Review of hydrological issues on water storage in international development

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Summary

Water is essential for all life is and occurs in various natural stores of the Earth's hydrological cycle, including lakes, wetlands, rivers and aquifers. However, natural spatial and temporal variability in climate means that water of sufficient quantity and adequate quality is not always available for human needs (drinking, growing crops, generating power, supporting industry or maintaining ecosystem services, such as fisheries). Almost 900 million people lack safe and reliable water supplies. To meet the Millennium Development Goals we need to improve water availability. Future anticipated climate change and population increases will exacerbate this problem. Economic performance of countries is linked to their ability to cope with floods and droughts. Many countries, particularly in Africa have exploited little of their water storage potential restricting the development of hydropower production and irrigated agriculture. The World Commission on Dams (2000) concluded that large dams had made an important and significant contribution to human development by providing stable water resources and flood alleviation, but the social and environmental costs had, in too many cases, been unacceptable and often unnecessary. Large dams may be high risk under unstable political regimes and changing climates. In certain circumstances reservoir may release greenhouse gases. DFID supported the Dams and Development Project that provided guidance on how to implement the Commission's recommendation, which included assessment of alternative options and improved stakeholder participation and environmental safeguards where dams are considered the best solution. Other organisations, such as the International Hydropower Association, the World Bank and IUCN also produced guidelines to make dams more sustainable, such as releasing sufficient water to maintain downstream ecosystems and their dependent livelihoods. Other water storage options include exploiting and enhancing natural storage, such as groundwater, managing catchments to maximise water yield, using virtual water, demand management, desalinsation and waste water reuse. Where dams provide the only option, networks of small dams may provide greater flexibility than single large dams.

Based on a review focused on hydrological issues, we suggest 10 principles in developing storage that could contribute to a DFID policy. These are summarised as:

1. Undertake a full water resources assessment and implications for economic growth and poverty alleviation using best science and appropriate long-term data sets.
2. Undertake a full options assessment before selecting the most appropriate development solution.
3. Undertake a full life cycle analysis of the options including design, construction, operation, long term viability and decommissioning.
4. Assess flexibility and vulnerability to climatic variability and change including water availability and sedimentation using best science and appropriate data.
5. For schemes having trans-boundary nature implications, assess the political security and vulnerability issues and use benefits sharing
6. Calculate a full carbon balance for water storage options, especially hydropower, including a baseline survey of current conditions
7. Ensure that full safeguards are implemented including appropriate environmental flow releases and effective management to reduce health risks
8. Ensure that dams are multi-purpose, where possible combining irrigation, fisheries, public supply, power generation and flood management
9. Evaluate the relative merits of large single dams against a distributed networks of smaller dams to assess overall costs, flexibility in water management, exposure to climate change
10. Ensure that all proposed developments are part of an integrated catchment approach including developing appropriate laws and institutional capacity

1. Background

Water is essential for many aspects of our lives including drinking, washing and cooking, growing food, supporting industry and producing energy. People also benefit further from water through its maintenance of ecosystems that provides additional goods and services. Managing the variability of the water cycle, so that water of appropriate quantity and quality is available where and when required, has been a key component of past economic development in many countries. Dams have made a significant contribution to human development for many centuries, as they can address both water resources and flood alleviation issues. Technological developments, during the 20th century in particular, enabled larger dams to be built that can store vast quantities of surface water. During the past few decades, there has been an increasing awareness that such large scale "hard" engineering can be an inflexible approach to water management with costs (direct and indirect) in some cases outweighing benefits. The World Commission on Dams (2000) report highlighted the potential negative aspects of dams, including environmental impacts and social injustice. This led directly to a period of reduced activity in dam building as the implications for water storage of the WCD report were debated. Networks of small dams can in some cases provide the storage required, but in a more flexible manner with more direct local community control. Groundwater (aquifer) storage on the other hand provides a natural solution in many regions. Groundwater is often preferred by farmers, as they have often have direct control over the resource. Yet over-exploitation, often for short-term gain, has led to significant problems in areas, such as Mediterranean Europe, India and China.

The debate over water storage has been reignited by global and region economic, demographic and climate changes in recent years. Climate change, which is likely to lead to significant changes in temperature and increases in rainfall variability (leading in some regions to more frequent droughts and floods and more unpredictable water availability) has heightened the need for additional water storage. Over the summer of 2008, oil prices rose from $30 to $140 per barrel giving further impetus for renewable energy sources, such as hydropower, that do not use fossil fuels that can exacerbate the greenhouse effect. The world's population, presently estimated to be over 6.7 billion, is expected to reach nearly 9 billion by the year 2042 billion (DESAPD, 2006) generating greater demands for food from irrigated agriculture and clean safe drinking water. Despite progress towards the Millennium Development Goals , almost 900 million people still lack access to safe drinking water. Statistical relationships between water availability and economic growth suggest that increased water storage is essential for poverty reduction. Additionally, some commentators have expressed concerns that during the next 25 years competition for water will be a catalyst for conflicts in many regions as countries fight for access to scarce resources. However, to date, the numbers of direct conflicts over shared waters remain low (Wolf ref) and other commenators (*e.g.* Grey and Sadoof, 2007) see water resources issues as a catalyst for cooperation. Whilst China and India, in particular, have major programmes of dam development, most developing countries have exploited a mere fraction of the potential for infrastructure-based surface water storage. For example, Africa has only exploited 7% of its hydropower power potential (IHA, 2008a).

These issues have created a demand from DFID Country Offices and Regional Divisions for an agreed policy position on water storage, within the context of climate change adaptation and mitigation, supporting economic growth and reducing conflict through sharing benefits from water infrastructure. There is also a demand from other stakeholders for clarity on scientific evidence of the options for improving water storage, the role of hydropower in low-carbon development and for the UK position on water storage. This report provides input into the establishment of policy position on water storage to address the Millennium Development Goals, poverty alleviation and economic growth.

2. Scope of the review

This review focuses primarily on hydrological issues including water availability and variability, climate change and water management options. It includes brief information on ecological and economic implications of water storage. Attention is given to reflection on the outcomes of the World Commission on Dams and its follow-up. It is recognised, however, that these issues must be puit within a wider context of including dam engineering and operating rules, investment strategies, capital finance, economic growth, regional markets, food security, governance, stakeholder participation, carbon footprints and political stability instruments and the infrastructure.

3. The water cycle

Any analysis of the need for water storage requires reflection on the water cycle, since the details of processes and quantities are fundamental to understanding water issues.

Cycles and stores

The general perception of the hydrological cycle is one of a single large cycle of evaporation from the oceans, precipitation on the land and discharge to the sea via surface runoff in rivers or aquifers. In reality most of the water that evaporates from the oceans falls back into the oceans as precipitation; only about 10 percent is transported to fall as precipitation over the land. Only one-third of the precipitation that falls on land runs-off to the oceans through the rivers and aquifers; most of the water evaporated over land is recycled - *i.e.* the resulting water vapour reforms clouds and precipitates again over land. These figures highlight the concept of small water cycles (Figure 1) in which water evaporated falls locally as precipitation and becomes available for evaporation again. For example, it has been shown that evaporation from the inner Niger delta wetlands in Mali creates the rain that feeds the pastures in the arid rangelands of west Mali and Mauritania. This counters to some extent the idea that all evaporation is a loss and emphasises land management as a key component of water management.

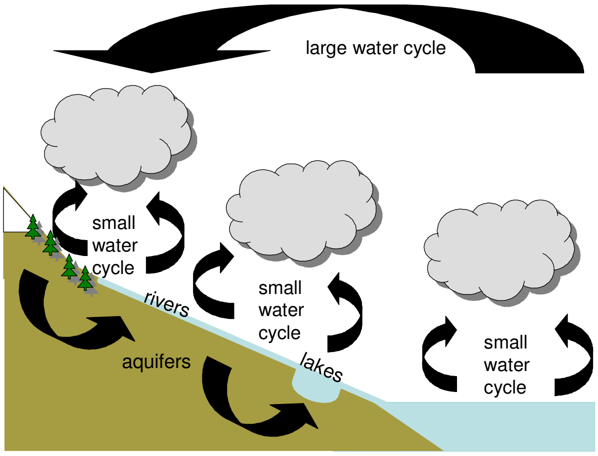


Figure 1 Components of the water cycle, including large and small cycles (after Kravčík et al., 2008)

Past urban drainage has focused on evacuating rain water rapidly via sewer systems from the land to major water courses, such that water is lost from small upstream cycles. In contrast, sustainable urban drainage focuses on soakways that encourage rain water to infiltrate into the ground, thus retaining water in small cycles. The concept of the small water cycles promotes retention of water in headwater catchment soils, aquifers and vegetation.

Heavily vegetated surfaces will have access to a large store of water in the soil, through their root zone (typically 1 to 10m), and will tend to be able to evaporate freely (with annual rates between 500 and 1500mm, a value controlled by the energy available from the sun). Bare soil and partially vegetated areas will evaporate freely for a few days after rainfall until the surface soil store (typically a few 10s mm) runs out. In these areas a large proportion of the precipitation will either run off the surface or percolate through the soil to the groundwater. Thus although much of the evaporation over land is recycled to rainfall, removing vegetation is likely to reduce rainfall. At a continental scale this is undoubtedly true; many modelling studies suggest a reduction of rainfall following deforestation, *e.g.* Amazon forest experiments (Marengo, 2006) show 1-2 mm day^{-1} reduction of rainfall following complete deforestation, c.f. total rainfall of 5-6 mm day^{-1}. At smaller scales, local atmospheric dynamics tend to dominate, but it is not entirely clear what proportion of land cover change is required to reduce rainfall. Effects are also geographically dependent and rainfall in maritime areas is less influenced by water recycling than continental interiors. Also semi-arid regions appear to be 'hotspots' of land/atmosphere interactions (*e.g.* Koster *et al,* 2002). Large-scale land use change can also affect large scale atmospheric cycles, for example Amazonian deforestation is likely to change rainfall patterns in Mediterranean Europe (Gedney *et al*, 2008).

The volume of frozen water in ice sheets, glaciers and permanent snow represents some 68.7% of freshwater globally (Gleick, 1996). The vast majority of this water (>99.5 %) is inaccessible in the remote polar ice sheets of Antarctica and Greenland (IPCC, 2007). However, mountain glaciers and ice-caps are still an important source of freshwater, particularly in densely populated regions of Asia and South America where melt-water contributes over 90% of the annual discharge of some rivers (Zemp and Haberli, 2007). Seasonal snow cover is also a critical storage medium. It is estimated that more than one-sixth of the Earth's population rely on mountain glaciers and seasonal snow packs for their water supply (Barnett *et al.*, 2005). Climatic warming clearly is a major threat to these important freshwater sources.

Groundwater currently provides the majority of water storage used in the world and is the largest store of unfrozen fresh water. It has the potential to provide water over a number of years and hence buffer water resources through both seasonal and multi-year variations and major droughts. However, in many regions, such as China and India, the exploitation of groundwater exceeds the long-term recharge, resulting in a lowering of the water table. Where water entered the aquifer in the distant past and is not currently being recharged, it is often described as 'fossil water' and its exploitation termed 'groundwater mining.' As with other mineral resources such as coal, iron or oil, fossil water is a limited exploitable resource with a finite life. For example, the groundwater in the Kufra and Sirte basins, in Libya, was last replenished during a wetter period several millennia ago, but the resource is vast and has been exploited to irrigate crops for the last 30 years and will continue to provide water for several decades to come. Over much of sub-Saharan Africa, hard crystalline rocks bear only limited groundwater potential.

The Earth's water cycle includes natural storage of water in the atmosphere, vegetation, soils, rivers, lakes and wetlands, aquifers and the sea. In some parts of the world, natural storage is limited, *e.g.* where rocks are impermeable or hold little water. Storage may be created artificially (or enhanced see Section 6) to provide water when it would not naturally be available. Each type of storage has its advantages and disadvantages; Table 1 provides some examples, but is not intended to be comprehensive.

Table 1. Characteristics of water stores

Store type	Depth	Residence time	Example advantages	Example disadvantages
Atmosphere	n/a	Days-weeks	Provides rainfall	Little control potential
Ice sheets, glaciers, permanent snow	n/a	Hundreds of years	Melt water provides reliable base flow, highest meltwater period often during a dry season	Little control potential Rapid thaw can induce flooding, outburst floods, ice avalanches, debris flows
Seasonal snow	n/a	Days-weeks-months	Spring-melt valuable in some regions for early cultivation of crops	Little control potential Limited to high latitude or high altitude (mountain) environments Rapid thawing can induce flooding
Ground ice	0-3 m	Months	Spring-melt augments river flows	Little control potential Rapid thawing can induce flooding
Permafrost	0-10 m	Hundreds of years		Little control potential Permanently frozen, limited to high latitude or high altitude (mountain) environments Climatic warming heightens risks of landslides, debris flows
Vegetation	n/a	Hours	Drives plant growth	
Soil surface	10-20 mm	2-3 days	Available for plant growth	May be evaporated to the atmosphere
Root zone	100-500mm	1 to 6 months	Directly available for agriculture	
Groundwater (shallow)	Less than 100 m	Years to tens of years	Large volume, little evaporation, high quality	Vulnerable to pollution and over-abstration
Groundwater (deep)	1-300 m	Hundreds of years	Large volume, little evaporation, high quality, large areal extent	Pumping costs can be high, if non-artetian
Fossil groundwater	10's-100's m	Millennia	Available in many arid areas	Not replenished
Rivers	n/a	1-6 months?	Abstraction, food, nature support	Unused water flows to the sea
Lakes (shallow)	n/a	1-12 months	Abstraction food, flood prevention	More likely to result in GHG emissions (whether natural or man-made)
Lakes (deep)	n/a	1-12 years	Abstraction, food, flood prevention	
Wetlands	1-10 m	6 months to 2 years	Ecosystem services, *e.g.* carbon sequestration	High evaporation rates; GHG emissions
Small reservoirs	n/a	6 months to 2 years	Potential flexibility to hedge drought risks, can target local communities	Difficult to ensure safeguards compliance with networks of small reservoirs
Large reservoirs	n/a	1 to 2 years	Large storage volume, can be multi-purpose (e.g. irrigation and flood control), provide fisheries, management flexibility, can provide low carbon energy	Lack of hydrological flexibility, suitable sites limited, social and environmental can be high impacts, high evaporation.

Spatial and temporal variations in the water cycle

The spatial and temporal distribution of water resources across the globe are determined largely by rainfall and evaporation, and follow factors that influence cloud formation, such as the amount of solar heating, surface temperatures, topography, and proximity to the sea and large lakes. Movements in large-scale atmospheric systems, such as Inter-tropical Convergence Zone (ITCZ), create highly seasonal rainfall in the sub-tropics that dominates rainfall and river flow patterns over much of Africa and Asia. Attempts to better understand hydrological variability have involved many different types of scientific studies. For example, recent work (Touchan *et al*, 2008) has demonstrated through the analysis of tree rings in North Africa, that over the last 500 years, an average of 16 major droughts occurred every 100 years, although this rose to 19 during the 20th century.

In addition to long term variations in climate, shorter-term fluctuations are important. The spatial and temporal nature of rainfall creates water resource variability of various types in different areas of the world (Table 2). For example, the El Niño-Southern Oscillation (ENSO) is an important temperature fluctuation in surface waters of the tropical Eastern Pacific Ocean, which usually occurs in late December and reflects the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin, Australia. ENSO is most prominent known source of inter-annual variability in weather and climate around the world (about 3 to 8 years) and is associated with floods and droughts.

Table 2 Examples of variability in water availability

Example water variability issue	**Example region**	**Implications**
Strong monsoon seasonal variability	Indian sub-continent, much of Africa, northern Australia	Storage required from wet to dry season
Decadal persistence in droughts	West Africa, eastern Australia	Storage in dams may be insufficient to last during prolonged droughts
El Niño	Global	Many countries may experience problems at the same time leading to increased food prices
La Niña	East Africa	Increased flood risk
Wet and dry millennial phases	North Africa and Middle East	Much water will be fossil and not replenished

4. Implications of variability in water resources

For many direct water use activities, such as domestic and industrial use, a constant rate of supply is needed all year round, although variations will occur in agriculture depending on crop growing seasons. Any gap between demand and supply of water will have wide-ranging implications including crop failure, thirst, power cuts, loss of transport links and degradation of ecosystem services. Kenya suffered a 16% fall in GDP as a result of the 1998-2000 drought and an 11% fall in GDP as a result of the 1997-1998 floods, partly because the country was unable to store and distribute water efficiently for irrigation and hydropower production (Economic Commission for Africa 2008). Reliable water availability has been termed 'water security', defined by Grey and Sadoff (2007) as '… the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production ,coupled with an acceptable level of water-related risks to people, environments and economies." Access to water is clearly a wider subject than availability and many other factors including cost, distance to water source, rights, authority and corruption can create water poverty (the opposite of water security) at household and community levels (Sullivan *et al*., 2003).

