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The sharing of water between society and ecosystems: from conflict to catchment based co-management.

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Abstract

I THINK THAT THIS IS NOT A GOOD ABSTRACT AS IT DOES NOT SAY ANYTHING ABOUT WHAT WE HAVE SAID OR WHAT THE IMPLICATIONS ARE

Despite the abundance of water on the Earth, it is becoming clear that the relatively small proportion that is fresh and accessible is coming under increasing pressure as the world population rises. As human water requirements grow, the water left to support ecosystems is reduced and the already considerable ecosystem impacts will continue to rise. Ensuring equity between economic, social and environmental sustainability will therefore become a major challenge. More equitable sharing of water resources between society and nature will require both quantities and values to be placed on human and ecosystem requirements. Scientific principals can be used to define the necessary water quantities. Social sciences address the issues of how water is valued in society.

Catchment based integrated water resources management (IWRM) provides a framework within which water resources can be managed more holistically. This makes it possible for human and ecosystem water needs and the interactions between them to be better understood. This knowledge provides the foundation for incorporating relevant social factors so that water policies and laws can be developed to make best use of limited water resources.

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Catchment based co-management can therefore help ensure more effective sharing of water between people and nature.

1. Introduction

Until comparatively recently there has been little debate about sharing water between society and nature. This is not surprising since there is so much water on the planet; we know that two thirds of the earth's surface is covered with oceans and textbooks on water show that the total volume of water on the Earth is vast, around 1.4 billion (10^9) km^3 (e.g. Maidment, 1992). However, less that 1% of this water is fresh and accessible, the rest being either saline, frozen or in deep underground aquifers. This still very large (11 million km^3) amount of fresh water is distributed very unevenly around the globe and this is reflected in the geographical variation in vegetation and human population. Recent attempts to map this variation of freshwater resources have not only quantified the variation in freshwater resources around the world, but also how human demand for these resources also varies globally (e.g. Shiklomanov, 1991; Alcamo et al. 1997). The combination of estimates of water supply with demands for water has revealed a number of very important issues. Firstly, although future water supply may be influenced by changes in amounts and timing of local rainfall due to climate change and/or variation, it is the demands for water for domestic, industrial and agricultural uses that will dominate future water scarcity. Furthermore, of these three human uses of water, irrigated agriculture accounts for by far the greatest amount (between 65 and 75% of total water use). The global consequences of this have been illustrated by several authors (e.g. Fischer and Heilig, 1997; Falkenmark, 1997, Gleick, 2000, Vorosmarty *et al.*, 2000) and been summarised by Wallace (2000) using Figure 1, a and b. This indicates that currently the most acute water shortages are in North Africa, with some degree of water stress throughout Southern Africa and the Middle East. By 2050 a staggering 67% of the worlds population (6.5 billion) may find themselves facing significant conditions of water stress[2], as shown in Figure 1b. Furthermore, as many as one in six people (1.5 billion) may have insufficient water to meet their basic requirements for growing food and domestic water. The main issues in these water scarce areas therefore tends to focus on the human problems of alleviating hunger and poverty and basic water supply for household use and sanitation.

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[2] The term 'water stress' is used here to describe conditions where per capita renewable water availability falls below the conventional threshold to meet all human needs, including an additional amount required to maintain ecological integrity. This is not to be confused with conditions simply relating to situations where people have inadequate domestic water supplies.

At the same time as evidence for this immense human water crisis has emerged, there has been growing concern for the impacts of human appropriation of water on ecosystems. Currently this concern dominates in areas where water is not scarce, where the main issues tend to be with water quality, environmental impacts and ecosystem protection. For example, a key issue identified by the Global Water Partnership was the increasing competition for water resources between the agricultural and environmental sectors (see Rijsberman and Molden, 2002). Rijsberman also points out that several studies have indicated that while the environmental sustainability lobby are pushing for a decrease (8%) in water allocation to irrigated agriculture, the agricultural communities are arguing for an increase (~15%) in water allocation to meet future food requirements.

Figure 1 c and d gives a broad global picture of where the pressures on ecosystems may be greatest, now and in 2050. The figure shows what percentage of the total available water resource would be left if the human needs were met at 2000 m^3 $person^{-1}$ $year^{-1}$. The figure of 2000 m^3 per person per year comes from an analysis by Falkenmark (1997) and comprises 1000 m^3 $person^{-1}$ $year^{-1}$ to meet basic needs (to grow food, for domestic purposes and a per capita industrial allowance) and a further 1000 m^3 $person^{-1}$ $year^{-1}$ to remove further water stresses. At present around one third of the land area of the world would have less than 50% of the available water resource to support ecosystems and 27% would have less than 25%, a figure below which severe environmental impacts may occur. Even when the water available for ecosystems is greater than 50% of the total resource there may be important environmental impacts. For example, experts have suggested that in Australia the probability of having a healthy river falls from high to moderate when the hydrological regime is less than two-thirds of its natural condition (Jones, 2002). The areas where there is least water for ecosystems are in East and West Europe, Africa and East and West Asia. Three areas, Northern and Southern Africa and Western Asia have insufficient water to meet even the basic human requirement (i.e. 1000 m^3 per person per year), therefore, unless food is imported and/or production intensified on both rainfed and irrigated agriculture, there may be little or no water left to support ecosystems.

