests. The presence of so many non-climate pressures is arguably the most novel component of this era of climate change. Past climate shifts did not have these 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 living 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. Management of agricultural runoff and effective sewage treatment can help reduce concentrated nutrient inflows and improve water quality substantially.

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

For most species, landscape connectivity via range shifts is a critical strategy in responding to weather extremes and climate changes. 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) such as 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-generation 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. 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.

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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. The construction of new infrastructure or the modification of existing structures should be undertaken cautiously and in light of a conservative assessment of future freshwater impacts. In other words, infrastructure and the management of that infrastructure must be considered strategically, over climate-relevant timescales. Viewed from this perspective, infrastructure may become a tool in facilitating changes in species and human communities through the process of adaptation.

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, and developing risk reduction strategies that include schemes to retain water on uplands, and the use of 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, 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. However, the development of industrial locations and plans for future growth in urban centres depend on assumptions about the availability of water. 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.

KEY READINGS

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 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 creditable and widely respected attempts to date to quantify economic impacts of current and projected climate change impacts.

(http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_Report.cfm)

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. (http://www.waterandclimate.org/index.php) 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.

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Formed in 2007, the HSBC Climate Partnership brings together HSBC, The Climate Group, Earthwatch Institute, Smithsonian Tropical Research Institute and WWF to tackle the urgent threat of climate change on people, water, forests and cities.

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