The distribution of water infrastructure is inversely related to the global distribution of water insecurity risks (UNDP, 2006). Many of the world's wealthiest nations also have the highest water security (Grey and Sadoff, 2007) and investment in water storage has enabled growth where hydrological variability is high (e.g. USA and Australia), although growth often requires ongoing non-infrastructural investment. However, direct cause-effect relationships are not always clear; wealth may enable extensive water storage, or water storage may be the source of their wealth. The USA invested heavily in multi-purpose dams starting in the 1930s with the Tennessee Valley Authority. The Hoover and Glen Canyon dams on the Colorado River supported the economic development of southwest USA. Many European states have invested available wealth in dam construction; *e.g.* hydropower in Norway and Switzerland and irrigated agriculture in Spain. In Australia, water infrastructure, particularly in the Murray-Darling basin, has been instrumental in industrial growth and development of agriculture and livestock production, but has created a reservoir-dependent society. Developing a large water storage capacity does not guarantee economic growth, due to other overriding governance and inter-country security issues. Furthermore, economic prosperity does not necessarily depend on investment in water infrastructure, if natural storage, such as groundwater is available and their economies are not reliant on water demanding sectors. Many Middle Eastern states, such as Saudi Arabia and United Arab Emirates, have sufficient groundwater for domestic use and have relied on income from oil sales to obtain food products produced in other countries. However, as fossil groundwater and oil reserves are depleted, their economics may change. In such rich countries, technologies such as desalinisation of seawater may overcome loss of natural freshwater storage, but these have relied on fossil fuels. Some countries (*e.g.* Kuwait, Saudi Arabia) are buying land for food production in other countries (*e.g*. Sudan, Pakistan), which creates new global political issues.

There are clear examples of countries experiencing high hydrological variability that have limited water storage and less successful economies, such as Ethiopia and Yemen, and high per capita storage does not guarentee high economic growth. The majority of developing countries have developed only a fraction of the infrastructure needed to cope with existing climatic variability – for instance Ethiopia has only 165 m^3 of water storage per capita (including the new Tekeze dam on the Atbara River) compared to 4,500 m^3 in Australia, a country with a very similarly climate variability. Climatic variability is estimated to cost Ethiopia one-third of its potential economic growth. Less than 6 percent of Ethiopia's irrigable land is under irrigation, whilst figures for neighbouring Sudan are 14% and for Madagascar, 32% (FAO data 1987). Furthermore, Ethiopia has only developed 1% of its 30-40 GW hydropower potential (like much of Africa, Table 3). To achieve the 750 m^3 per capita level of South Africa would cost Ethiopia around $35 billion; or five times its current GDP, but this could be recovered within a few decades. Development of water resources also has important political knock-on implications for countries downstream. If Ethiopia develops consumptive uses, such as irrigation, it may have hydrological implications for Sudan and Egypt, whereas hydropower is non-consumptive and may only change the timing of flows. The Nile Basin Initiative supported by the World Bank is promoting sharing of benefits from water rather than sharing the water itself. Sadoff and Grey (2002) classify these benefits as from the rivers (such as hydropower), to the river (e.g. improved environmental stewardship and sustainability), because of the river (cooperation, development, stability and peace) and beyond the river (regional integration and trade).

Table 3 Percentage of potential hydropower exploited (source: IHA)

Continent	**%**
Africa	7
North America	69
South America	33
Europe	75
Asia	22
Australia	49

There are many distributional effects that are hidden from national wealth statistics, such as GDP or the UN gini coefficient. For example, hydropower generation at the Manantali dam in Mali has led to better electricity supplies to urban areas in Senegal, Mali and Mauritania, but there has been little rural electrification and rural people have suffered loss of ecosystem services (such as fisheries) due to alterations to the river flow regime downstream. Some argue that major water resources projects stimulate broad regional economic growth which has significant direct and indirect benefits to poor people, through generating employment and improving services, such as roads and healthcare, whilst some organisations focus on appropriate local technologies (e.g. treadle pumps) that do less for GDP but more for direct poverty alleviation. These issues can be addressed through careful assessment of potential impacts and implementation at the planning stage of avoidance, minimisation and/or mitigation strategies.

5. Our changing world

Water storage cannot be assessed in isolation, but must be seen in the context of other issues that have a significant impact on supply of water resources, demand for water and the ability to utilise storage.

Population increase

In September 2008, the world's population was estimated to be about 6.7 billion. Growth rates during the 20th century were significantly higher than before. In particular, from 1950 to 1984, the Green Revolution transformed agriculture around the world with grain production increasing by 250%. The energy for the Green Revolution was provided by fossil fuels in the form of fertilizers, pesticides and hydrocarbon-fuelled irrigation. Population growth rates peaked in 1963 at 2.2% per year; the current rate is around half this figure (1.14% or 75 million people, in 2000). On its current growth trajectory, the global population is expected to reach 9 billion by 2042 with most growth in developing countries.

As the population has risen, so has per capita water use due to changes in lifestyle. Daily per capita use of water has now reached 350 l in N. America and Japan, 150-200 l in Europe and 10-20 l in sub-Saharan Africa. Agriculture is the highest water user; 1000 l are required for each kg of wheat grown, 1400 litres for each kg of rice and 13,000 litres for each kg of beef.

Figure 2 shows the likely increase in water demands over to 2030 (Shiklomanov 2000). It can be seen that the major increase is in water for agriculture, which uses large quantities of water because transpiration is an essential part of photosynthesis that cannot be reduced. However, evaporation from free water on plants and soils can be reduced by improved irrigation practices. Nevertheless, agriculture will undoubtedly require increases in water storage to satisfy demand.

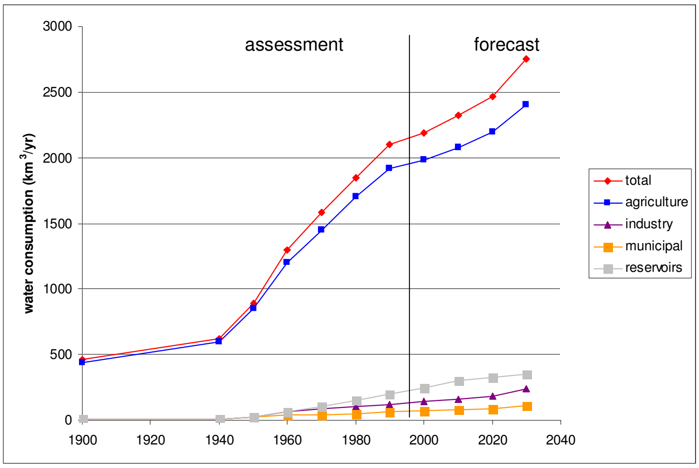


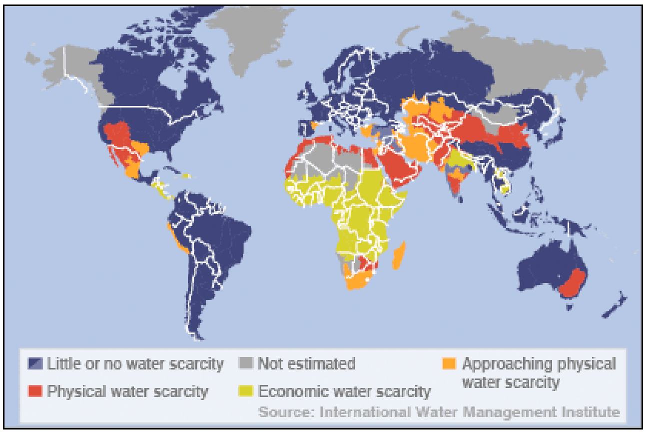
Figure 2 Likely increase in water demands over the next 30 years (Shiklomanov 2000).

As the total volume of consumption rises, so will the utilized percentage of available renewable water resources. In South America, the figure remains around 1-2% in 2025, but in Asia it could reach 85% and in North Africa it is predicted to reach 130% as fossil water is mined; this is clearly unsustainable. In 2006, one out of six people lacked access to safe drinking water, 900 million people (WHO/UNICEF JMP, 2008). The Comprehensive Assessment of Water

Management in Agriculture (Molden, 2007) concluded that 1/5 of the world's population lived in areas of physical water scarcity (Figure 3).

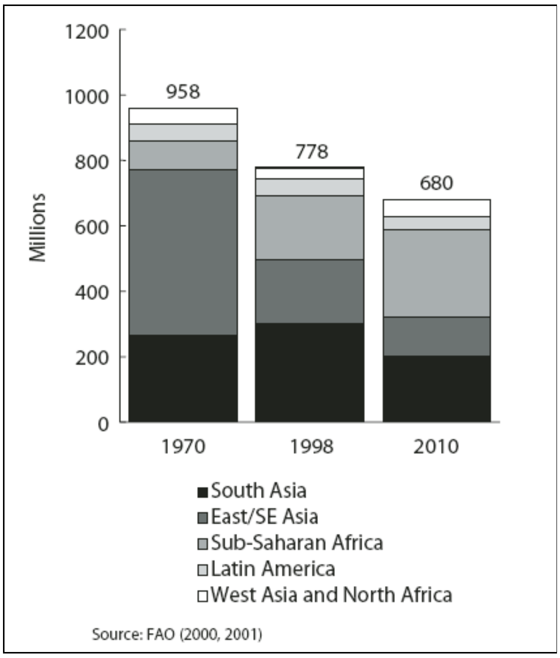
Changes in food security

The doubling of cereal production from 1970-1998 in east and SE Asia provided an increase in food and reduced food insecurity, in spite of a growth of population of some one billion people during that period (Seng *et al.* 2004). As illustrated in Figure 4, FAO forecasted a continued decrease in food insecurity in Asia by 2010, but an increase in Africa. By 2030, it is estimated that only about 5% of the population of Asia will be affected by food insecurity (Rosegrant *et al.* 2001). However, to further reduce food insecurity under rising populations coupled with the threat of climate change and global economic insecurity, there is much need for more localised, less capital intensive solutions to meeting water security needs, so alternative forms of water storage are important considerations.



Source: International Water Management Institute

Figure 3. Areas of physical and economic water scarcity (IWMI, 2005)



Source: FAO (2000, 2001)

Figure 4 Decreasing food insecurity 1970 - 2010

The report of the Commission for Africa (Our Common Interest, 2005) highlighted the severe poverty and lack of economic growth in many parts of Africa. It found that only 4% of arable land in Africa is currently irrigated, compared with 40% in Asia, and recommended investment in infrastructure (including water storage) to increase the area of arable land that is irrigated by 50% by 2010, on the way to doubling it by 2015, as one of the solutions. The feasibility of this objective was hampered by a lack of reliable assessment of water availability. Furthermore, reservoirs need space; some 500,000 km^2 of valley bottom land, often the most fertile agricultural land, has been used for reservoir construction.

Commodity prices

Commodity prices can influence water resources in a variety of ways. High oil prices can stimulate the development of alternative energy sources, such as hydropower. High grain prices can affect demand for irrigation water. Crude oil prices change in a similar manner to other commodities with wide price swings in times of shortage or oversupply. The crude oil price responds changes in demand as well as supply in OPEC and non-OPEC countries. Until March 2000 oil prices were around $22-$28 and only exceeded $24 per barrel during conflicts in the Middle East. Since 2000 crude oil prices have risen steadily, with occasional jumps, such as the $25 to $130 a barrel leap in September 2008. This had significant implication for the economies of most countries with direct impacts on the price of water because of higher pumping costs. Alternative energy sources, particularly hydropower, are being sought to avoid future price rises and to achieve low carbon growth. Wind, solar and wave power have some potential but only generate power during certain conditions. Another option is to grow biofuels. First generation biofuels, such as soya and maize, need the same amount of water (irrigation in many countries) as if they were grown for food. However, crops such as *jatropha*, which produces seeds containing up to 40% oil, used in the Phillipines, do not require irrgation, are drought and pest resistant and can be growth on poor soils (Fairless, 2007).

The rise in 2008 in the price of food crops, such as wheat, was due to a number of factors including higher demand for grain to feed livestock in China (where increasing affluence means more people want to eat meat), drought in Australia for three years running (meaning it had to import wheat), market concerns over continued export of grain, speculation and the extra demand for food crops (such as maize for use in biofuels) in both Europe and USA. This was also partly due to rice-growing land in countries, such as the Philippines, being lost to industrialisation and urbanisation. Flooding in Indonesia and Bangladesh and cold weather in Vietnam and China also hit production.

Smallholdings are fragmenting in many countries. Because of population growth and the loss of farmland, the average farm size in China and Bangladesh has fallen from about 1.5 hectares in the 1970s to barely 0.5 hectares now; in Ethiopia and Malawi, it fell from 1.2 hectares to 0.8 in the 1990s. On average, the smaller the farm, the greater the burden of the cost of doing business with big retailers. Smaller smallholders are also at a disadvantage in access to irrigation water, getting loans, new seeds and other innovations on which higher yields depend.

Climate change

The latest report from the Intergovernmental Panel on Climate Change (IPCC, 2007) indicates that the evidence for the warming of the earth in the last decades is now unequivocal, with an increase of nearly 0.8°C in global average temperature since the late 19th century. The IPCC further concludes that this trend is *very likely*[1] to be due to increases of anthropogenically generated greenhouse gases. Recent projections (IPCC, 2007) suggest that this warming trend will continue, resulting in an increase in global temperatures of between about 1°C and 6°C by the end of this century and significant changes in rainfall and evaporation.

Increasing CO_2 levels, and associated temperature increases, intensify the global hydrological cycle and will increasingly do so (Huntington, 2006). Through the 20th century there has been no consistent trend in observed rainfall averaged over the global land surface (although there are considerable uncertainties due to sparse rainfall networks in underdeveloped regions of the world and catch problems in high latitudes). There is, however, a tendency for the higher latitudes to receive more precipitation and sub-topics less, although sub-tropical India may have more rain. There is some evidence for increasing intensities of rainfall and increasing droughts (*e.g.* Klein Tank & Konnen, 2003, Dai *et al.* 2004, Burke *et al,* 2005). It is predicted that snow cover will decrease (with potential problems in areas, such as the Indian sub-continent) which rely on glacier storage (see below) and it is *likely*[1] that heavy precipitation and drought events will increase.

An increase of about 3% has been reported in continental streamflow from major world rivers from 1910-75. There is, however, no consistent evidence that the frequency of flooding has increased globally (Huntington, 2006; Kundzewicz *et al*., 2005). Since the 1970s some increases in the combined percentage of areas with severe drought or moisture surplus were found (Dai *et al*., 1998). The modest increase in global runoff may be a result of increasing CO_2 levels reducing evaporation (Gedney *et al*., 2006). Drought severity is predicted to increase in

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[1] For the definition of this term see page 23 of IPCC (2007)

much of Africa, southern and eastern Europe, China, India, Brazil and Australia (Figure 5). An intensification of the hydrological cycle may mean an increase in extremes – floods and droughts (Meehl *et al.,* 2007, Burke *et al.*, 2005). Inter-annual variability may also increase – with an intensification of the El Ninõ and North Atlantic Oscillation cycles – leading to more droughts and large-scale flooding events. These cycles are global phenomena that will impact different regions simultaneously (although often in different ways). As well as altering water supply, climate change may affect demand by, for example, increasing irrigation demand and leading to loss of ecosystem services, such as from wetlands.

While there is considerable uncertainty about the magnitude of climate changes in the future the majority of climate models (and the underlying physics) agree with the sign and general regional patterns of the projected changes of temperature and rainfall for the 21st century.