By 2050 the global picture will have changed markedly with half of the land area having less than 50% of the available water resource to support ecosystems and ~ 40% with less than 25%, Figure 1 d. The number of areas where there is a danger of severe environmental degradation increases by 2050 to include the Caribbean, East and West Africa, South-Central and Eastern Asia. By this time large areas (over 50%) of tropical forest and wetlands have less than three quarters of the water resource and nearly 25% are in areas where there is less than a quarter of the water resource left after meeting human requirements. The crude analyses illustrated in Figure 1 have their limitations, mainly because of their spatial (national average) and temporal scale (annual average), gross assumptions about per capita water requirements and further assumptions about the proportion of total food production from irrigated agriculture. Despite these criticisms they remain useful enough for making three important points, (i) future global water scarcity will affect most of the world's population, (ii) population growth dominates future water scarcity and (iii) there are widespread implications for ecosystems in many parts of the world. More accurate, higher time and space resolution water scarcity assessments are described in Wallace and Gregory (2002).

The crux of the dilemma facing mankind is illustrated in Figure 2. This shows how the human and ecosystem proportions of the total fresh water available on the planet change from 1950 to 2050. In this very short period of 100 years the balance of water used by humans and left for nature changes drastically. Assuming a per capita water use of 2000 m^3 per person per year, human requirements in the 1950's would have amounted to ~ 13% of the available resource, leaving the rest for nature. At present to meet basic needs and avoid excess pressure on water resources, , humans would require ~ 30% of the available resource, but this could rise to almost 50% if populations grow according to the current UN projections. If this happened, ecosystems would be left with only 50% of the available fresh water. With 35% of the entire land surface and 25% of tropical forest and wetlands having access to less than ¼ of the freshwater resources, the environmental consequences would be enormous. On the other hand, by 2050, 6.5 billion people may live in situations which could be described as 'water stressed', with 1.5 billion of these having inadequate water for their basic needs. By comparison, in 1950, this simple analysis indicates that only 50 million people lived in such conditions, and relatively few had inadequate water for their basic requirements.

People clearly benefit from the direct use of water domestic purposes, agriculture and industry, but they also benefit from the water provided to ecosystems. Ecological processes keep the planet fit for life providing non-agricultural foods, air to breathe, medicines and much of what we call “quality of life” (Acreman, 1998). In particular, millions of people worldwide, particularly in poor communities, depend greatly on natural resources of ecosystems including fish and timber. In many communities who live in or near wetlands, their social structure is geared around the hydrological regimes, such as the annual flood (Acreman et al, 2000). People also benefit from hydrological functions of ecosystems, such as flood protection and water quality improvement. In addition, many people feel that the human race has a moral duty to protect the biodiversity of our planet (Acreman, 2001). Thus providing water to ecosystems also serves economic, social, ecological and ethical needs.

Clearly, water links society and nature and so the remainder of this paper explores societal and ecosystems water needs and how this precious resource can be shared between them. Is the picture quite so bleak as it appears above, or can we accommodate future human requirements for water without unacceptable impacts on aquatic and terrestrial ecosystems? What can catchment based water management techniques bring to help resolve this apparently intractable dilemma?

2. Societal water needs

Different sectors of society use water in a variety of different ways. Wide variations also exist in the relative importance of water in different countries, and therefore assessing how societies benefit from water use is very complex. In addition to economic criteria for assessing the importance of water to society, other important criteria include human health, aesthetic and spiritual values, as well as some recognition of the intrinsic psychological and empowering value of simply having secure access to a convenient water supply. It is interesting to note that while domestic water needs are absolutely fundamental to our survival, emphasis placed upon them within many water management strategies is rather low. Water allocations continue to be heavily weighted in favour of agriculture, with often inadequate amounts being provided for domestic use. Water management can be improved by quantifying all of the ways in which water use benefits society. In economic terms, this is referred to as an investigation of the ‘returns to water’, but it should be stressed that this is only one way in which the benefits of water use can be assessed.

(a) The returns from water use

There are many issues to be considered in any quantification of the returns arising from the use of water, and these must not only be identified using economic criteria. When decisions are made about how water is managed, economic and political considerations are often given priority. For example, when water storage is provided for both industry and agriculture, the justification for the associated expenditure is provided by an examination of the economic returns on the capital invested. These would be assessed on the basis of electricity generation potential or increased crop outputs and often little else is considered. However, when assessing domestic water provision, a problem is encountered in defining appropriate measures of the returns on investment. While monetary measures work for many criteria, certain important attributes of the value of domestic water cannot be measured in this way. For example, no definitive method of valuation has been agreed to effectively quantify the value of good health, or the lower child mortality rates normally associated with clean domestic water provision. Similarly, the difficulties associated with valuation of environmental attributes are well known. While some progress has been made on the valuation of a range of goods provided by nature (Sullivan, 2002; Abramovitz, 1997; Roodman, 1999), methods to value ecosystem functions and services are less developed, despite the ever-growing literature on this subject.