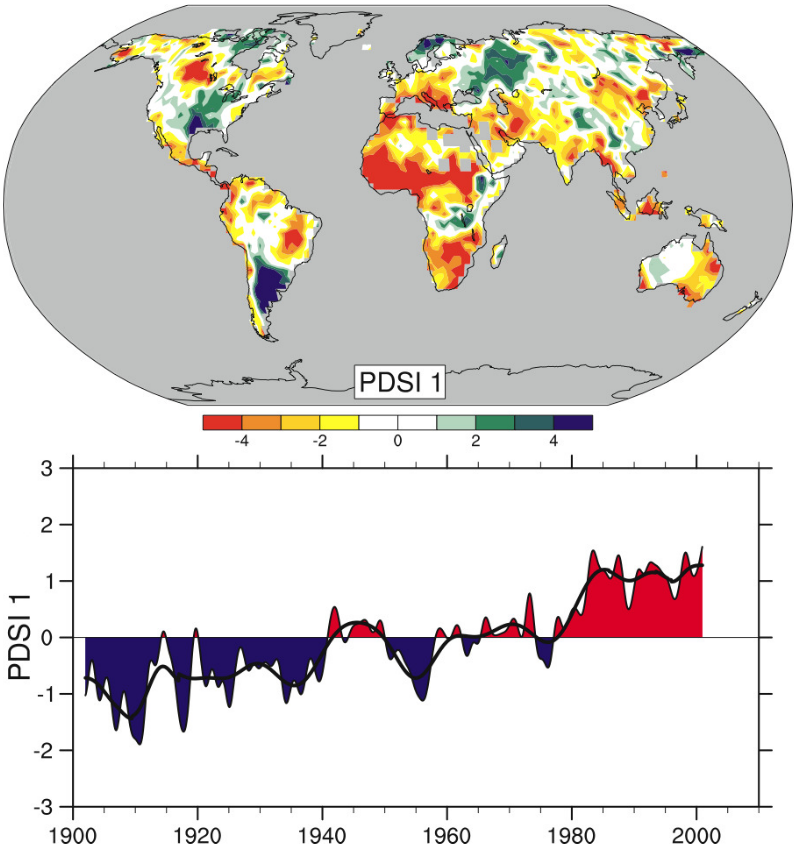


Figure 5 Drought severity index

The uncertainty in magnitude of impacts is because of both the uncertainties in the projections of the future emissions of CO_2 and differences in the projections of the various (over 20) climate models used. The regional detail, particularly in rainfall and runoff, provided by the climate models is very uncertain, with considerable divergence between the models. The best way to consider these projections is as possible futures. It is also valuable to consider the results from a number of climate models (and emission scenarios) rather than just one. This then provides a measure of uncertainty in the prediction.

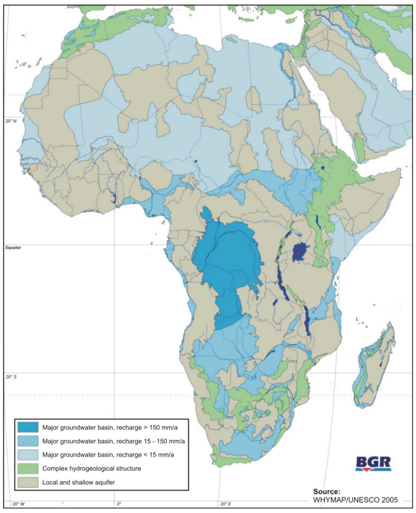
Glacial retreat

Mountains have been referred to as the "water towers" of the world (Messerli and Ives, 1997). Mountain glaciers are important natural freshwater reservoirs, gradually releasing water that has been stored as ice for many tens or hundreds of years. There has been a general shrinkage of the world's glaciers ever since the end of the Little Ice Age, towards the end of the 19th century (Dyurgerov, 2005; Oerlemans, 2005) and since the early 1980s, glaciers in many parts of the world have been losing mass at unprecedented rates (Dyurgerov and Meier, 2000). Such general retreat of glaciers corresponds to increases in the global mean surface temperature over the last hundred years, whilst recent accelerated retreat is consistent with more rapid temperature increases from 1979 to 2005 (Trenberth *et al*., 2007). Predicted increases in global mean surface temperature are thought likely to result in deglaciation in many mountain regions over coming decades (Zemp and Haberli, 2007).

Most major rivers originate in mountains and more than half of humanity relies on freshwater from mountains (Liniger *et al.,* 1998). In some arid areas, mountains are estimated to supply up to 95% of the total annual outflow from catchments (Viviroli and Weingartner, 2004). The retreat of glaciers, coupled with increasing demands for water, has led to fear of severe water shortages in many parts of the world (Gore, 2006; Stern, 2007). Highly populated regions adjacent to the Himalayan and Andean mountain ranges are considered particularly vulnerable to the impacts of glacier retreat (Barnett *et al*., 2005; Zemp and Haberli, 2007). It has been claimed that, at the present rate of climate warming, Himalayan glaciers may disappear within 40 years (Hasnain, 1999; Cruz *et al*., 2007) and that this would lead to significant reductions in river flow and potentially major water shortages (WWF, 2005, The Times, 2005). However, it has been demonstrated (Rees and Collins, 2006) that in retreat, glaciers contribute a component to river flow in excess of that related to contemporary precipitation. Indeed, rivers all over the world have benefited from the general de-stocking of glacial ice since the end of the Little Ice Age: a “discharge dividend” that will cease to exist if glaciers disappear (Collins, 2008). Under climatic warming, the volume of water released annually from a glacier might initially increase, as a greater proportion of the ice-surface is exposed to melting, but such releases eventually will decline as available ice area diminishes (Stahl and Moore, 2006; Wanchang *et al.,* 2000). As the proportion of ice-cover within a catchment decreases the variability of river flows both between and within-year will also increase, as catchment runoff is increasingly derived from precipitation. At the same time as glacier retreat there is likely to be an increase in rainfall in this region. Therefore, the regions ability to cope and adapt will be driven in part by the willingness and ability to build water storage infrastructure to retain increased monsoonal rainfall. Unfortunately, our understanding of the timing and extent of such changes and their affects on water resources availability remains poor.

Groundwater and climate change

How groundwater resources will respond to climate change is uncertain, and depends on changes to rainfall, aquifer characteristics and, critically, the additional demands that may be put on groundwater as a consequence of changing patterns of demand.



Source:
WHYMAP/UNESCO 2005

Figure 6. WHYMAP for Africa showing major groundwater basins and recharge

One of the key uncertainties surrounding the impact of climate change is the effect on the sustainability of groundwater-based rural water supplies. In Africa, for example, roughly 60% of population live in rural areas and depend on small-scale, unreticulated groundwater supplies. Based on research carried out over the last decade, several conclusions can be drawn (Calow *et al.* 2009; MacDonald *et al*., *in press*).

Firstly, climate change is unlikely to lead to the catastrophic failure of rural drinking water supplies from groundwater and is likely to impact significantly on other uses. Domestic supply from handpumps requires only 3-10 mm recharge per year, which should be achievable for much of the continent (Adelana and MacDonald, 2008). Nonetheless a sizeable minority – perhaps 90 million people - could be adversely affected if rainfall declines significantly in very low rainfall areas (200-500 mm yr^{-1}) where groundwater recharge is already marginal. Figure 6 shows an estimate of groundwater resources, and recharge across Africa. The outputs of global climate change models can be used to provide broad indications of the likely changes in water availability for groundwater recharge (Figure 7). However, because the actual processes and mechanisms of recharge are localised and complex, depending on land use, geology, soils and topography, such continent-wide estimates should be treated as broad-scale indications of likely changes, which need considerable refinement and downscaling to be used at local levels.

Secondly, the main determinants of water security in most rural areas will continue to be access (economic water scarcity) rather than availability related (physical water scarcity), with source failure occurring where there is overwhelming demand on too few sources, but where increases in coverage of water storage and reticulation systems would solve problems without threatening resource sustainability. Increasing coverage to meet the MDGs, and ensuring that targeting and technology decisions are informed by an understanding of local environmental conditions, remains paramount.

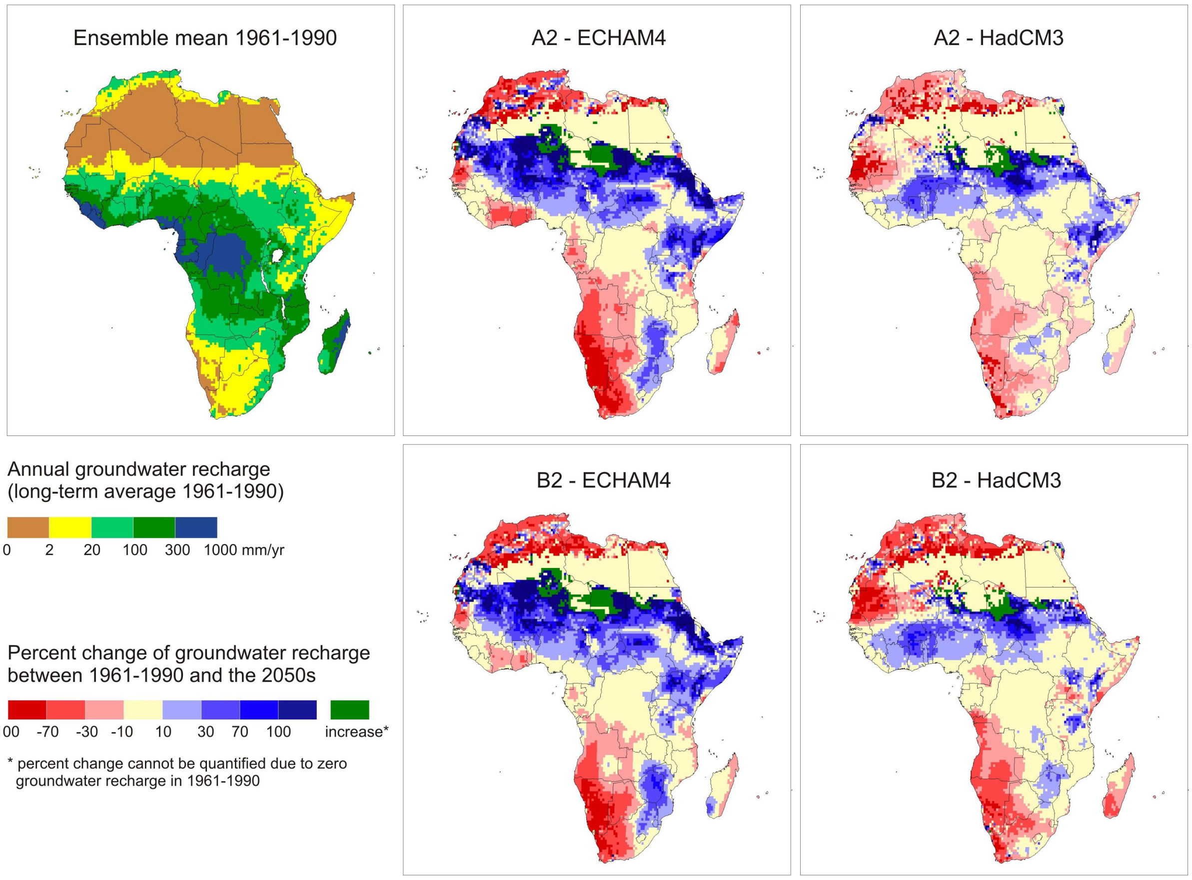


Figure 7. Potential impacts of climate change on recharge using the WaterGAP Global Hydrology Model (after University of Frankfurt; Petra Döll

Natural groundwater storage will continue to provide a vital buffer against drought and groundwater development is vital to meet the MDGs. Uncertainties and risks should not be under-estimated. In marginal recharge areas, groundwater storage may become non-renewable, and research into the impacts of climate change on the timing, duration and intensity of recharge events, and the mapping of renewable and non-renewable groundwater, is essential. More intense rainfall may not result in increased recharge, and may lead to less recharge if infiltration capacity is greatly exceeded and rapid runoff occurs, with attendant soil erosion issues. However, where evaporation is very high, recharge may only occur where intense rainfall ponds or flows for limited periods, *e.g.* wadi recharge. Land management to maximise groundwater recharge and minimise soil erosion will become vital, as will a quantitative understanding of the interaction of the processes involved. In addition, adaptation policies that promote irrigation development as a means of strengthening household resilience to climate `variability need to be carefully planned to ensure sustainable development of available storage (JMP 2004; MacDonald *et al* 2008).

Sea level rise and salt-water intrusion

Although sea-level has risen about 130 m since the last ice age, from 3,000 years ago to the 19th century sea level was almost constant, rising at less than 0.2 mm yr^{-1} (Houghton, 2001). Since 1900 the level has risen at 1 to 2 mm yr^{-1}; since 1993 satellite altimetry from TOPEX/Poseidon indicates a rate of rise of 3.1 ± 0.7 mm yr^{-1}. Sea-level rise can be a product of global warming through two main processes: thermal expansion of sea water and widespread melting of land ice. Global warming is predicted to cause significant rises in sea level over the course of the twenty-first century.

As sea level rises, the relative level (and thus the hydraulic gradient) between sea water and coastal aquifers changes. This can be compounded by lowering the aquifer water table by pumping. This gradient increases the potential for sea water to flow into the aquifer. Intrusion of sea water can affect the quality of water not only at site where intense pumping takes place, but across the aquifer at other well sites and undeveloped areas. Where topography and aquifer storage permit, gradual sea-level rise will be matched by a corresponding rise in groundwater level as the base discharge level rises and hydrodynamic equilibrium is maintained. However, the water resources of many areas, such as low-lying coastal zones and small islands are particularly vulnerable. The Maldives provide an extreme example. The highest point on the islands is less than 2 m above sea level. There are no rivers or streams and only a few freshwater wetlands and lakes. The main water resource is groundwater in basal aquifers, generally unconfined in nature and extending below sea-level. They are vulnerable to saline intrusion owing to the freshwater-sea-water interaction (Ibrahim *et al.,* 2000) and heavy exploitation.

Land use change

Forests disappear as a result of climate change, fire, hurricanes or other disturbances, however most deforestation in the past 40,000 years has been lost due to a range of human activities including clearance for arable agriculture, logging, fuelwood collection, fire management, grazing and indirectly acid rain. Although deforestation has decreased in the past 30 years, around 13 million ha are lost annually (some 6 million ha of which are largely pristine). Forests are known to regulate stream flow and reduce runoff, but to a lesser extent than widely believed. Forests are high users of water (FAO 2003); the canopies of tropical forests intercept up to 35% of rainfall, which is largely evaporated directly back to the atmosphere (maintaining small water cycles). Furthermore, much of the water that infiltrates the soil is used directly by the trees, thus reafforestation will not increase low flows in the dry season (Hamilton and Pearce, 1987). Indeed, replacing forest cover with other land uses, such as grassland, almost always results in increased runoff and stream flow. Species such as Eucalyptus are particularly high water users, as their roots can penetrate 50 m and thus continue using water when water table levels fall and other trees would stop. In South Africa, commercial tree planting requires a licence because of the additional water required; this is effectively an abstraction licence. On a local scale this runoff reduction tends to hold for small-scale rainfall events not responsible for major floods. After prolonged periods of rainfall, the forest soil becomes saturated and water no longer infiltrates into the soil, but instead runs off along the soil surface. Thus forests have only a limited influence on large floods. For example, it unlikely that floods in Central America resulting from hurricane Mitch in 1998 were exacerbated by deforestation (FAO/CIFOR, 2005).

For much of history, wetlands have been perceived as unhealthy waste-lands, harbouring disease, insects and even monsters. Drainage and destruction of wetlands became accepted practices throughout the world as demand for agricultural and urban land increased. Some estimates show that the world may have lost 50% of the wetlands that existed since 1900, much of this occurred in the northern countries (OECD, 1996). Increasing pressure for conversion to alternative land use has been put on tropical and sub-tropical wetlands since the 1950s. Wetlands have high economic value (Table 6) and support important biological diversity. Wetlands are also considered to augment low rainfall flows in rivers. Given that wetland soils are saturated for most of the time means that most wetlands have little available storage; indeed headwater wetlands are often termed 'contributing areas' by hydrologists because they generate flood runoff (Bullock and Acreman, 2003). Floodplains on the other hand often have large above ground storage capacity and may significantly reduce flood risk downstream. Part of the issue is that the term wetlands (according to the Ramsar Convention) covers a wide range of habitat types from coral reefs to underground lakes and it has been mistakenly assumed that functions and services that exist in one wetland type occur equally in all wetland types.

Another important land use change is the development of irrigated agriculture. Some widespread impacts of this change were anticipated, such as high evaporation rates and high salinity discharge waste. Perhaps, not foreseen are the implications of leakage from canals and downward percolation of water from paddy-fields that recharge local groundwater resources. Increased irrigation efficiency has often involved reducing leakage and percolation, but this has had an unintended negative effect of reducing local groundwater levels.

6. The role of dams

Opponents of dams argue that, in many instances, the environmental and social costs outweigh the benefits gained from dam construction and have aggravated, rather than alleviated, poverty. However, while dam proponents accept that mistakes and omissions have been made in the past, they believe that dams are commonly the best, and often the only, way to provide water security against disease, floods, famine and climate change. Furthermore, the positive and negative socio-economic and environmental impacts are well-known and can be mitigated, whilst the impacts of alternatives are relatively unknown (Alhassan, 2009).