Water is increasingly perceived as a 'strategic resource' and water accounts have now started to be constructed which stress the economic importance of water. Although these water accounts can help in identifying problems related to the emission of pollutants and to the general management of water, they are considerably limited in not recognising the real global importance of water. For example, social and/or political considerations are not taken into consideration, although they are very important in the management of water in developing countries. Neither should the management of water be limited to issues such as waste management and land use. All of the above social, political, economic and environmental considerations are very closely linked and should be considered as such if the management of water resources is to improve. The concept of 'critical natural capital' (Berkes and Folke, 1994; Noel and O'Connor, 1998) recognises the importance of ecosystems and stresses the idea of that, for instance, some key species may be critical to an ecosystems function, or that the pollution of a certain habitat can have repercussions on other habitats and species. The controversial work of Costanza et al., (1997) has served to highlight the importance of ecosystem functions and services, however, it is still unclear how these essential attributes of nature can be incorporated into human management systems. As a result, it is extremely difficult for market-driven water managers to incorporate the values of nature into day-to-day water management techniques.

If we look at the returns from water use by sector, we can see that in some countries, different sectors play different roles in economic performance, and the use of water in these sectors may be a determining factor in the economic progress. The relationships between water availability, sectoral water uses, GDP and the Human Development Index can be examined using simple linear correlations, as shown in Table 1. For example, in the agriculture sector in poor countries there is some positive correlation between water use and the contribution of agricultural outputs to the GDP, whereas in richer countries, there appears to be no clear relationship. At first sight, this suggests that agricultural water management in the poorer countries may be more economically important than in richer ones. However, these figures take no account of rainfed farming systems that provide significant amounts of food throughout the world, much of which may be unaccounted for in national accounts due to home consumption.

Table 1 also shows a similar picture in the industrial sector. In poor countries higher levels of industrial water use tend to generate greater contributions to the GDP, whereas there is no such correlation in rich countries. This suggests that in poor countries, when water is used for industry, the economic returns are of greater importance to the nation than in richer countries. In poor countries there is a high negative correlation between the contribution of agricultural activity to the economy and the country’s score on the human development index, indicating that a high level of agricultural dependence may be associated with lower levels of economic and social well-being. This also confirms that developing economies heavily dependent on agriculture have little say in world commodity prices, often getting very little return for the use of their resources, including water. From this sample of countries, there also appears to be a stronger link in the higher income group between per capita water use and per capita GDP. This again suggests that richer countries are in a better position to get higher benefits from their water use than poor countries. This is clearly an area of research that should be explored much further, since it suggests that how water is managed within an economy can have a direct impact on the economic welfare of society. A related issue, which merits further work, is the distributional impact (in society) of the ways in which water is managed, and how more effective water management could contribute to poverty alleviation. Examples of poor distributional impact can be seen in many of the large dams throughout the world that have been built for commercial irrigation schemes or electricity generation. In many of these schemes the beneficiaries of tend to be the richer members of society and/or the political elite, while those coping with the impacts of the scheme are often poor subsistence householders who, not only do not have electricity, but are also likely to lose important livelihood benefits provided by functioning downstream ecosystems.

(b) The need for equity in water allocation

Equity in water management must address how water is shared both between people now, and between current and future generations. Inequity in water allocations today means that there are about 1 - 2 billion people who lack access to adequate safe water, while millions of others consume some 14 times their basic minimum requirement. The reasons for this situation are complex, but undoubtedly they need to be addressed by more equitable and sustainable policies for water management (Biswas, 1989). However, when we consider how this situation may be exacerbated in the future, as illustrated by Figure 1 a and b, it is clear that significant actions need to be taken soon if we are to avoid greater inequity of this kind in the future. Extreme inequity can lead to human disasters (disease, famine etc.) or even wars, which are not taken into account in Figure 1.

The impact of human population growth is also a major factor when considering the future challenges for the equitable allocation of water between humans and ecosystems. This is illustrated in Figure 2, which shows how increases in human water uses over the next 50 years may reduce the amount of water available for ecosystems. These figures highlight the need for more holistic water management that includes ecological requirements, otherwise irreversible changes in ecosystems may occur, resulting in a significant loss of benefits to mankind. In determining water allocations it is necessary to recognise that ecosystem goods and services are important in different ways to different groups. This is can be illustrated by the ways in which in-stream flows are regarded in different parts of the world. For example, in the Western United States many river courses have been totally disrupted (McCully, 1996). However, recent experiments of flood releases from reservoirs, such as Glen Canyon Dam on the Colorado, have been undertaken to determine the flows required to maintain channel morphology (sediment transport) and provide habitat for key fish species (Rubin and Topping, 2002). In the Murray Darling Basin, in Australia, the maintenance of an effective in-stream ecosystem flow requirement has been the key objective of their water policy. The Australian management approach has been developed to address the ecological crisis resulting from widespread algal blooms, and salinisation both of the soil, and of estuarine waters, such as at the mouth of the Murray-Darling system. It has required the development of significant institutional agreements, along with inter-state cooperation on trade in water rights (Powell, 1998). In the USA, policies in favour of large scale electricity generation facilities have been developed on the basis of being economically efficient. Although good and bad examples of water management can be found in both the USA and Australia, the examples provided here illustrate the different emphasis that may be placed on ecological issues in different places.