The World Commission on Dams

In 1997, following many years of increasingly antagonistic debate between pro and anti dam lobbies, the World Bank and IUCN held a meeting in Gland, Switzerland (Dorcey *et al*, 1997). Participants agreed unanimously that insufficient data were available to conclude unambiguously whether dams were achieving their development objectives. They recommended the establishment of an international independent commission with a clear and achievable mandate. The World Commission on Dams started work in August 1998 to produce a global review of the development effectiveness of dams, a framework for options assessment and decision-making processes and internationally acceptable criteria and guidelines for planning, construction, operation, monitoring and decommissioning of large dams. The Commission's report (World Commission on Dams, 2000) concluded that dams have made an important and significant contribution to human development, but the social and environmental costs have, in too many cases, been unacceptable and often unnecessary. A key principle of the Commission was equity, *i.e.* that decisions made concerning dams should not be biased towards any particular group, and all key stakeholders should perceive the process and outcomes to be fair and legitimate, which requires transparency in the procedures and decision making criteria. The report made many recommendations including increased participation from stakeholders and provision of environmental flows downstream of dams. The report recommended that water and resources development should include appropriate options assessment through stakeholder participation, recognition of entitlements, sharing of benefits and avoidance of negative impacts and maintain downstream ecosystems and their dependent livelihoods. However, there is often great disparity between the views of different stakeholders and the WCD report did not give sufficient emphasis to the equally important need for a decision-making process, established by government, to mediate between these different interests. The WCD Chair indicated that the Strategic Priorities and Best Practice Guidelines were principles to guide decisions, rather than strict rules for compliance. Although there is disagreement on some aspects of the detailed recommendations, particularly from India and China, there is wide acceptance of the core values (Box 1) and strategic priorities.

The WCD report had significant implications for the UK, both domestically and internationally, particularly the involvement of stakeholders at the options assessment phase. It impacted on the work of many organisations including government departments, local authorities, export credit agencies, the private sector, research institutes, non-governmental bodies and local communities. The WCD invited Governments and international organisations to respond to its report. The UK government felt that the WCD process was a good example of inclusive dialogue between different interest groups and that its overall approach should be supported. The process and outcomes served a very important role, but was difficult to implement, partly due to lack of criteria to assess performance.

Box 1 WCD Core values

Equity: Decisions made concerning dams should not be biased towards any particular group, and all key stakeholders should perceive the process and outcomes to be fair and legitimate. This requires transparency in the procedures and decision making criteria.
Efficiency: The process should be both cost and time effective, making best use of available resources and knowledge.
Participatory decision making: It should include a wide range of key stakeholders, with particular attention given to those with rights and risks.
Sustainability: Stakeholders include the next generations as well as their own, and use of natural resources should not lead to environmental degradation.
Accountability: All those involved in decision-making should be accountable for their actions.

The Dams and Development Project (DDP)

The United Nations Environment Programme (UNEP) led a two-year follow-up *Dams and Development Project* to disseminate the WCD report (funded partly by DFID). OECD's Development Assistance Committee has incorporated a review of WCD recommendations as part of programme to harmonise environmental guidelines. A reference was made to WCD guidelines in the communiqué of the G8 in Trieste. The Asian Development Bank is to re-examine its own procedures, including its environment and social development policies, and determine the extent to which the Report's recommendations may necessitate changes in these procedures. The DDP work was split into 2 phases:

DDP Phase 1: November 2001 to July 2004

The aim of DDP phase 1 was: "to promote a dialogue on improving decision making, planning and management of dams and their alternatives based on the World Commission on Dams core values and strategic priorities."
This phase succeeded in:

- Raising awareness on the core values and strategic priorities.

- Stimulating their analysis in the national policy and regulatory frameworks.
- Helping to bring key national policy dam issues into discussion.
- Promoting a multi-stakeholder approach to debating highly sensitive issues.
- Supporting the development of locally appropriate recommendations on policy and procedure to improve decision making on dams endorsed by a broad range of multi stakeholder groups.

DDP Phase 2: February 2005 to April 2007

The aim of phase 2 was: “further promoting dialogue and producing recommendations on policy as well as facilitating the development of tools to improve decision making and best practices for water and energy management.”

The main achievement in creating a "compendium of relevant practices" essentially deals with nine key issues on the planning and management of dams:

- Stakeholder participation
- Identification of options
- Addressing outstanding social issues
- Environmental management plans
- Compensation policy
- Social impact assessment
- Benefit sharing
- Compliance mechanisms
- International policy on shared river basins.

Overall, the debate on dams and development carried out during DDP Phases 1 and 2, indicated some strong shift departing from a polarized discussion on 'whether dams should be built or not', to a discussion now around 'how to build a good dam' when a dam is the preferred option. The dams and development community is now more inclined to discuss issues in a more amicable and constructive manner.

During the DDP, the International Rivers Network has followed the progress of several dams to see if WCD processes have been implemented. They concluded that major projects, such as dams at Bui (Ghana), Lom Pangar (Cameroon), Epupa (Namibia), Bakun (Malaysia) and Mphanda Nkuwa (Mozambique) have not followed WCD guidelines. However, there is no complementary global information collection from governments or dam associations with which to compare the IRN findings. In contrast, there are many illustrations of dam developments demonstrating good practice against sustainability criteria. For example, the 50 MW Bumbuna project in Sierra Leone is seen as a good model of local community benefit sharing, where a Trust has been set up, supported by the World Bank, with a multi-stakeholder board which has empowered local communities in deciding on how the funds are used. Viet Nam has also put in place a pilot test and new policy guideline for benefit sharing with project affected people.

Forward directions

Many organisations have been guided by the WCD process. The International Hydropower Association has produced sustainability guidelines (IHA, 2004) to promote greater consideration of environmental, social and economic aspects in the sustainability assessment of new hydro projects and the management and operation of existing hydro-power schemes. The complementary sustainability assessment protocol (IHA, 2006) sets out a series of aspects or criteria for assessing energy options (Table 4) and provides a risk-based framework for assessing sustainability in the form of score for each aspect (Table 5).

Table 4 Sustainability aspects to assess new energy projects (IHA, 2006)

No	Aspect	Key elements
1	Need for the project	Evidence of future energy requirements and evaluation of options
2	Government and proponent policies	Adequacy to accept sustainability standards and ensure good practice
3	Political risk	Stability of political environment
4	Site selection and design	Maximises opportunities, avoids environmental and social impacts
5	Design construction and operational risks	Ability to design, construct and implement the project including procurement of goods and services
6	Project financial risk	Finance availability and terms for design and construction
7	Economic viability	Short and long term viability and likelihood of achieving its economic and service delivery objectives
8	Markets, innovation and research	Understanding of market conditions and ability to respond through research and development programmes
9	Additional benefits and capacity building	Delivery of additional benefits to affected stakeholders, e.g. employment, education, health care, amenity, flood control
10	Reliability assessment	Reliability of generation and network assets and fuel
11	Operational efficiency	Efficiency of fuel use and energy payback ratio compared to other options
12	Community acceptance	Degree of community support, stakeholder consultation and feedback
13	Social impact assessment	Understanding of community values, compensation, mitigation and enhancement strategies
14	Extent and severity of stakeholder impacts	Social, economic and cultural impacts on directly affected stakeholders
15	Safety and hazards	Safety and emergency preparedness, compliance with international standards
16	Cultural heritage	Protection and conservation of historic and indigenous heritage
17	Environmental impact assessment	Suitability, adequacy and effectiveness of environmental impact assessments, compensation, mitigation and enhancement
18	Extent and severity of environmental impacts	Areal extent, value of environment impacted, degree to which it can be avoided, mitigated, compensated or enhanced
19	Air, water and ground emissions	Assessment of emissions over life of project, environmental consequences and management costs
20	Greenhouse gases	Assessment of direct and indirect greenhouse gas performance over the life of the project

Table 5 Scoring Sustainability Assessment aspects

Score	Performance	Description
5	Outstanding/strong/comprehensive	At or near international best practice
4	Good to very good	High standard performance, meets most objectives
3	Satisfactory	Meets basic Sustainability guidelines
2	Less than satisfactory	Gaps in meeting Sustainability guidelines
1	Poor/very limited	Poor performance, map gaps in compliance
0	Very poor	No evidence of meeting sustainability guidelines

An initiative launched in March 2008 by IHA, WWF and The Nature Conservancy is the Hydropower Sustainability Assessment Forum, a collaboration of representatives from different sectors. The Forum aims to develop a broadly endorsed sustainability assessment tool to measure and guide performance in the hydropower sector. Work in 2008-2009 centres around developing the IHA Sustainability Assessment Protocol into simple guidelines and a measurement tool (with thresholds for each issue), that are practical, objective and able to be implemented across a range of contexts. A subsequent work phase (2010 onwards) will focus on potential protocol applications including pathways towards a sector standard. This work draws on the WCD Core Values and Strategic Priorities along with other existing principles and policies. Forum members include representatives of developed and developing countries (including notably China), environmental and social NGOs, commercial and development banks and the hydropower sector. Funding to date comes from the Norwegian, Icelandic and German governments, IHA and The Nature Conservancy. The recommendations of the Forum to date include having a four section protocol addressing: (1) strategic assessment; (2) project preparation; (3) project implementation; and (4) project operations. Relevant issues for each section encompassing economic, technical, governance, social and environmental issues have been outlined. Current challenges include making the tool suitable multi-purpose dams and for basin-scale assessment, that incorporates combined impacts of various schemes, and aggregating issue scores to produce a single index.

Dams and floods

Floods in 1998 devastated large areas of central China, resulting in damage in excess of US$30 billion and in 2004, 46 million people were affected by floods in China. Floods in 2000 affected 3.5 million people in Cambodia (one-third of the population) and 5 million in Viet Nam, with associated costs of US$145 million and US$285 million, respectively. In the same year, floods in Bangladesh displaced more than 5 million people and in India 30 million. Floods in 1999 in Viet Nam led to the deaths of 400 people and damage to property worth US$120 million. In August 2008 breaching of the Kosi river embankments left more than 2 million people homeless, destroyed 250,000 homes and inundated 247,000 acres of farm land in Bihar India.

Dams, by design, have significant water storage potential and can play a significant role in reducing floods downstream. Often flood management is a secondary function; for example the Three Gorges dam on Yangtze generates hydropower, but is also designed to reduce the frequency of major downstream flooding from once every 10 years to once every 100 years. The dam has a flood storage capacity of 22 km^3 and is intended to minimise the impacts of even a "super" flood to the millions of people, farmland and industry of Wuhan, Nanjing and Shanghai that lie next to the river downstream. Many other dams have a significant flood management function, but this varies around the world. Dams clearly only provide flood storage when the reservoir is not full (although there may be some attenuation even when full and water passes the spillway). Effective flood control requires careful management of the dam, including drawdown of water level prior to a flood, which may compromise other uses. Whilst the USA has over 1000 dams purely for flood management and further 1000 multipurpose dams that include flood management, none of the Indian dams registered in the ICOLD World Register of Dams has a flood control function (India has not particularly favoured flood control by regulation, preferring to use levees).

Environmental flows

Goal 7 of the MDGs commits nations to ensure ‘environmental sustainability’ and reverse the loss of environmental resources. The World Commission on Dams report reported the negative impacts on ecosystems of alterations to flow regimes downstream of dams. This highlighted the importance of appropriate flow releases, including floods, from dams to maintain and restore degraded ecosystems and their dependent livelihoods. Research in this area has led to establishment of the new scientific discipline of hydro-ecology (Richter *et al*., 1996; Poff *et al*., 1996; Acreman, 2001) that demonstrates the link between river flows and ecosystem function and the provision of ecosystem services. The concept was championed by IUCN as part of their Water and Nature Initiative (supported by DFID) which produced a tool-kit for environmental flows (Dyson *et al*., 2003) and how to make appropriate payments for ecosystem services (Smith *et al*., 2006). The World Bank has also adopted the concept of environmental flows as part of its safeguards policy for water infrastructure (Brown and King, 2003).

One of the major developments has been the move away from the concept of a minimum ecological flow as this implies that a river ecosystem could be maintained by a constant low flow release from a dam. It is now accepted that releases need to reflect the complex, constantly-changing nature of river flow regimes, including high, average and low flows, including the realisation that too much water at the wrong time can be as damaging to the ecosystem as not enough. Rates of change in flow also need to be considered as, for example, rapid reductions in flow as turbines are closed may leave fish stranded in shallows and rapid increases may wash fry downstream.

Achieving appropriate water quality is also a key aspect of environmental flows. The temperature of released water may be different from natural, especially if the reservoir is deep and water is released from low outlet structures. Deep water in stratified reservoirs may also contain noxious substances such as hydrogen sulphide and methane (Petts, 1998). Furthermore, released water is likely to be low in suspended sediment, which is deposited in the reservoir; release of water with a low sediment concentration may cause erosion downstream of the dam.

There are cases where dams can benefit environmental flows, such as by providing water managers with the means to restore flows to their natural or historical patterns when they have been altered by climate change or other factors. Furthermore, releases from reservoirs may be made to optimise environmental services, such as fish breeding or flood recession agriculture, that may not be possible during natural droughts and extreme floods; such as in the Waza-Logone floodplains, Cameroon (Loth, 2004).

A benefit of dams has often been the reduction in flood magnitude downstream (see above). Nevertheless, floods are now recognised as of great importance to rural economies, supporting a variety of local livelihoods. For example, the fertile floodplain wetlands of the lower Senegal River, which forms the frontier between Senegal and Mauritania are of vital social, economic and ecological importance in this semi-arid Sahelian fringe of the Sahara desert. Natural inundation covers up to 250,000 hectares of the floodplain supporting 25,000 hectares of flood recession agriculture (including maize, beans, watermelon, potatoes and millet), grazing, forests (which provide fuel-wood and construction timber), fisheries and wildlife habitat. The economic value (at 1995 prices) of the floodplain has been estimated (Acreman, 2003) at US$56-136 per hectare for recession agriculture, US$140 per hectare for fishing and US$70 per hectare for grazing. However, construction of the Manantali dam upstream in Mali in 1986 led to loss of flooding. As a result, the Senegal River basin authority (OMVS) instigated a programme of flood releases as a key element of catchment management to restore the wetlands and their values to local communities. This action restored much of the economic value. OMVS is now assessing the economic trade-off of environmental flows, as making floods releases has a cost of loss of hydropower production potential.

Maintaining a natural flow regime downstream of a dam may be difficult operationally, requiring real-time forecasting to coincide releases with upstream inflows to the reservoir and tributaries joining the river below the reservoir. Planning for the Grand Falls dam on the Tana in Kenya included assessment of different reservoir releases that would combine with inflows downstream of the dam to inundate the floodplain in the lower valley (Acreman, 1996). Some dams have limited capacity to make releases and generating managed floods or achieving specific timing of release may be very difficult or costly, especially if retrofitting of large release structures is required. As part of Lesotho Highlands Water Project Treaty, Mohale dam outlets were resized and a new valve was added to Katse dams to environmental flow release needs.

DFID funded a major contribution to the work of World Commission on Dams to assess the benefits of managed floods to rural livelihoods (Acreman *et al.,* 2000). Further to this work, many estimates of economic value have been undertaken in developing countries (Table 6) where the livelihoods of rural communities are very frequently directly linked to wetlands ecosystem productivity (Emerton, 2007; Acreman and Mountford, 2008).

Table 6. Economic values of wetlands (Acreman and Mountford, 2009)

Wetland	Goods and services	Economic value	Reference
Hadejia-Nguru wetlands, Nigeria	Fishing, agriculture and fuel-wood	US$32 per 1000 m^3 of water,	Barbier *et al.* (1991)
Indus delta mangroves, Pakistan	Fisheries	US$100 million foreign exchange in 1997	Meynell and Qureshi (1995)
Barotseland floodplain, Zambia	Flood attenuation Groundwater recharge Nutrient cycling Carbon sequestration	$0.4 million $5.2 million $11.3 million $27 million	Turpie *et al.* (1999)
Waza-Logone floodplain, Cameroon	Fishing, grazing, recession agriculture	$2.5 million per year	Loth (2004)
Hail Haor wetland, Bangladesh	Fish, plants, livestock grazing, timber	$8 million per year	Colavito, 2002
Coastal wetlands, Youngsan, Korea	Recreation, amenity, existence	$176 million per year	Pyo, 2002
Muthurajawela Marsh, Sri Lanka	Flood attenuation	$5 million per year	Emerton and Kekulandala 2002
Nakivubo swamp, Uganda	Waste water treatment	$2 million per year	Emerton *et al.*, 1999

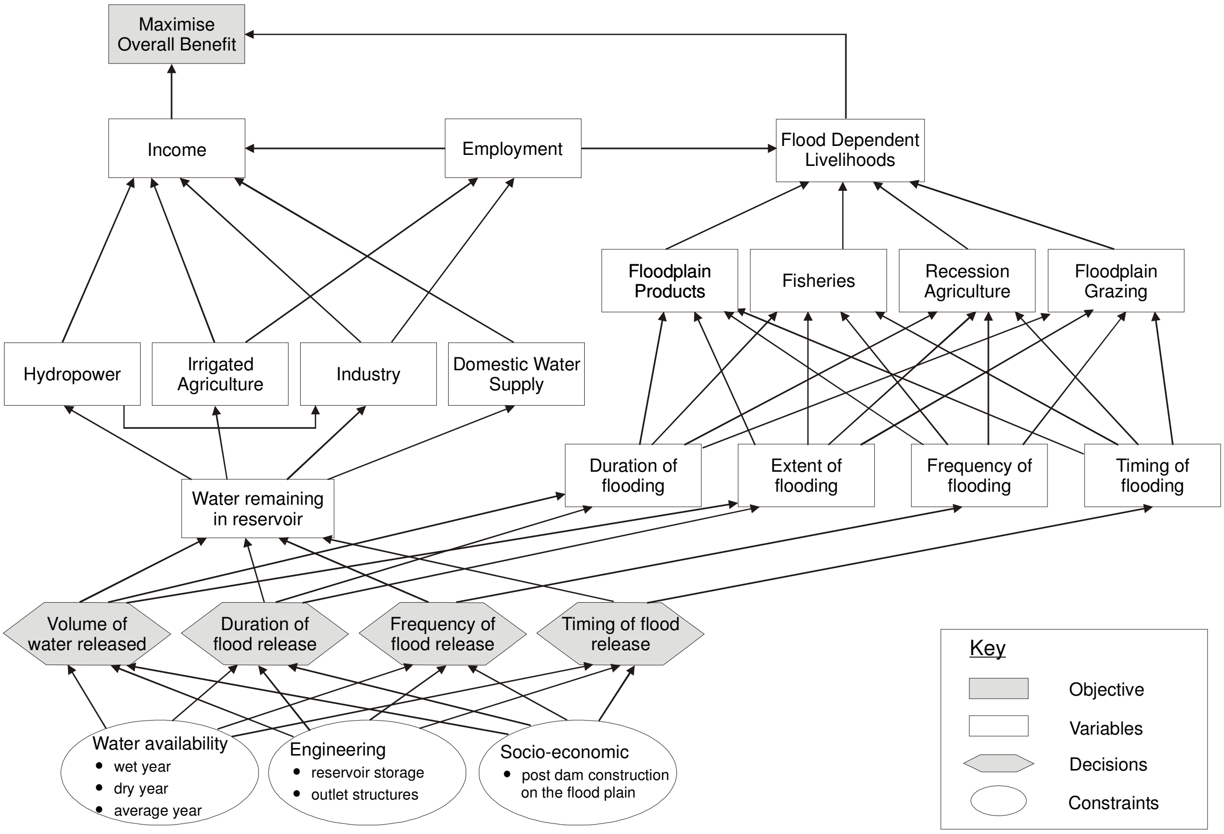


Figure 7. The complex interaction of factors that must be considered when making decisions about managed flood releases (Acreman and McCartney, 2002).

Figure 7 illustrates the trade-off between water left in the reservoir for direct uses (e.g. irrigation and hydropower production) and the water released to maintain downstream ecosystems and their dependent livelihoods (indirectly supporting people). These inter-relationships must be considered in making decisions about water use. In any specific situation, the relationship between physical and socio-economic dynamics will not be well understood. Consequently, many of the links between variables will be uncertain, unpredictable and imprecise and many will be understood only in a qualitative rather than a quantitative way. It is the uncertainty in these relationships, and often the lack of relevant data, that makes decision-making so difficult (Acreman and McCartney, 2002).

Despite advances in methods and numerous assessments in many parts of the world, there are few cases where environmental flows have been implemented. This is primarily because water has been previously allocated to direct use and it would need to be 'recovered' for allocation to the environment. Even in the case of the Senegal River, it is uncertain whether environmental flood flow releases from Manantali will continue due to loss of hydropower potential. However, the World Bank claims some achievements in ecosystem restoration through environmental flows in the Tarim, China and Northern Aral Sea.

Greenhouse gas emissions from reservoirs

The most important greenhouse gases (GHG) are water vapour (which currently contributes 36–70% to the greenhouse effect), carbon dioxide (which contributes 9–26%) and methane (which contributes 4–9%), although methane (CH_4) is 12 times more potent per unit of gas than CO_2. All water bodies generate water vapour by evaporation, with area of water surface being an important factor, along with temprature and windspeed, so that reservoir construction with increase water vapour. Established natural vegetation generally absorbs CO_2 and has low, or even negative, methane releases. Exceptions to this general rule are wetlands (including river margins), which absorb CO_2, but release methane. Agricultural land can be a net emitter of GHGs through the release of nitrous oxide from the applied fertiliser. Ploughing and drainage of carbon rich soils can also change a surface from an absorber of CO_2 to an emitter. Some of the carbon sequestered by vegetation is washed into river systems either as dissolved organic carbon (DOC) or particulate matter. It is not clear how much of this river carbon is 're-gassed' to the atmosphere and how much is fixed in sediments.

Hydroelectric schemes themselves produce fossil fuel free electricity, although associated infrastructure may cause carbon emissions, and therefore have the potential to reduce our carbon footprint. The International Hydropower Association (2008b) reports that hydropower currently offsets 2.1 billion tonnes of CO_2 emissions each year. If developed, the remaining realistic hydropower potential could offset a further 7 billion tonnes. However this must be balanced by the possibility of increased methane release (particularly on formation of the water body) and the disruption of the natural carbon cycling between the land, river and atmosphere. GHG emissions vary with reservoir location, power density (W capacity per m^2 flooded), flow rate, and whether dam or run-or-river plant. Recently, the GHG footprint of hydropower reservoirs has been questioned (Fearnside, 2004; UNESCO, 2006). Some reservoirs have been shown to absorb CO_2 at their surface, but most emit small amounts as water conveys carbon in the natural carbon cycle (Tremblay, 2005). High emissions of CH_4 have been recorded at shallow, plateau-type tropical reservoirs where the natural carbon cycle is most productive (Delmas, 2005). Deep water reservoirs at similar low latitudes tend to exhibit lower emissions. Methane from natural floodplains and wetlands may be suppressed if they are inundated by a new reservoir since the methane is oxidized as it rises through the covering water column (Huttunen, 2005; dos Santos, 2005). Methane formation in freshwater produces by-product carbon compounds (phenolic and humic acids) that effectively sequester the carbon involved (Sikar, 2005).

Further research is needed to establish the extent to which shallow tropical reservoirs may increase methane emissions. Several Brazilian hydro-reservoirs were compared using life-cycle analyses with combined-cycle natural gas turbine (CCGT) plants of 50% efficiency (dos Santos *et al.*, 2004). Emissions from flooded reservoirs tended to be less per kWh generated than those produced from the CCGT power plants. Large hydropower complexes with greater power density had the best environmental performance, whereas those with lower power density produced similar GHG emissions to the CCGT plants. For most hydro projects, life-cycle assessments have shown low overall net GHG emissions (WEC, 2004a; UNESCO, 2006).

Since measuring the incremental anthropogenic-related emissions from reservoirs remains uncertain, the UN Framework Convention on Climate Change (UNFCCC) has excluded large hydro projects with significant water storage from the Clean Development Mechanisms (CDM). The IPCC Guidelines for National GHG Inventories (2006) recommended using estimates for induced changes in the carbon stocks.

Overall it is apparent that all freshwater systems, whether they are natural or man-made, emit greenhouse gases (GHG) due to decomposing organic material. This means that lakes, rivers, estuaries, wetlands, seasonal flooded zones and reservoirs emit GHG. In cool and temperate regions, GHG emissions from reservoirs are higher just after impoundment, but fall within the first years to reach levels similar to those of neighbouring lakes. In some tropical freshwater reservoirs, these conditions can persist for additional years, but also eventually reach levels similar to those of neighbouring lakes and flood plains. Freshwater reservoirs are collection points of material coming from the whole drainage basin area upstream. As part of the natural cycle, organic matter is flushed into these collection points from the surrounding terrestrial ecosystems. In addition, domestic sewage, industrial waste and agricultural pollution will also enter these systems and produce GHG emissions, the cause of which should not be attributed to the collection point. A desk-study of GHG emissions from creation of hydropower reservoirs in India (World Bank, 2007) concluded that they would be low, because India's reservoirs are to a large extent located in regions where natural conditions restrict processes that give rise to methane emissions, although lack of data makes these conclusions uncertain.

Health impacts of reservoirs

Dams can clearly have a positive health impact by for example increasing irrigated food production and available nutrition from reservoir fisheries. However, impoundments have in some notable cases been accompanied by serious health hazards. Increased incidence of malaria and schistosomiasis, for example, has been recorded in a number of water projects in various parts of Ethiopia. Lake Kariba supports an important inland fishery and water during the dry season attracts large herds of buffalo, eland and other species, but the dam has had negative effects on the health of local people as disease vectors, such as snails that convey schistosomiasis, have proliferated (Masundire, 1996).

Rift valley fever is another mosquito-borne viral disease that is endemic in East Africa, but unitl1987 had not been recorded in west Africa, when an outbreak occurred after filling of Gorgol and Diama reservoirs in the Senegal valley, causing around 200 human deaths. Abortion rates amongst sheep and goats were about 80% due to the virus. Schistosomiasis was also never reported historically in the Senegal valley. The first cases occurred around Manantali and Diama dams in 1987; by 1989 the prevalence rate had risen to 72% (Verhoef, 1996). Some of the negative health aspects can be remedied by reservoir operations that mimic natural hydrological variations, such as letting irrigation canals dry out to kill snails. The World Health Organization's Panel of Experts on Environmental Management for Vector Control (PEEM) has developed guidelines, which should be followed.

Sedimentation of reservoirs

Heavy storms often trigger landslides and river-bank erosion, carrying sediment into reservoirs. This can be greatly exacerbated by poor land use practices. In a study of sediment carried by rivers throughout the world (Walling and Webb, 1987), much of the Mediterranean (specifically the northwest of Africa, Italy, the Balkans, including Greece and Turkey) has been classified in the highest category, with more than 500 tons km^2 yr^{-1}. On large catchments much eroded material remains on the slopes, whereas in small catchments it tends to find its way to the river. Data for Tunisia show that due to high sediment loads of rivers, the expected life of a dam is 50-100 years compared to design life exceeding 200 years.

The Indus River in Pakistan is fed by snow and glacier melt water from the Karakoram and Himalayan mountains and monsoonal rainfall. The river carries a high sediment load; the annual suspended sediment load into Tarbela reservoir is about 200 million tonnes per year. This means that, over time, the reservoir has developed a significant fine-grained sediment delta that is now encroaching on the intakes. Unless action is taken to provide protection of the intakes through construction of a sediment flushing channel and underwater protection barrier, the reservoir operation will be seriously at risk (Lorrai and Pasche, 2007). As the dam meets about 50% of Pakistan's irrigation needs and almost 35% of its power and energy demands, ensuring its continued operation is vitally important. Proposal for sediment management were developed by TAMS (1997) and results of the recommendations given by Attewill (1998). Despite the large costs of the proposed remedial works (around US$700 million at 1997 prices) the economic benefits in terms of agriculture and energy ensure a 21.6% economic internal rate of return on this proposed investment. The annual agricultural economic benefits rise to $240 million by 2030 and energy benefits costs approach $540 million annually (this would be the fuel costs of providing the power through alternative thermal power station). Thus sediment can be managed economically given the right conditions, even for a reservoir such as Tarbela where sediment inflows are very high by world standards. One option is build 'dead storage' into the dams to allow for future sedimentation, such as being included in the new Tekeze dam in Ethiopia.

It is increasingly recognised that good land management needs to be integrated with water management to address erosion and sediment issues (see integrated catchment management below). For example, the Tanzanian government is working with farmers in the Kihansi catchment, above the hydropower dam, to ensure soil erosion is minimised.

Regional aspects of dams

Hydropower dams are constructed both to support local energy demand and in some cases to export energy. Nepal is a good example of a country with hydropower potential that exceeds internal demand. Government policy has greatly helped proliferate decentralised small and micro hydropower systems in the hilly and mountain districts of Nepal. Larger schemes are also planned or under construction, such as 70 MW Middle Marsyangdi Hydro Project. However, large-scale hydropower projects are feasible in Nepal only when India is prepared to buy power at commercial rates and to share the benefits accrued.

When built, Cahora Bassa in Mozambique was potentially the world 5th largest producer with a capacity of 4,100 megawatts, which is more than 20 times the national demand. It was intended that the extra electricity would be exported to South Africa, but during the civil war, the power lines were destroyed by the Renamo guerillas and for many years satisfied only a small local demand. Today there is a regional network for electricity transmission across southern Africa and Mozambique experts to other countries. As part of agreements between the riparian countries of the Senegal River, organised by the river basin development authority (OMVS), electricity from Manatali dam in Mali is shared across the river basin.

In the Democratic Republic of Congo (DRC), two hydropower dam (Inga I and II) exist on the Congo River with a combined capacity of 1775 MW. There plans for Inga III (4320 MW) and Grand Inga (40 GW), which will be the world's largest hydropower scheme, with transmission lines proposed to Egypt, Nigeria and Southern Africa. However, DRC is one of Africa's most politically volatile and corruption-plagued countries, implying that it may not provide stable energy security.

Large and small dams

One of the objectives of dam storage is to increase water security where the climate is variable. As discussed above, future changes in climate may be bring more variability. Consequently, more and larger dams may be the most appropriate and some cases the only solution. Much depends on the individual river basin and how the climate changes, More frequent droughts may reduce capacity and increased floods may reduce dam safety and augment sedimentation rates. As illustrated by the Tekeze dam in Ethiopia, larger dams with ‘extra’ storage may provide a buffer and increased flexibility to deal with sedimentation, droughts or providing environmental flows. A small number of large dams may also mean that environmental impacts are focused in a few (sacrificial) catchments, leaving others potentially in more natural ecological condition, and it may be easier for authorities to monitor and control compliance to safeguards. However, in some cases, investing in and becoming dependent upon a single large dam could be hydrologically a high risk strategy. Large dams also tend to focus on national or regional level economic growth, rather than directly addressing local livelihoods and poverty.

An alternative strategy is to invest in a network of smaller dams. These may be tailored for local needs, more directly addressing local livelihoods and poverty, and permit more input and control from local users. Managing many small dams can be a challenge, making it difficult to implement appropriate safeguards. Dispersed networks of small dams may provide more flexibility and reduce hydrological risk. Environmental and social impacts will become distributed, but it is difficult to generalise whether their cumulative impacts will be greater or less than a few large dams. Where the dams are small enough not to impede fish migration or alter river flows and sediment movement, such as with many run-of-river schemes, their impact may be low.

Small multifunctional dams have a range of benefits including local water storage for domestic and small scale industrial use and for small-scale aquaculture. This is in keeping with the tried and tested traditional approach to water storage found in communities across Asia, particularly well illustrated in Indonesia. Networks of small dams also provide increased flexibility and spread hydrological risks between sites which may be increasingly advantageous under climate change if rainfall becomes more spatially variable. However, there are generally greater evaporation losses from small dams than storage in a single large reservoir. In Mugabe, Zimababwe, >90% of water from a small community reservoir was lost to evaporation, although the 10% used was very important to livelihoods and wellbeing of the community.

7. Groundwater storage

How much groundwater is stored?

Groundwater is the largest global store of freshwater on the planet that is not frozen. Many estimates of the have been made, but available fresh groundwater globally is in the range 8.0 to 10.5 million km^3. Estimates of annual recharge to aquifers range from about 0.011 to 0.013 million km^3, i.e. about 1/800th of global fresh groundwater storage. Annual volumes of river flow are three times this amount. The annual recharge approximates to base-flow discharge to rivers but does not include direct groundwater discharge to oceans. This is estimated to be about 0.002 million km^3 (Marget, 2008).

For a global population of 6 billion, water consumption is about 2200 km^3/yr (Shiklomanov, 2000). Each human comprises about 50 l water so population growth of say 3 billion by 2042 will take only 0.15 km^3 out of the water cycle but will increase demand by at least a half. In addition to the global fresh groundwater resources, there is estimated to be between 12.8 and 13.6 million km^3 of brackish and saline groundwater down to a depth of 2 km. Larger estimates of saline and inaccessible groundwater include that at greater depth and that in low permeability rock types, hence largely non-recoverable. Taking a median global estimate of 9.8 million km^3 of fresh groundwater (UNESCO 1979, Shiklomanov 1990, 2003)

- 3.6 million km^3 (1 million km^3 in Africa) of fresh groundwater is found in the top 100 m and
- 6.2 million km^3 (1.5 million km^3 in Africa) of predominantly fresh groundwater is found between 100 and 200 m depth.

Groundwater in the hydrological cycle

Groundwater provides a buffer to climate variability, smoothing out periods of intense precipitation and drought. This effect can be seen on an annual scale, for example recharge in temperate or seasonal monsoon climates, as well as over extended periods of several years. Groundwater discharge maintains river's flow during seasonal dry periods, analogous to annual release of snow and ice melt water.