There are other examples throughout the world where some progress has been made to incorporate ecological water needs into policy for water management. Most notably, in South Africa, the Water Act (1998) has been accepted into national planning systems, in such a way as to explicitly ensure that an ecological reserve is to be maintained. Even in this case, however, the implementation of this policy is not proving to be easy, as there is insufficient knowledge on the relationships between river flows and ecological health. Another fundamental component of South African Water Law is the commitment to the establishment and maintenance of a basic minimum water allocation to all of the population. This provides an additional limit on abstraction rates, and as a result, legislation has been introduced to regulate organisations involved in any flow reduction activity, such as commercial forestry. This is a good example of a system, which is not only trying to implement Integrated Water Resource Management, (Falkenmark et al., 1999, Falkenmark, 2002) but is also trying to incorporate land management into that as well. This also demonstrates that even when scientific evidence is still unclear, there is a pressing need to introduce and enforce regulations to limit abstractions where water resources are scarce, relative to the demands upon them.

How land and water are used in agriculture is another factor in determining human pressure on water resource systems. Many of these resources are used to produce non-food, lifestyle items, such as tobacco, while at the same time, more resources are being used to produce crops that can generate substantial subsidy payments. For example, market distortions such as these have been widespread as a result of the EU's Common Agricultural Policy, and such policies tend to generate a waste of resources, while at the same time having potentially detrimental environmental impacts. This can be demonstrated in the South East of England where large areas of land are put under extensive cultivation of subsidised crops using high levels of inorganic fertilizers and pesticides. This has created problems of loss of habitats and biodiversity, and an increased risk of groundwater contamination.

All land-use decisions are determined by consumer preferences and farmer crop choice. These decisions can affect water demands and alter global picture of future water scarcity shown in Figures 1 and 2. It has been shown that water consumption rates are lower (by a factor of 5) in the production of protein from vegetable sources than for protein produced from animals (Falkenmark, 1997, Penning de Vries, Rabbinge and Groot 1997). Figure 3 provides an illustration of how water needs could be modified as a result of changing preferences away from animal based diets. It is generally accepted that as counties develop, people tend to increase the animal protein in their diets, thus increasing water use. While this does conform to the current development paradigm, it is possible that preference for animal protein will change, particularly in the developed world, following concern about intensive farming techniques and animal welfare. Given this significant difference in the level of water requirements associated with different food types, it is possible that changes in dietary patterns could impact significantly on agricultural water demand. Figure 3 provides an illustration of how water needs could be modified as a result of changing preferences away from animal based diets. This diagram shows how the demand for water resources for food production is likely to increase as a result of demographic change over the next 30 years, and how this pattern is likely to be influenced if dietary choice moves away from animal to vegetable protein[3]. This simplified analysis indicates that there is much potential for changing agricultural water requirements, and changes in the types of food eaten may bring about a significant reduction in the water needed for food. Much more detailed analysis would be needed to fully investigate the inter-related impacts of population growth and changing consumption patterns inevitably brought about by the normal development process. Clearly, as people in developing countries become better off, their consumption will impact on all forms of production, and on prices, while at the same time, changing consumption patterns in more developed economies will also have some effect. Such analysis is beyond the scope of this paper, but there is a need to examine such interactions if we are to better understand future pressures on water resources.

In any economy, all production and consumption involve exploitation and use of natural resources. It is an ironic fact that this is not reflected in the theoretical foundation on which conventional economic analysis is built. Price and value are determined on the basis of preferences and scarcity (Stiglitz, 1979) and at the time when Adam Smith was writing his ‘Wealth of Nations’ natural resources were considered to be ‘so abundant as to be unlimited in supply’. As a result, market economists build their models of economic processes around a fundamental assumption that nature is a ‘free good’, an inaccurate reflection of today’s world where both the ‘scarcity value of nature’ and our preferences to use it, have increased, (as shown in Figures 1c and 1d). The question of how to address these problems more effectively are raised by a number of economists who are no longer willing to accept the conventional assumptions underlying much of economic theory (Costanza et al., 1997a, Opschoor, 1998; Norgaard, 1991).

The value of water varies considerably from place to place and also from use to use. For example, for a given quantity of water, the value from use for navigation may be much less than that from use in a textile plant. For irrigation, the value of the water may be much higher if the crop grown is carrot than if it were wheat. Crop selection has a big impact both

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[3] This is based on a 30% reduction overall of water required for food production , following a switch to a lower meat diet.

on the use value of water, and also on the amount of water used. Since agriculture has the largest share of water allocation in many countries, the value generated from it needs to be fully quantified and, if necessary, methods introduced to regulate agricultural water use. It must be remembered however that in many countries, decisions made about food production are taken much more on that basis of politics than economics. For example, some countries chose to subsidize food production for strategic reasons, to ensure national food self-sufficiency.

One accepted way of valuing water is through an examination of what values other alternative uses could generate. This is known as the ‘opportunity cost’ of water, and can be used as way of improving water allocation decisions. Unfortunately this is not straightforward, as it is often the case that such calculations suggest that the cultivation of higher value (non-food) crops would lead to a reallocation of water for that purpose. If this were taken to the extreme, then water would be allocated in such a way as to act as a disincentive for food production, causing a problem of food security. In some places problems such as this have occurred where cash crops such as cotton have been produced in preference to food crops, and when too many farmers made this choice, food shortages have arisen. Nevertheless, the opportunity cost methodology does give some insight into the value of water. There is still much work to do to refine techniques of quantifying any kind of natural capital, including water, and to date, no widely accepted method of valuing water and the ecosystem services associated with it currently exists.

It is now well known that poor groups in society tend to depend more directly on natural resources than do the richer groups (Chambers, 1995, Desai, 1995, DFID, 2002). They are often much more conscious of managing natural resources effectively, and many traditional societies have norms and taboos which serve as a control mechanism on consumption. For example, the Lozi people of the Barotse floodplain in Zambia practice indigenous knowledge systems to manage natural resources of the wetlands (Chiuta, 1995). Contrary to popular belief, they are often guardians of a well maintained environment, although there are also many examples of the poor being the instigators of environmental degradation, more due to their ever increasing numbers than any deliberate destructive strategy (DFID, 2002).

The need to incorporate the important values embodied in nature is a prerequisite to achieving a sustainable future (Daly, 1999; Faucheux and M. O'Connor, 1998). There is clearly also a need to consider the range of possible preferences and philosophical positions held by various stakeholder groups, when considering the values attributed to nature. In this situation, nature itself is a stakeholder without a voice, and so Jacobs (1997a) has suggested that a more eco-centric perspective needs to be taken. One way in which the values of ecosystem goods and services can be incorporated into natural resource management is through the adoption of decision making strategies, which do not rely exclusively on monetary valuation. Multi-criteria analysis is one example of such a technique, and this approach allows both quantitative and qualitative criteria to be incorporated into a decision, thereby allowing a wider range of values to be incorporated. This is illustrated in Figure 4, which shows how riverine ecosystem values can be incorporated into decisions on the management of dams. This figure highlights the wide variety of issues that should be considered when managing water resources. Although there has been some criticism of the application of subjectively defined weights in any multi-criteria technique, such an approach does try to encompass a more holistic view of the complexity of water resources management.

This more holistic approach to water management can also be achieved through the use of integrated water management tools such as the recently developed Water Poverty Index (WPI) (Sullivan, Meigh and Fediw, 2002). This approach, which explicitly incorporates environmental attributes into its framework, allows decision-makers to discriminate between different locations or communities on the basis of a suite of water related indices. These indices can be consolidated into five main criteria: (i) an assessment of water resources, including ground and surface water, variability of those resources, and their quality[4];(ii) access (by percentage of population) to water both for domestic use and for irrigation, (iii) a measure of how water is used for productive purposes, (iv) values reflecting the capacity to manage water, based on education, health, membership of water user groups, and access to finance, and (v) the environmental impact of water utilisation. This currently serves as a proxy for the incorporation of ecological water needs.

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[4] In this assessment, water quality is incorporated as a means of considering how water resources for human and livestock use are influenced both by natural factors (such as fluoride or arsenic), and by pollution. The impact of both of these issues on human health is clearly important, and attempts have been made to incorporate these explicitly in a number of ways into the structure of the WPI.

Normalised scores (between 0 and 100) for each of these criteria can be identified, largely from existing data, and by applying a simple formula, it becomes possible to generate an overall index value. The formula which has been used to calculate the WPI values is a weighted average, as shown below:

$$WPI = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \qquad [1]$$

where *WPI* is the Water Poverty Index value for a particular location, X_i refers to component *i* of the WPI structure for that location, and w_i is the weight applied to that component. Each component is made up of a number of sub-components, and in this instance, all of the weights have been set at 1.

The computation of the WPI facilitates comparison between locations, and if repeated, we can use this to assess progress (or otherwise), over time. By plotting the components together on a pentagram, the nature and relative importance of the water management issues at each site can be compared. Figure 5 provides an example of how the Water Poverty Index varies between four different communities in northern Tanzania.. In this example, we can see how this technique allows decision makers and communities to understand more clearly what particular components within the water sector need to be developed. For example between these four communities, improvements in access are most needed in Samaria[5], where the resource itself also needs to be developed. In the case of Kijenge, a peri-urban community, capacity to manage water is relatively high, but benefits from the use of water need to be better developed. This can be contrasted with the situation in Nkoaranga, a rural community, where capacity to manage may be a little less, but the returns from water use are greater. This suggests that investment in capacity building would be particularly productive in Nkoaranga while development of more effective water use, and improved access, would be more applicable in each of the other locations studied. Displaying the information in this format makes it easier for policy makers and stakeholders to understand the full range of water related issues, and how best to respond to these to promote more effective and equitable development in the water sector.

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[5] In this community, it was found that households spend on average between 6 and 7 man-hours per day to collect water for their domestic needs. (Sullivan et al., 2002)

The Water Poverty Index is very useful for enabling the participation of various stakeholders in policy-making and valuation methodologies, a process that has been very widely advocated. Other approaches, such as 'deliberative democracy' (Jacobs, in Foster, 1997) in the area of environmental valuation, and 'multi criteria appraisal' (Stirling, 1997) in the area of policy making, have become more widely accepted in recent years. Deliberative democracy, like citizens juries, presents the advantage of animating a debate and hence environmental awareness amongst a community, and this in turn constitutes a combination of environmental education and the construction of environmental values that are then communicable to policy-makers.