Depending on the flow path taken, the 'active groundwater' component of the water cycle can take months, years, or decades to discharge at the surface. Some flow paths involve time scales of centuries or millennia. This water is usually thought of as 'fossil groundwater' as it is not being replenished at the present time. In some locations where there is little or no available surface water, groundwater storage, although limited and more difficult to develop, may be the only feasible option. These difficult hydro-geological environments include:

- the weathered basement in Africa and
- small island states (SIDS) with limestone aquifers and freshwater lenses

In its natural state, the water cycle finds a balance, not necessarily on an annual basis, where, on average, groundwater discharge equates to groundwater recharge. This balance is disturbed by groundwater abstraction resulting in falls in groundwater levels and consequent reductions in base-flow to rivers. However water resources can be sustainably managed to minimise impacts on environmental flows by using delays in the system and by creating additional storage in aquifers. Fossil water needs to be managed as a non-renewable resource and effectively exploited by 'mining.'

As stated earlier, 11 000 to 13 000 km^3 of water is recharged annually to aquifers at a global scale, a significant proportion of which is used to meet the current demand of about 2200 km^3 for fresh water to grow food, wash and drink, and meet industrial demand. However, the majority of this water is not consumed but returned to the water cycle, mainly through evaporation, but also as wastewater, treated or untreated, which impacts on surface and groundwater quality.

At global and regional scales, distribution of groundwater storage may be affected by changes in precipitation, but the reaction will be slower than for surface water so longer period (seasonal, annual and inter-annual) are more critical. At the local level the impacts of abstraction and pollution of groundwater storage are of much more immediate concern. Continued overexploitation of groundwater will result in deteriorating water quality as deeper, older and poorer quality groundwater are accessed and consequent reduction in baseflow to streams will impact ecological and environmental services. Salinization of soil and groundwater from agricultural and land use practices as well as contamination with agricultural, industrial and waste water all contribute to the pollution of the fresh groundwater store. Protection of quality at a level equivalent to that expected of a surface impoundment is required if energy consuming treatment is to be minimised.

Groundwater use

Groundwater storage has a number of advantages as a resource over surface water storage. Aquifers provide natural storage and thus do not need dams and reservoirs that take up large areas of sometimes fertile agricultural land, although pumping is required to bring water to the surface. Groundwater recharge and storage are processes that occur over years, decades and longer so are less sensitive to short term reductions in rainfall. Groundwater is also not subject to evaporation, although evaporation rates impact on recharge. Some rock types such as sandstone and limestone can provide ample water storage, but, hard crystalline rocks that underlie much of sub-Saharan Africa bear only limited water. Yet around 250 million people in Africa alone live on land underlain by this rock type and, particularly in rural communities, rely on groundwater. Groundwater is often preferred by farmers, as wells provide direct control over the resource and greater flexibility in its use, *i.e*. there is no reliance on complex upstream management systems that are an essential part of irrigation schemes. However, individual wells are not independent and proliferations of small wells in conjunction with cheap electricity to drive pumps have lowered water tables in many regions including Spain and India. In northern China, for example, there were 2.6 million wells at the end of 1997, resulting in the water table falling 42 meters in 30 years (Brown 2000). Where there is no management of use of groundwater, the over exploitation of the resource is controlled by increasing pumping costs, drying of shallower wells and deterioration of water quality. These factors are increasingly imposing demand management through introduction of regulations, change of crop or land use to less water intensive or higher value crops or improved harvesting of water and management of recharge to aquifers to replenish the storage.

The future for fossil water

Evidence of climate change is, in places, recorded in the location and quality of groundwater. In North Africa and the Middle East, for example, extensive bodies of relatively fresh groundwater exist in desert areas where no recharge to the aquifers has occurred for millennia. For example, in Libya, isotopic evidence indicates that it infiltrated into the Tertiary sands aquifer during pluvial periods between 35,000 and 10,000 years ago.

As with other mineral resources such as coal, iron or oil, fossil water is an exploitable resource that can be ‘mined’ and has a finite life. The groundwater in the Kufra and Sirte basins, in Libya, has been exploited to irrigate crops for the last 30 years and will continue to provide water for several decades to come. This groundwater is being transported several hundred kilometers to the populated coastal region in pipelines, 4 m in diameter – a massive engineering project known as the Great Man-Made River Project.

Enhancing recharge (Managed aquifer recharge and storage)

For centuries, we have not relied solely on natural recharge to replenish groundwater storage, mainly through managing soil moisture to capture intermittent precipitation. More recently, as hydrological and IWRM understanding has increased, deliberate recharge of aquifers to store water has also been practised more widely. This is generally known as ‘artificial recharge’ or ‘managed aquifer recharge’ as this implies intentional modification for beneficial use. Numerous schemes and methods exist to manage recharge of groundwater and they are as varied as the ingenuity of those involved in their construction and operation. Broadly, they can be grouped into the following categories:

- Spreading methods
- Open wells and shafts
- Drilled wells and boreholes
- Bank infiltration
- Sand storage dams
- Roof-top rainwater harvesting,

The effectiveness of recharge schemes is governed by climate, hydrogeology, topography, source water availability and quality, operational and management issues, regulatory controls as well as environmental and socio-economic considerations. The complex interaction of some or all of these factors will determine the degree of success, which itself can be viewed from a variety of perspectives. Managed aquifer recharge for storage should be used in conjunction with other sources and stores of water in rivers, lakes, impoundments as well as groundwater that is replenished without intervention.

Any method by which groundwater can be increased is thus potentially a great benefit for water resources. Disadvantages come in the form of the costs to re-pump the water from the aquifer and vulnerability to pollution from landfill sites or agricultural chemicals leaching through the soil. In Israel more sophisticated techniques using urban waste water have been practice for the last 30-40 yeas, but is being developed more widely as an option as population increases have put pressure on water resources. It is particularly useful technique in hot arid countries where rainfall may be infrequent and evaporation is high. In India, for example, MAR is practised widely through millions of structures that capture monsoonal rainfall and infiltrate it into the often low storage capacity basement aquifers. The Central Ground Water Board (CGWB, 2005) estimated that an area equating to about 14% of the land area of India is suitable for infiltrating the 36,453 million m^3 of water available for recharge annually. This is equivalent to an average infiltration of 80 mm, one order of magnitude higher than that estimated at three localised, site specific studies (Gale *et al*. 2006). These figures indicate the uncertainty associated with estimates of water available for recharge as well as the effectiveness of interventions. It is currently, and will continue to be, an area of debate resulting in further monitoring and research as the impacts of large scale implementation of watershed interventions are felt.

In North Africa and the Middle East rainfall is generally very low (less than 500 mm per year). Furthermore, much of this may fall as intense storms each lasting only a few hours creating flash floods, much of which evaporates. To make best use of this water, groundwater recharge dams have been built in some locations. These are built where an aquifer is near the surface and the soils are very permeable. The dam creates a temporary artificial wetland, holding-back flood water and allowing it to percolate through the soil and into the aquifer. A disadvantage of the system is that sediments brought down by the flood waters build-up behind the dam and seal the bed of the reservoir and thus impede infiltration. However, at many sites the soil is removed and used on agricultural land as it is often very fertile. There are two schemes within Israel that make use of floodwaters to recharge the groundwater. In the Shiquma scheme, north of the Gaza Strip, a small dam has been constructed to create a reservoir which holds flood water. The water is then pumped to large depressions (infiltration basins) in the sand dunes near the coast where it percolates into the ground to recharge the dune aquifer. The average annual recharge is around 3.5 million m^3. The scheme has suffered from clogging of the bed of the infiltration basins with fine sediments that form crusts in the dry season and inhibit percolation. In addition, pumping costs make the water expensive, US$ 0.3 m^{-3} (compared with US$ 0.8 m^{-3} for desalinisation of sea water). The Nahalei Menashe scheme, near Caesarea, does not suffer in the same way from sediments as the flow is diverted into a reservoir that is off-line and the water flows by gravity to the infiltration basins.

There is potential for artificial recharge in other areas of the Mediterranean. Proposals have been put forward, for example, for the Gaza Strip (Blom, 1995). Groundwater recharge currently takes place through the bed of Wadi Gaza, which could be doubled by construction of small weirs to create a 50 hectare temporary reservoir. This would assist the serious water stress problem within the Gaza Strip where withdrawals of water from the aquifer exceed the freshwater recharge by 39 million m^3 yr^{-1} and the safe yield by 49 million m^3 yr^{-1}. Artificial recharge is also being employed for water resources management in more humid areas such as The Netherlands, where water from the Rhine is being used to recharge the aquifer in the sand dunes near Amsterdam to increase water supply.

8. Alternatives to large scale water storage

Indigenous knowledge

Future predictions of increased climatic variability and change will require adaptations to water management, including expanding efforts to promote rainwater harvesting, improved soil management techniques that decrease soil erosion and increase soil water holding capacity (African Drought Adaptation Forum, 2008). Many regions of the world, such as the African Sahel, have been characterised by historical severe and frequent droughts and local communities, through their indigenous knowledge systems, have developed and implemented extensive mitigation and adaptation strategies that have enabled them to reduce their vulnerability to past climate variability and change, which exceed those predicted by models of future climate change (Nyong *et al*, 2007). Examples of physical systems include the kundi water harvesting tanks in Rajastan, India. This collect water from circular micro-catchments sloping towards the centrally located storage structure. The quality of water from kundi is good and if maintained properly no serious water contamination occurs. Local materials such as clay, silt, lime, ash and gravel are traditionally used to construct the catchment. Examples of social and economic strategies developed by pastoral herders in the Sahel include reciprocal exchanges of livestock, re-stocking alliances, dowry and marriage prices as a form of live-stock redistribution and selective breeding, communal insurance schemes and labour exchanges (Niamir-Fuller, 2000). This indigenous knowledge needs to be considered in the design and implementation of modern mitigation and adaptation strategies.

Virtual water and water footprints

Virtual water is the amount of water that is embedded in food or other products needed for its production. For example, to grow one kilogram of wheat we need about 1,000 litres of water, i.e. the virtual water of this kilogram of wheat is 1,000 litres and 14,000 $l\ kg^{-1}$ for beef. The per capita consumption of virtual water contained in our diets varies according to the type of diets, from $1 m^3\ day^{-1}$ for a survival diet, to $2.6\ m^3\ day^{-1}$ for a vegetarian diet and over $5\ m^3$ for a USA style meat based diet. It is clear that moderating our diets especially in the developed world could make much water available for other purposes, but cannot be achieved by the water sector alone, as this is a wider cultural/economic issue.

With the trade of food crops or any commodity, there is a virtual flow of water from producing and exporting countries to countries that consume and import those commodities. A water-scarce country can import products that require a lot of water for their production rather than producing them domestically. By doing so, it allows real water savings, relieving the pressure on their water resources or making water available for other purposes. However, there is an alarming trend for poorer water-scarce countries to grow and export fruit and other water hungry crops to richer wetter countries because of their warmer climate. The wine trade between producers in Australia, South Africa and the Mediterranean and consumers in north Europe is a clear example; as is the growing of tomatoes in Morocco and citrus fruit in Israel and southern Africa. At the local scale, production of high value crops (e.g. fruit and flowers) may be a good use of water generating jobs for local poor, such as the flower industry in Kenya.

At the global level, virtual water trade has geo-political implications: it induces dependencies between countries. Therefore, it can be regarded either as a stimulant for co-operation and peace or a reason for potential conflict. The water footprint of a nation shows the total volume of water that is used to produce the goods and services consumed by its inhabitants. Since not all goods consumed in one particular country are produced in that country, the water footprint consists of two parts: use of domestically-sourced water resources and use of water embedded in products imported from outside the borders of the country. The water footprint includes both the water withdrawn from surface and groundwater and the use of soil water (in agricultural production). One option would be to develop water credits along the lines of carbon credit as current food import prices do not appear to regulate virtual water trade sufficiently. An extension of the concept of virtual water is 'virtual storage', where water-hungry crops are grown in years of plentiful rainfall and stored for use in dryer years. A further recent development in the virtual water area is the purchase or lease of land by rich countries (such as Kuwait) in poorer countries with more water resources (such as Pakistan) to grow their food for them. As an example, Korea's Daewoo corporation has leased roughly half of the arable land in Madagascar. Overall, water foot-printing is of primarily important where the source country suffers from water inadequate water and is of much lower relevance when they have enough water.

Desalinisation

Desalinisation is the process of removing salt and other minerals from water, normally sea-water, to make it potable. Desalination requires large energy inputs and specialised, expensive infrastructure. The process is used largely in the Middle East. Israel is now desalinising water for US$0.53 per cubic meter, whilst in Singapore the cost is US$0.49 per cubic meter. Many large coastal cities in developed countries are considering the feasibility of seawater desalination, due to its cost effectiveness compared with other water supply options. Cost can be reduced by, for example, cogeneration where excess heat from power production for desalination, in an integrated, or "dual-purpose", facility. However, many major water issues are far from the sea, such as New Delhi, or in high places, such as Mexico City requiring high transport costs.

Desalinisation does not necessarily use sea water, but also brackish surface and groundwater where salinity levels are lower. Thames Water is planning to desalinate water from the Thames estuary for London, with intake only on the ebb tide when salinity levels are at their lowest.

Demand management

Water demand management can be defined as any method, - whether technical, economic, institutional, financial or social - that will accomplish one (or more) of the following tasks:

1. Adjust the nature of the task or the way it is undertaken so that it can be accomplished with less water or with lower quality water;
2. Reduce the loss of water as it flows from source through use to disposal;
3. Shift the timing of use from peak to off-peak periods;

The FAO campaign 'more crop per drop' is based around technical solutions, such as drip-irrigation and improved water scheduling. However, investments, market incentives, institutional capacity and political will are often lacking to improve modernize irrigation systems and to respond to the needs of people in rural areas.

Water pricing is common form of demand management. In Tunisia, a direct link was found between water prices and water use for households above subsistence levels. However, increasing water prices to reduce demand has drawbacks. In Jordan (where water costs about $1 per cubic metre, but is valued at over $5) to achieve economic efficiency would mean a typical family paying 5% or more of its income for water.

Demand management approach must be tailored to particular cultures and religions. The Quran and the Sunnah includes statements and teachings defining a correct use of water. In many parts of the Muslim world, awareness campaigns and water conservation programmes are based on religious principles. In China water conservation awareness programmes are being introduced through the creation of examples of ‘water saving society’ in Wuwei and Jinchang. In the UK, suggestions have been made to label food according to the amount of water used to produce it (in the same way that washing machines are labelled with water use) to reduce demand from where water use is not sustainable. However, this could have detrimental impacts on poor farmers (in the same way as ‘food miles’), it would not necessarily guarantee environmental benefits (as it would depend on the alternative water use) and it is likely that consumers would be confused by the many criteria being developed – organic, fair-trade, food miles.

Dublin Principle 3 (ICWED, 1992) states that women play a central part in the provision, management and safeguarding of water. Women and men assume distinct responsibilities in using and managing water and water systems. In many societies, women and girls collect every litre of water for cooking, maintaining health and hygiene, raising small livestock and growing food. Because of differing gender roles, women and men have different stakes in water use. Demand management approaches thus need to take gender-based.

Demand management frequently requires a combination of actions including legislation. In South Africa, where a national water crisis is predicted by 2025, the government has issued a Water Act that recognises there are limits to the development of new dams and water transfers and strongly advocates water conservation and demand management. A case study within the province of KwaZulu-Natal is being used to demonstrate how the projected demand of this region will be met through the application of multiple strategies of demand management, integrated catchment management and conventional augmentation.

A new dam at Kidunda on the Ruvu River in Tanzania has been proposed to increase water security for Dar Es Salaam. However, loss of water from pipelines in and around the city as been estimated to exceed 50%. Reducing water loss may be initially a more environmentally and economically better options, before developing the dam.

Waste water reuse

Some major water uses, such as domestic are largely non-consumptive and a high proportion of the water is returned to rivers, lakes and the sea. Even in irrigated agriculture drainage of used water is an important water resource as it can be reused. Moreover, it encourages flushing of salts that prevent salinisation of soils. However, domestic waste water is often of poorer quality than fresh water supplied as it has increased levels of nutrients, pesticides, organic material and other pollutant. Nevertheless, many types of agriculture do not require high quality water. Provided that waste water passes WHO quality guidelines it can be safely used for crop production. These guidelines differentiate vegetables and salad crops that are eaten uncooked, from cereal, fodder crops and trees.