3. Ecosystem needs

The idea that an allocation of water should be made for the natural environment was taken up at UNCED in 1982, where the governments of the United Nations made an ethical commitment to the environment in the form of the World Charter for Nature. This expresses absolute support of the governments for the principle of conserving biodiversity. It recognises that every form of life is unique and warrants respect, regardless of its direct worth to humankind and that the lasting benefits of nature depend on maintenance of essential ecological processes and life-support systems and upon the diversity of life forms (McNeeley *et al*, 1990). The concept promotes conservation of ecosystems as a public good independent of their utility as a resource and hence water rights to species and ecosystems. The declaration from the Second World Water Forum in The Hague 2000 highlighted the need to ensure the integrity of ecosystems through sustainable water resources management. The World Summit on Sustainable Development held in August 2002 in Johannesburg, reinforces the role of environmental protection as a key pillar of sustainable development. South Africa has taken a lead in implementing the concept (Rowlston and Palmer, 2002). Its Water Law states that "the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems". Tanzania is currently developing similar legislation that also gives high priority to ecosystem needs. Again this demonstrates a pragmatic approach being taken to pre-empt the possible generation of future water stress.

As the water resources of the world come under increasing pressure, (see Figure 1) their allocation between different uses becomes more critical. With a water crisis facing many countries, it seems an immense task just to manage water so that there is enough for people to drink let alone for agricultural and industrial uses, thus many people believe that providing water to other users, such as "the environment", should be given a low priority. Indeed the situation is often presented as a conflict of competing demand, as though it was a matter of choice between water for people and water for wildlife. This ignores the benefits to mankind of functioning ecosystems, including natural resources (eg. fish, timber and medicines), hydrological functions (eg. flood protection and water quality improvement) and support of biodiversity. Water for ecosystems should thus be seen as water indirectly for people. Barbier *et al* (1991) showed that the net economic benefits of water used to maintain resources and functions of the Hadejia-Nguru wetlands in Nigeria (agriculture, fishing, fuel wood) were many times the returns from using the water for intensive cereal irrigation.

Figure 6 summarises the trade-off between allocating water to direct and in-direct human uses. The upper part of Figure 6 shows the impact of allocating water to natural ecosystems, which in turn provide valuable goods (eg. fish), services (eg. water regulation) and amenity/touristic/ethical value (landscape and species). In this case the impact on the hydrological cycle is frequently positive, as, for example, ecosystems improve water quality. Additionally, it satisfies the growing belief amongst many people that humans have a moral duty to protect wildlife, through providing sufficient water to maintain flora and fauna.

The lower part of Figure 6 shows the direct use of water through the development of highly managed systems, including reservoirs, intensive irrigation schemes, dams, river embankments and water purification plants. This has led to production of crops, industrial products, electricity, protection from floods and provision of clean water, thus improving economic and social security. However, this has often caused negative impacts in the form of pollution. Clearly the economic and social well-being of many people has been vastly improved. In addition, through the provision of food and water to starving and thirsty people in drought stricken countries, technology has contributed to ethical objectives of those who do not face this problem. Furthermore, there are many who suffer from development options, such as those who live off natural resources downstream. A major question is whether such highly-managed systems are sustainable.

(a) Optimising the trade-off between direct and indirect use of water

The important question is "at what level to maintain the Earth's ecosystems?" The concept of sustainability suggests that we need to maintain the Earth's ecosystems so that they yield the greatest benefit to present generations, whilst maintaining the potential to meet the needs and aspirations of future generations. The problem is to decide how much water should be utilised directly for people for domestic use, agriculture and industry and how much water should be used indirectly by people to maintain ecosystems that provide environmental goods and services.

Figure 7 shows the problem conceptually as a trade-off between natural and highly managed systems. As natural systems are modified more and more, the benefits of the natural system decline (solid line); eg. hydrological functions, products and biodiversity are lost. At the same time, benefits from the highly managed system increase (dotted line); eg. food production rises. It is suggested that the benefits from the highly managed systems reach a plateau, whilst the benefits of the natural system will decline to zero at some point. The total long term benefits (grey line) can be calculated by adding the benefits of the natural and highly managed systems. The total rises to a maximum before declining. It is at this point that the balance the level of management is optimised. Obviously, the value that society places on goods and services and ethical considerations will determine the exact form of these curves. Indeed the perceived benefits will vary between different groups and individuals. It is essential therefore that the costs and benefits to society of allocating water alternatively to maintain ecosystems and to support direct use in the form of agricultural, industrial and domestic uses are quantified.

(b) Determining the water needs of ecosystems

Two broad approaches have been adopted: objective-based water allocation and scenario-based allocation (Acreman and Dunbar, 2002). As its name suggests, the objective-based approach requires pre-definition of objectives for ecosystem, then the water required to achieve these is calculated. This may be driven, for example, by legal requirements such as the European Union Directives that specify a target ecological status. The application of the objective-based approach by water managers forces the identification of threshold flows below which there would be significant changes in river ecology. For example, experts have suggested that in Australia the probability of having a healthy river falls from high to moderate when the hydrological regime is less than two-thirds natural (Jones, 2002). In South Africa it is recognises that different rivers will have different objectives. The Department of Water Affairs and Forestry classify rivers according to four target classes, A-D (Table 2). The environmental flow allocated to the river depends on the target class.