Waste water is a constant guaranteed source and its reuse can help with food security and reduce waste disposal issues. Effluent from sewage treatment works is normally considered as a useless form of water which must be treated at great cost before being discharged to receiving rivers and seas. However, there is increasing recognition that waste water can be reused directly or stored for later use. In Phoenix and Las Vegas, USA, wastewater is pumped into the ground to replenish aquifer storage for later reuse. Similar approaches are now being trialled in Adelaide, Australia and various parts of India. In Jordan, waste water represented in 2004 10% of the water supply to agriculture (Hamdy and Ragab, 2006). Waste water use is not without its own issues; soil and groundwater pollution are amongst the highest risks, along with exposure (to nematodes, bacteria, virus and protozoa) of agricultural workers. A recent study by IWMI (McCartney *pers comm.*) estimated that worldwide approximately 200 million farmers are irrigating some 20 million ha with wastewater of varying quality. The majority is in the developing world and some does not meet WHO standards. However, it also provides nutrients so can be popular with farmers and there is evidence that wastewater irrigation can lift some farmers out of poverty.

Use of natural infrastructure

Greater attention is being given to the role of natural ecosystems in managing the hydrological cycle and their potential as alternatives to major engineering works. As an example, well managed headwater grasslands and forests reduce runoff during wet periods, increase infiltration to the soil and aquifers and reduce erosion (Acreman & Lahmann, 1995), such as sustaining flows during drought periods and reducing runoff during floods. Floodplain wetlands on the other hand often have large above ground storage capacity and may significantly reduce flood risk downstream (Bullock and Acreman, 2003). Wetlands also perform important water quality functions. The Nakivubo papyrus swamp in Uganda receives semi-treated effluent from the Kampala sewage works and highly polluted storm water from the city and its suburbs. During the passage of the effluent through the wetland, sewage is absorbed and the concentrations of pollutants are considerably reduced. The 2000 water law of South Africa states not only that water should be reserved to maintain the ecological functions on which humans depend, but that these ecosystem are the source of the water.

The value of these ecosystem services may be considerable and often cheaper than technical alternatives to regulate water quality. For example, New York City has a protection programme for the upper parts of the catchment which costs only 10% (US$7 billion) of alternative technological water treatment facilities. However, the influence of watershed and forest management practices on stream-flow patterns is relatively small, and is mainly limited to watersheds up to 500 km^2 in area. As such, watershed management, such as forestry, alone will not be able to protect entire river basins from catastrophic floods and droughts.

Use of natural ecosystems often has additional benefits of conserving biological diversity, natural heritage and social and cultural values in addition to goods and services to people, thus can provide a more sustainable option. Whilst natural infrastructure cannot provide alternatives to physical infrastructure, such as large dams and embankments, they can form part of portfolio of options.

Integrated catchment management

Integrated catchment management is an iterative process of evaluating, planning, restoring and organising land and resource use within a watershed to provide desired goods and services while maintaining and supporting the livelihoods of resident populations. This process provides an opportunity for stakeholders to balance diverse goals and resource uses, and to consider how their cumulative actions may affect long-term sustainability of water and other natural resources. Embedded in this concept is the recognition of the interrelationships of many different activities such as fisheries, urban development, agriculture, mining, forestry, recreation, conservation and other human influences, as well as the linkages between upstream and downstream areas.

Urbanisation is generally associated with increasing impervious areas and drainage systems that are designed to evacuate water as quickly as possible to receiving water courses. This normally results in a loss from small water cycles and a loss in recharge to under-lying soils and aquifers, which may increase the severity of droughts. It may also create a flood risk problem further downstream in receiving water courses. The concept of sustainable urban drainage schemes (SUDS) involves promoting infiltration of water to the land via soakaways.

Hydrological boundaries rarely coincide with political boundaries. Figure 8 shows a map of rivers and aquifers in North Africa showing the extent to which they cross national boundaries. Whilst the transboundary nature of these water resources may lead to conflict, they can also be used to build collaboration. The Senegal River basin authority (OMVS) is a good example of this, where the benefits from the Manantali dam in Mali have been shared by providing improved electricity supplies to Senegal, Mali and Mauritania. The Nile Basin initiative has helped improve water resources management in a region with a history of tension over water and a new treaty is being negotiated.

Unless a catchment scale approach is taken, developments may easily conflict with each other. Water supplies for Gaborone, Botswana, come from a reservoir on the Notwane River. However, inflows to this reservoir are adversely affected by numerous small farm dams throughout the catchment, which are typical of uncontrolled storage development in many countries of southern Africa. These small dams are constructed by farmers for cattle watering and sometimes provide water for small scale irrigation. A study by Meigh (1995) for the Department of Water Affairs found that the uncontrolled development of such small dams had decreased natural inflows to Gaborone dam by 25% and to a second water supply dam, Bokaa, by about 13%. Without a more detailed socio-economic study of the benefits of these small dams, it was not possible to weigh their benefits against the costs of lost urban water supply due to their construction. Nevertheless, as this type of small farm dam is common in many neighbouring countries (South Africa, Namibia and Zimbabwe) their impact upon large scale water resources projects in undoubtedly significant.

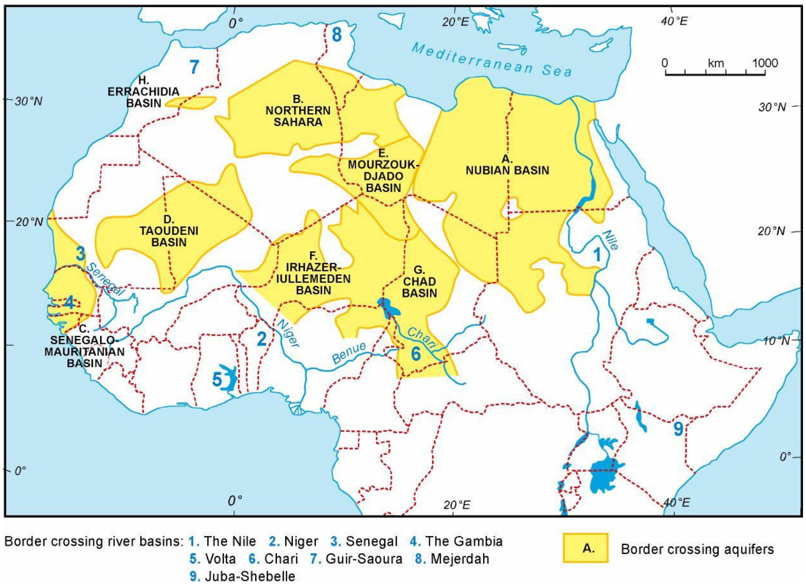


Figure 8 Transboundary rivers and aquifers in North Africa.

9. Towards a DFID policy for water storage

The DFID (2008) Water Policy recognises that water resources are vital for supporting economic growth, reducing conflict and building resilience and supporting adapting to climate change. But most of the world's poorest countries have to cope with high rainfall variability and minimal infrastructure to store and distribute water. Climate change is likely to cause more frequent and severe floods and droughts that will increase the vulnerability of poor countries and the poorest members of society. Almost 900 million people lack safe and reliable water supplies. The Commission for Africa suggests that the area of irrigated land needs to have doubled by 2015 to grow sufficient food. Fluctuations in oil prices and the drive for low carbon growth make hydropower a more attractive option. Whilst policy frameworks and institutional capacity are weak, availability of sufficient water of appropriate quality at the right time is a major limitation to DFID's ambition to "ensure that water resources are managed in an effective and equitable way that promotes economic growth, improves security and helps countries cope with climate change". DFID has pledged to develop Africa's ability to store water and better manage water resources for agriculture and industrial growth, which includes boosting hydropower. Where this means dams, DFID will encourage investment to be guided by WCD principles, but it is acknowledged that the risks associated with dams may increase under climate change.

Policy principles

The study has focus on hydrological issues of water storage. Consideration of a wider range other social and economic factors is required to formulate a comprehensive policy on water storage. Nevertheless, the following 10 principles could contribute to defining a DFID policy.

1. Undertake a full water resources assessment early in the project development cycle that includes recognition of hydrological cycles at various scales and water in various natural stores such as aquifers, glaciers, soils, vegetation, wetlands and lakes. This should identify

the key hydrological constraints and implications for regional, national and local economies and poverty alleviation. Assessments must be made using best science and appropriate long-term data sets.

2. Undertake a full options assessment linked clearly to development objectives that include use of natural infrastructure, demand management, waste water re-use, watershed protection, micro-hydro, water harvesting, improved irrigation efficiency and aquifer enhancement before selecting the most appropriate development solution. Options should include conjunctive use of a range of measures, such as surface and groundwater. The options assessment should consider institutional capacity, market potential (national and regional) and links with other investments and regional and country programmes.

3. Undertake a full life cycle analysis of the options including design, construction, operation, long term viability and decommissioning. All options should be evaluated using multi-criteria analysis and not just financial cost and benefits and should consider lead-times distributional effects (particularly implications for the poor), equity and environmental impacts, based on appropriate data. The options analysis should be followed-up with post-construction studies to evaluate effectiveness and to ameliorate unforeseen negative impacts.

4. Assess flexibility, sensitivity and vulnerability of options to climatic variability and change including water availability, sedimentation and sea-water intrusion using best science and appropriate data.

5. For trans-boundary schemes (water sharing, power, food distribution), assess the potential for food and power security, regional markets and regional integration, and benefits sharing, to develop improved cooperation. Compare these with risks of political in-security and vulnerability issues

6. Calculate a full carbon balance for water storage options including a baseline survey of current (pre-development) conditions. Where hydropower development forms part of the storage function, compare full carbon balance with alternative (including thermal) energy sources.

7. Ensure that full safeguards are defined and implemented including appropriate dam safety, environmental flow releases and effective management to reduce health risks. This requires that the trade-offs between direct and indirect water use are evaluated and that policy and institutional arrangements are in place to undertake effective EIA and HIA and then to implement any recommendations.

8. Ensure that dams are multi-purpose, where possible combining irrigation, fisheries, public supply, power generation and flood management. This will require a multi-sector approach and identification of mutual benefits and trade-offs.

9. Evaluate the relative merits of large single dams against a distributed network of smaller dams to assess overall costs, flexibility in water management, exposure to climate change, implications and compliance and for local livelihood opportunities and poverty reduction.

10. Embed all proposed developments within an integrated catchment approach to ensure that various measures to improve storage within a river basin or aquifer unit are complementary and not conflicting. This will require assessment of buy-in by different sectors and stakeholders. Ensure that downstream impacts are understood before commissioning so that net increase in storage is achieved not just a redistribution of the resource. This includes developing appropriate laws and institutional capacity to manage water through comprehensive training programmes in IWRM.

European and global initiatives for Sustainable Development

It will be important for any policy on water storage promoted by DFID to contribute to EU compliance with international environmental agreements, including both the Convention on Biological Diversity (CBD) and the RAMSAR Convention. Increases in water storage are needed, not only to meet the MDGs, but also to ensure compliance with regulations in the more developed economies, such as the EU Water Framework Directive (WFD), and in those countries such as South Africa, Tanzania and Uganda where new water laws are already in force, or are being implemented. Goal 7 of the MDGs also commits nations to ensure "environmental sustainability" and "to integrated the principles of sustainable development into country policies and programmes and reverse the loss of environmental resources"

Following the agreements made at the World Summit on Sustainable Development (WSSD) in Johannesburg, the EU has strengthened many aspects of its commitment to Sustainable Development. This has resulted in the adoption of a renewed Strategy of Sustainable Development.(CEC, 2006, EU SDS 10117/06), and the core objectives of all EU government policies are related to this. The overall goal of this strategy is "is to identify and develop actions to enable the EU to achieve continuous improvement of quality of life both for current and for future generations, through the creation of sustainable communities able to manage and use resources efficiently" (CEC, 2006, p3) In relation to this, it will be important that DFID, in the promotion of water storage options, bear in mind their mandate to support communities to manage and use resources more efficiently.

It is notable that in this policy statement from the Council, the issue of environmental protection is the first thing to be mentioned because a key objective is to "Safeguard the earth's capacity to support life in all its diversity, respect the limits of the planet's natural resources and ensure a high level of protection and improvement of the quality of the environment" (CEC 2006 p4). This means that storage projects developed and promoted by DFID must bear in mind this major new crosscutting policy initiative of EU governance. A further key objective is to "ensure that the European Union's internal and external policies are consistent with global sustainable development and its international commitments" (ibid p4). A key principle of this Sustainable Development Strategy is to 'ensure that policies are developed, assessed and implemented on the basis of the best available knowledge and that they are economically sound and cost-effective'. By supporting and promoting environmentally sensitive and cost effective water storage options, the DFID strategy on water storage can provide support for this EU SDS, as well as providing compliance with the UK's own national policy on Sustainable Development. The UK strategy is supported by 68 indicators under 20 areas: greenhouse gas emissions: resource use: waste: bird populations; fish stocks: ecological impacts of air pollution: river quality: economic growth: active community participation; crime; employment; workless households; childhood poverty; pensioner poverty; education and health inequality; mobility; social justice; environmental equality and well-being (Defra, 2008). Clearly, many of these are related directly to water storage.

Particularly with respect to impacts on habitats and biodiversity resulting from storage options, it will be important that DFID policy complies with and complements the CEC policy document on the conservation and management of natural resources, which explicitly commits the EU to "halting the loss of biodiversity, and contributing to a significant reduction in the worldwide rate of biodiversity loss by 2010".(CEC, 2006, p13). This document also points out that individual member states are obliged to support the EU Biodiversity Strategy, both within the EU and globally (*i.e.* the Convention on Biological Diversity), and with respect to the significant losses in freshwater biodiversity as documented in the Millennium Ecosystem Assessment (MEA 2005; see Figure 12.), any efforts to increase water storage must be evaluated in the context of all resulting chemical, physical and ecological impacts on freshwater systems.

This EU policy highlights the need for education as a tool for behavioural change. As support for the UN Decade of Education for Sustainable Development (2005-2014), it underlines the requirement for member states to implement the UNECE Strategy for Education for Sustainable Development adopted in Vilnius in 2005. To this end, it requires that states should promote education for sustainable development with special emphasis on teacher training, and targeted training for professionals to assist in the achievement of better management of natural resources. It will be important that any strategy to promote better water storage capacity within countries incorporates an element of capacity enhancement. This should take the form of training programmes to support effective management of the relevant storage options, and this which will serve to contribute to this UNECE strategy.

How much new storage is needed and where?

It is estimated that there are now more than 45,000 large dams[2] worldwide, with a total storage capacity of about 6000 km^3 of water. However, dams are not evenly distributed geographically (China alone has 22,000). Various measures could be used to assess the amount of storage required, such as meeting some international standard. South Africa, with 750 m^3 per capita, has been suggested as a "standard" (AIF, 2007), though even here a national water crisis is predicted by 2025. Furthermore, needs vary between countries and suitable sites for storage may not be available. National figures also mask within country variations. For example, Tanzania has abundant water resources adjacent to major natural lakes, but scarce resources in the central Rufiji basin. Another option is to consider potential for irrigation or hydropower; Ethiopia has only developed 6% of its irrigable land and 1% of its hydropower potential (Table 7). However, it is not clear that there is sufficient water available to irrigate the land available.

Table 7 Reservoir storage per capita

Country	Storage per capita (m^3)	Storage need to meet 750 million m^3 capita threshold
Ghana	14275	
Zambia	8023	
Zimbabwe	7796	
Australia	4717	
Brazil	3386	
China	2486	
Lesotho	1563	
Laos	1406	
Thailand	1277	
USA	1116	
Mexico	1104	
South Africa	750	
India	159	651,700
Ethiopia	43	52,900
Nigeria	212	70,988
Namibia	370	788
Sudan		
Madagascar		
Kenya		11,524
Uganda		15,781
Burkina Faso		2,247
Senegal		8,454

A more qualitative assessment approach is to identify hot spots where water resources are particularly under stress due to rising populations, limited groundwater, climate change impacts or historical land use changes (Table 8). However, any such short list is incomplete and implies

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[2] Large dams (as defined by the International Commission on Large Dams, ICOLD) are those dams more than 15 m high or with a storage capacity of more than 3 million m^3.

that other regions have no water resource issues. The most comprehensive approach is encourage countries (and river basin authorities in the case of transboundary waters) to develop comprehensive water resources assessment and plans that include water storage options.

Even if storage is expanded, water resources shortages cannot be realised without a range of other things in place such as a governance structure, institutions with capacity to manage, laws to ensure equity, access to water at a local level and data to enable efficient control.

Table 8 Water resources hot spots

Water resources issues	**Example regions**
Climatic warming resulting in reduced seasonal snow cover and retreating glaciers	South Asia (Indus, Brahmaputra, Ganges river basins), South America (Peru, Bolivia, Ecuador)
Rising sea level and sea water intrusion	Small islands and coastal settlements
Over-exploitation of aquifers	India, China
Forestry plantations	South Africa
Reduced rainfall and increased evaporation	West Africa, East Africa
Only fossil water available	Libya, Saudi Arabia

References

Acreman, M.C. & Lahmann, E. Hydrological management and protected areas. *Parks*, 5, 2, 1-5.