The major problem with the objective-based approach has been the difficulty in identifying critical threshold flow levels. Many relationships between river flow and ecological indices are straight lines or smooth curves, such as the change in fish abundance with flow (e.g. Sheldon *et al*, 2000). These do not provide evidence of specific flow thresholds to support ecological objectives. Welcomme (1996) found a linear relationship between flooded area and fish catch (Figure 8) on African floodplains, thus there is no clear threshold point below which the flooded area is insufficient to maintain the fish population. Some studies have indicated a continuum of change in ecological communities, such as macro-invertebrate, with alteration of flow regime (Extence *et al*, 1999).

Where no specific ecological objectives have been set, which is the case for the majority of aquatic ecosystems, scenario-based environmental flow allocation provides an alternative approach. In this approach various river flow scenarios are used as the basis of negotiation between stakeholders. Scenarios often include a natural flow regimes and several flow regimes produced by different degrees of water abstraction or impoundment of the river. For example, to assist the Lesotho government in setting environmental flows from dams within the Lesotho Highlands Development Project, Brown & King (2000) produced, for various scenarios, the economic benefits of selling impounded water to South Africa and the impacts on dependent communities of the resulting degraded river ecosystems. In the UK, Dunbar *et al* (2000) modelled the impact on salmonid fish habitat of five different groundwater abstraction options in the River Wylye to assist in setting abstraction licences. This approach is designed to address trade-offs between the needs of the abstractor and the environment. The advantage is that the scientists do not need to define hydro-ecological thresholds and various stakeholders can be involved in the process. The disadvantage is that the approach is inconsistent, as different groups of stakeholders reach different decisions.

The water needs to meet specific ecosystem objectives, such as conservation of particular species or communities is a complex issue that has been the subject of considerable study world-wide. Much of the focus has been on minimum flow requirements. However, there is increasing recognition that magnitude, duration, frequency and timing of many elements of the flow regime of rivers are important to their ecology rather than just low flows (Poff *et al*, 1997; Richter *et al*, 1997). For example, Booker *et al* (2002) found that in urban rivers in Birmingham, UK, fish habitat was critically low at high flows since velocities were higher than maximum fish swimming speeds because refuges had been removed through channelisation aimed at reducing flooding.

Some species have specific requirements during a particular life stage. For example, Acacia trees in the riverine forests of the Indus river valley require inundation from flood water for their moisture, which also brings important nutrients. At least in their early stages of growth, the trees must be flooded for at least 10 days per year. Once acacias are about 8-10 years old their roots are normally able to reach the permanent water table. Even tree species that grow in saline water, such as mangroves, have requirements for fresh water. For example, ecological studies of the Indus delta by the Sindh Forestry Department (Qureshi 2001) estimated that each 100 acres (40 ha) of mangrove forest requires 1 cusec (0.028 m^3 sec^{-1}) during July and August to remain healthy and support the associated fisheries. For the estimated 260,000 hectares of mangroves a total volume of 27 MAF (33,300 million m^3) would be needed. The floodplain forests upstream of the delta have a different water requirement. They need to be inundated at least twice in 5 years to enable saplings to become established. By combining these requirements, an ecological minimum flow regime can be defined, in terms of volume, distribution through the year and inter-annual variability, to maintain the ecosystem of the lower Indus.

In some cases biological response models are employed to predict changes in physical habitat for particular species or life stages that result from alterations to the flow regime. The most widely used method is the PHABSIM (Physical Habitat Simulation) initiated by the US Fish and Wildlife (Bovee, 1998) and developed for use in other countries including UK, New Zealand, France and Norway (Parasiewicz & Dunbar, 2001). PHABSIM assumes that a given species has preferences for certain habitat characteristics, such as water depth or flow velocity. A hydraulic model within PHABSIM, which requires calibration using field measurements, determines the spatial variation in depths and velocity and predicts how this changes with flow. A key output from PHABSIM is a quantitative relationship between in-stream physical habitat and river flow for key species (e.g. see Elliott *et al.* 1996). PHABSIM has been used to estimate the ecological effects (in terms of available physical habitat) for historical or future anticipated changes in flow caused by abstraction, dam construction or climate change. However, it does not normally consider indirect impacts, for example reduced river flows may increase concentrations of pollutants or reduce dissolved oxygen.

4. Integrated Water Resources Management

Many of the problems of environmental degradation resulting from human use of water resources have come about because of a lack of understanding of how changes in the quantity and quality of water at one point in space and time can affect terrestrial and aquatic ecosystems at another point in space and time. In recognition of this Falkenmark (1999) has written about upstream and downstream impacts of water use and the need to better understand the linkages between water and the landscape that it flows through. Falkenmark has also highlighted three key omissions in past as being (i) the focus on river ('blue') water that locks the debate into irrigated food production and ignores the important contribution of rainfed ('green') production, (ii) ignoring what happens to water after its use – i.e. alterations to the downstream quantity and quality of water and its potential reuse and (iii) the need to consider environmental/ecosystem water requirements.