Acreman, M.C. 1996 Environmental effects of hydro-electric power generation in Africa and the potential for artificial floods ***Water and Environmental Management*, December 1996**

Acreman, M.C. (ed) 2001 *Hydro-ecology: linking hydrology and aquatic ecology.* IAHS Pub. No. 266. pp. 213.

Acreman, M.C. 2003 *Case studies of managed flood releases. Environmental Flow Assessment Part III.* World Bank Water Resources and Environmental Management Best Practice Brief No 8, World Bank, Washington DC

Acreman, M.C., Barbier, E.B. Birley, M., Campbell, K. Farquharson, F.A.K., Hodgson, N. Lazenby, J., McCartney, M.P., Morton, J., Smith, D. & Sullivan, C. 2000 *Managed flood releases – issues and guidance.* Report to DFID and the World Commission on Dams. Centre for Ecology and Hydrology, Wallingford, UK

Acreman, M.C. and McCartney, M.P. 2002 Framework guidelines for managed flood releases from reservoirs to maintain downstream ecosystems and dependent livelihoods

Acreman, M.C., Mountford, J.O. 2009 Wetland management. In: Ferrier, R., Jenkins, A. (eds) Catchment management handbook.

Adelana, S., MacDonald, A.M. 2008. *Applied Groundwater Studies in Africa*. IAH Special Publications in Hydrogeology, Volume 13, CRC Press/Balkema, Leiden, The Netherlands, 507 pp

Africa Infrastructure Consortium 2007 Africa: water development, hydropower and growth. http://www.icafrica.org/en/

African Drought Adaptation Forum 2008. Report of the 3rd Forum meeting, Addis Ababa, Ethiopia. International Strategy for Disaster Reduction, UNDP Drylands Development Centre, UN Economic Commission for Africa. http://www.undp.org/drylands/docs/drought/ADDF3/3rd_African_Drought_Adaptation Forum_Report.pdf

Alhassan, H.S. 2009 Butterflies vs hydropower: reflections on large dams in contemporary Africa. *Water alternatives*, 2, 1, 148-160.

Allan, J. A. 2003 Virtual water - the water, food and trade nexus: useful concept or misleading metaphor? Water International, 28, 4–11.

Attewill, L.J.S., White, W.R., Tariq, S.M. and Bilgi, A., 1998 Sediment management studies of Tarbela dam, Pakistan. "The prospect for reservoirs in the 21st century", Proc. 10th Conference of the British Dam Society, 9-12 Sept. 1998, University of Wales, Bangor.

Brown, C. and King, J. 2003 Environmental flow: concepts and methods. Water Resources and Environment, Technical Note C1. World Bank, Washington D.C., USA.

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(7066): 303-309.

Chapagain, A.K. and Hoekstra, A.Y. 2004 Water footprints of nations. *Value of water research report series no 16*. UNESCO IHE, Delft. The Netherlands.

Collins, D.N., 2008. Climatic warming, glacier recession and runoff from Alpine basins after the Little Ice Age maximum. Journal of Glaciology, In-press accepted.

Council of the European Union 2006 Review of the EU Sustainable Development Strategy (EU SDS) – Renewed Strategy (10117/06) Brussels, 9 June 2006

Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C. and Huu Ninh, N., 2007. Asia. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (Editors), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 469-506.

Defra 2008 Sustainable development national indicator framework http://www.defra.gov.uk/sustainable/government/progress/national/index.htm

Delmas, R., 2005 Long term greenhouse gas emissions from the hydroelectric reservoir of Petit Saut (French Guiana) and potential impacts. *Global Warming and Hydroelectric Reservoirs, CDD 363.73874, pp. 117-124.*

Department of Economic and Social Affairs Population Division (2006) *World Population Prospects*. United Nations. pp. p. 37-42. http://www.un.org/esa/population/publications/wpp2006/WPP2006.

DFID 2008 *Water: an increasingly precious resource, sanitation: a matter of dignity*. DFID London.

dos Santos, M.A. (ed.), 2005: Carbon budget in tropical reservoirs. *Global Warming and Hydroelectric Reservoirs, CDD 363.73874, pp 95-100*

Dyurgerov, M.B. 2005 Mass balance of mountain and sub-polar glaciers outside the Greenland and Antarctic ice sheets. Supplement to Occasional Paper No. 55. Institute of Arctic and Alpine Research, University of Colorado, Boulder.

Dyurgerov, M.B., Meier, M.F., 2000. Twentieth century climate change: Evidence from small glaciers. PNAS, 97(4): 1406-1411.

Dyurgerov, M.B. and Meier, M.F., 2005. Glaciers and the changing earth system: a 2004 snapshot. Occasional Paper No. 58. INSTAAR/OP-58. Institute of Arctic and Alpine Research, University of Colorado, Boulder, pp. 117.Dyson, M., Bergkamp, G., Scanlon, J. 2003 Flow. The essentials of environmental flows. IUCN, Gland, Switzerland.

Economic Commission for Africa 2008 *Africa Review Report on Drought and Desertification* Economic Commission for Africa, Addis Ababa

FAO/CIFOR 2005 *Forests and floods. Drowning in fiction or thriving on facts?* RAP Publication 2005/3 Forest Perspective 2. FAO, Bangkok

Fairless, D. 2007 Biofuel: The little shrub that could - maybe. *Nature* 449, 652–655

Fearnside, P.M., 2004: Greenhouse gas emissions from hydroelectric dams: controversies provide a springboard for rethinking a supposedly clean energy source: *Editorial Comment. Climatic Change, 66, pp. 1-2.*

Gedney, N., Cox, P.M.. Betts, R.A., Boucher, O., Huntingford, C., Stott, P.A. (2006) Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* 439: 835–838.

Global Water Partnership 2000 *Towards water security; a framework for action*. GWP, Stockholm.

Gore, A., 2006. An Inconvenient Truth: The Planetary Emergency of Global Warming and What We Can Do About It. Bloomsbury Publishing, 336 pp.

Grey, D and Sadoff , C. W. (2007) Sink or Swim? Water security for growth and development *Water Policy* 9 (2007) 545–571

Grey, D. & Sadoff, C.W. (2006). Water for Growth and Development in Thematic Documents of the IV World Water Forum. Comision Nacional del Agua, Mexico City.

Haeberli, W., 1996. Fluctuations of mountain glaciers. In: V.M. Kotlyakov (Editor) Variations of snow and ice in the past and at present on a global and regional scale. International Hydrological Programme IHP-IV Project H-4.1. UNESCO, Paris, pp. 35-43.

Hamdy, A., Ragab, R. 2006 Reuse of treated wastewater in irrigation: challenges and perspectives. In: Ragab, R., Koo-Oshima, S (eds) *Proceedings of the International workshop on environmental consequences of irrigation with poor quality waters*. CEH, ICID, FAO.

Hasnain, S.I., 1999. Glaciers beating retreat. In: Down To Earth, 7(23), New Delhi, India. April 1999. pp. 1-6.

Houghton, J.T. 2001 Long-term mean sea level accelerations. *Climate Change 2001: The Scientific Basis*

Huttunen, J., 2005: Long-term net methane release from Finnish hydro reservoirs. *Global Warming and Hydroelectric Reservoirs, CDD 363.73874, pp. 125-127.*

Ibrahim, S.A., Bari, M.R., Miles, L. 2002 Water resources management in Maldives with an emphasis on desalination Asian Development Bank. http://www.adb.org/

International Data Base 2008 US Census Bureau. http://www.census.gov/ipc/www/idb/worldpopinfo.html

International Conference on Water and the Environment Development 1992 Issues for the Twenty-first Century, Dublin.

International Hydropower Association 2004 Sustainability guidelines International Hydropower Association, London.

International Hydropower Association 2006 Sustainability assessment protocol International Hydropower Association, London.

International Hydropower Association 2008a *Hydropower: making a significant contribution worldwide*. International Hydropower Association, London

International Hydropower Association 2008b *Greenhouse gas emissions from Reservoirs* http://www.hydropower.org/downloads/F6%20GHG%20Emissions%20from%20Reservoirs.pdf

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

JMP 2004. *Global water supply and sanitation 2004 report*. Joint Monitoring Programme WHO/UNICEF. World Health Organisation: Geneva

Karyabwite, D. (2000) Water Sharing in the Nile River Valley. UNEP

Koster RD, Dirmeyer PA, Guo Z, Bonan G, Chan E, Cox P, Gordon CT, Kanae S, Kowalczyk E, Lawrence D, Liu P, Cheng-Hsuan Lu, Malyshev S, McAvaney B, Mitchell K, Mocko D, Oki T, Oleson K, Pitman A, Sud YC, Taylor CM, Verseghy D, Vasic R, Xue Y, Yamada T , 2002. Regions of Strong Coupling Between Soil Moisture and Precipitation. *Science Vol. 305. no. 5687, pp. 1138 - 1140*

Kravčík, M., Pokorný, J., Kohutiar, J., Kováč, M., Tóth, E. 2008 *Water for the recovery of the climate. A new paradigm*. People and Water/Association of Towns and Municipalities, Slovakia.

Liniger, H., Weingartner, R. and Grosjean, M., 1998. Mountains of the World: Water Towers for the 21st Century. Report prepared by Mountain Agenda for the UN Commission on Sustainable Development Centre for Development and Environment, University of Bern, Switzerland, pp. 32.

Lorrai, C and Pasche, N. 2007 Tarbela dam-case study. Report of the Swiss Federal Institute of Technology Zurich.

Loth, P. 2004 The return of the water. Restoring the Waza-Logone floodplain in Cameroon. IUCN, Gland , Switzerland. 153 pp.

Marengo, JA, 2006. On the hydrological cycle for the Amazon Basin: a historical review and current state of the art. *Revista Brasileira de Meteorologia, v.21, n.3, 1-19*

Meigh, J.R.,1995 The impact of small farm reservoirs on urban water supplies in Botswana. *Natural Resources Forum*, 19, 1, 71-93.

Mohamed, Y. A., Savenije, H. H. G., Bastiaanssen, W. G. M., and van den Hurk, B. J. J. M.: 2005 New lessons on the Sudd hydrology learned from remote sensing and climate modelling, Hydrol. Earth Syst. Sci. Discuss., 2, 1503-1535, 2005

Molden, D. (ed) 2007 The Comprehensive Assessment of Water Management in Agriculture. Earthscan, London, IWMI, Colombo

MacDonald A.M., Calow R..C., Macdonald DMJ, Darling W.G. and O'Dochartaigh B.E. 2008 What impact will climate change have on rural water supplies in Africa?

Messerli, B. and Ives, J.D. (Editors), 1997. Mountains of the World – A Global Priority. The Parthenon Publishing Group, London, 495 pp.

Millennium Ecosystem Assessment 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Masumoto, T. (2002). Changes of watershed management against floods in international rivers. In: Wu, B.S. et al.,ed., (2002) *Flood Defence* Vol. I. New York, Science Press, pp. 416–424.

Niamir-Fuller, M. 2000 The resilience of pastoral herding in Sahelian Africa In: Berkes, F., Folke, C., Colding, J. (eds) *Linking social and ecological systems. Management practices and social mechanisms for building resilience* Cambridge University Press,

Nyong, A., Adesina, F., Elasha, B.O. 2007 The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel *Mitigation and adaptation straetgies for global change* 12, 5, 787-797

OECD 1996. *Guidelines for Aid Agencies for Improved Conservation and Sustainable Use of Tropical and Sub-Tropical Wetlands*. OECD Guidelines on Aid and Environment, No.9. Organisation for Economic Cooperation and Development, Paris, France.

Oerlemans, J., 2005. Extracting a Climate Signal from 169 Glacier Records. Science, 308(5722): 675-677.

Popkins, B., Horton, S. and Kim, S. (2001). *The nutrition transition and prevention of diet-related chronic diseases in Asia and the Pacific*. Manila, Asian Development Bank.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. and Stromberg, J. C., 1997. The natural flow regime. Bioscience 47, 769-784

Rees, H.G. and Collins, D.N. 2006 Regional differences in response of flow in glacier-fed Himalayan rivers to climate warming. *Hydrological Processes*, 20, 10, 2157-2169

Richter, B. D., Baumgartner, J. V., Wigington, R. and Braun, D. P., 1997. How much water does a river need? *Freshwater Biol.*, 37, 231-249

Rosegrant, M., Paisner, M., Meijer, S. and Witcover, J. 2001. *Global Food Projections to 2020*. Washington, D.C., IFPRI.

Sadoff, C.W., Grey, D. 2002 Beyond the river: the benefits of cooperation on international rievrs. *Water Policy*, 4, 389-403

Seng, V., Craswell, E., Shu, F. and K. Fischer (eds) 2004 *Water in agriculture.* ACIAR Proceedings No. 116e Canberra.

Sikar, E., 2005: Greenhouse gases and initial findings on the carbon circulation in two reservoirs and their watersheds. *Verhandlung Internationale Vereinigung für Limnologie, 27*

Smith, M., de Groot, D., Bergkamp, G. 2006 *Pay-establishing payment for watershed services*. IUCN, Gland, Switzerland. 109 pp.

Sperling, F. (ed.) 2003. Poverty and Climate Change: Reducing the Vulnerability of the Poor through Adaptation. Interagency report by the AfDB, ADB, DFID, UK, BMZ, Germany, DGIS, The Netherlands, OECD, UNDP, UNEP and the World Bank.

Stahl, K. and Moore, R.D. 2006 Influence of watershed glacier coverage glacier coverage on summer streamflow in British Columbia. *Water Resources Research*, 42, W06201.

Stern, N., 2007. The Economics of Climate Change - The Stern Review. Cabinet Office - HM Treasury. Cambridge University Press, 579 pp.

Sullivan, C.A., Meigh, J.R., Giacomello, A.M., Fediw, T., Lawrence, P., Samad, M. Mlote, S., Hutton, C., Allan, J.A., Schulze, R.E., Dlamini, D.J.M., Cosgrove, W., Delli Priscoli, J., Gleick, P., Smout, I., Cobbing, J., Calow, R., Hunt, C., Hussain, A., Acreman, M.C., King, J., Malomo, S., Tate, E.L., O'Regan, D., Milner, S., Steyl, I. 2003. The Water Poverty Index: Development and application at the community scale. *Natural Resources Forum,* 27, 3, 25-41The Times, 2005. Himalayas' melting glaciers will open floodgates to catastrophe. In: The Times, London. 12 July 2005. pp. 34.

TAMS Consultants Inc., HR Wallingford Ltd. & Institute of Hydrology (1997) Tarbela Dam Sediment Management Study - Final Report. Commissioned by Pakistan's Water and Power Development Authority (WAPDA).

Touchan, R., Anchukaitis, K.J., Meko, D.M., Attalah, S., Baisan, C. and A. Aloui (2008) Long term context for recent drought in northwestern Africa . *Geophysical Research Letters* vol. 35, L13705 2008

Tremblay, A. (ed.), 2005: Greenhouse gas emissions - fluxes and processes. *Hydroelectric Reservoirs and Natural Environments. Springer, Berlin.*

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Tank, A.K., Parker, D., Rahimzadeh, F., Renwick, J.A., M. Rusticucci, Soden, B. and Zhai, P., 2007. Observations: Surface and Atmospheric Climate Change In: S. Solomon et al. (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 235-336.

UNDP 2006 *Human development report*. Macmillan, New York,

UNESCO, 2006: Workshop on GHG from freshwater reservoirs. 5-6 December, United Nations Educational, Scientific and Cultural Organization Headquarters, Paris, France, *UNESCO IHP-VI website, <www.unesco.org/water/ihp/> accessed 02/07/07*

Verhoef, H. 1996 Health aspects of Sahelian floodplain development. In Acreman, M.C., Hollis, G.E. (eds) *Water management and wetlands in sub-Saharan Africa*. IUCN, Gland, Switzerland.

Viviroli, D. and Weingartner, R., 2004. The hydrological significance of mountains: from regional to global scale. Hydrology and Earth System Sciences, 8(6): 1016-1029.

Wanchang, Z., Ogawa, K., Besheng, Y. and Yamaquchi, Y. 2000 A monthly stream flow model for estimating the potential changes of river runoff on the projected global warming. *Hydrological Processes,* 14, 1851-1866.

World Bank 2004. *Towards a Water-Secure Kenya: Water Resources Sector Memorandum*. World Bank, Washington, DC.

World Bank 2007. *Review of greenhouse gas emissions from the creation of hydropower reservoirs in India*. World Bank, Washington, DC

WWF, 2005. An overview of glaciers, glacier retreat, and subsequent impacts in Nepal, India and China. World Wildlife Fund Nepal Program, pp. 70.

Zemp, M. and Haberli, W., 2007. Glaciers and Ice Caps. In: Global Outlook for Ice and Snow. United Nations Environment Programme, Nairobi, Kenya, pp. 115-152.