Many authors (e.g. Rijbersman, 2000, Wallace and Gregory, 2002) have also pointed out that it is necessary to not only understand the linkages within the physical water system and the ecosystems it supports, but also the linkages with the social systems that depend on and manage the water resources. This mixture of physical and social issues is very complex and it is therefore vital to have some frame of reference within which this complexity can be addressed. Within the hydrological community this frame of reference is the catchment, a generally well-defined geographical unit where it is possible to describe water inputs and outputs as well as flows within the system. Using a catchment as the unit of study allows the impacts of change in one part of the catchment to be predicted in another part of the catchment. For example, deforestation or afforestation of the uplands in a catchment can alter flows and water quality downstream, an issue that has been long studied by hydrologists (e.g. see Calder and Newson, 1979). Catchment frameworks have also been used in the design and impact assessment of dams on rivers (Acreman *et al*, 2000). The approach has been so useful that it has led to the concept of 'Integrated Water Resources Management (IWRM)', i.e. using a catchment framework to assess and manage the complete array of water supply and demands within the specified basin. This approach is considered as vital, especially in water scarce areas where the competition for limited water resources is most acute. These areas tend to be ones where agricultural productivity is low and largely rainfed. However, Rijsberman and Molden (2001) has pointed out that water used by rainfed agriculture can also impact downstream ecosystems if the water evaporated by the crops reduces runoff. Rijsberman also advocates the co-management of both rainfed and irrigated agriculture within a catchment context. Using this approach he concludes that it would be possible to meet future food production requirements without increasing the allocation of water to agriculture, but that this would require productivity improvements in both rainfed and irrigated agriculture that exceed (by a factor of two) current performance.

Although the concept of IWRM has existed for some time in scientific circles, it has taken some time to be recognised and used by water managers. For example, it is only very recently that water managers in the UK have agreed to use catchments as the operational water management unit. Encouragingly, new water legislation in both Southern Africa and China has adopted the catchment as the basis for their new water laws, requiring new water administration organisations to operate on a catchment basis (e.g. Wallace and Zhang, 2002). The new water law in Southern Africa also introduces the concept of legally protected environmental flows, effectively giving 'water rights' to the environment. Since the use of catchments for IWRM is a major step forward, we need to consider their use in contributing to the issue of the sharing of water between society and nature. What are the strengths and weaknesses of IWRM ?

The physical linkages within a catchment offers the possibility of quantifying the interactions between different water users (e.g. the impacts of water abstraction for irrigation on river flows downstream). To do this clearly requires some hydrological knowledge of the catchment, which in most parts of the world is either incomplete or entirely missing. However, if we wish to predict the full range of environmental impacts, we also need to understand the relationships between river flow regimes and the in-stream aquatic and riparian ecosystems they support. This is a new and very challenging area of physical science, where there are some early examples of progress (e.g. the PHABSIM work referred to earlier). The key challenge is to quantify the impact of sub-optimal water supply on ecosystems. This evaluation must take into account the temporal and spatial variations of ecosystem requirements, not least because this information may be vital in finding the best match between ecosystem and human requirements. Only then can rational decisions be made on how best to apportion limited water supplies between different parts of the ecosystem and society.

The critical timing of water requirements for ecosystems and humans has been illustrated in the Diawling National Park, in the delta of the River Senegal in Mauritania. This area is affected by seasonal variations in water availability and salinity, which has generated particular vegetation types, such as mangroves with associated species, including penaeid shrimp and mullet (Hamerlynck, 2001). In the late 1980s, the delta was separated hydrologically from the river by construction of the Diama dam and right-bank embankment. These maintain water levels in the Senegal River for gravity irrigation and navigation, but caused degradation of biodiversity of the Park and loss of natural resources, including grazing and fisheries, in the buffer zone on which local communities depend. Thus construction of the embankments led to increased poverty of these people. Restoration of the Diawling Park involved releasing water through the embankment via a sluice gate. On 1 July initial releases are made to dampen the soil, simulating rainfall. On 1 August releases are increased so that the water level rises at maximum 1 cm per day, so that the growth of grasses, such as *Sporobolus robustus* and *Echinocloa colona* can keep pace. The grass provides habitat for fish that spawn on the floodplain and for the nesting of crowned cranes. Annual fish production increases with flooded area by around 100 kg ha^{-1}, providing food and income for many local people. The flooded wetlands also provide habitat for many thousands of migratory birds. After 45 days of inundation, salt has been leached from the soils and the water is allowed to drain off, to prevent colonisation by unwanted species such as *typha* and cypergrasses. In the dry season the *Sporobolus* is exploited for the production of mats, providing the main source of income for local women. The *Echinocloa* provides excellent grazing for the thousands of cattle visiting the delta. This is a good example of integrate water resources management.

Where surface water dominates, the catchment provides the most appropriate management unit. However, frequently the underlying aquifer does not coincide with the surface river basin. Thus, where groundwater plays a significant role, a group of basins overlying the aquifer may constitute the appropriate unit of water resource management. For issues where air quality is influential, such as acid rain, the “airshed” (as apposed to the watershed) will be more appropriate implying the integrated management of source areas, which may be industries in the UK, with affected areas in Scandinavia (Acreman, 1998).

In the broader context of the sharing of water between society and nature, the biggest challenge is to see how the catchment framework can be used for the non-physical (social, legal, economic and institutional, etc.) factors that are important to water use and its management. The institutional dimension is important since water management organisations need to be able to link individual waters users and sub-catchment systems (e.g. dams, irrigation schemes, towns, etc.) to the complete catchment level. Economic factors cross catchment boundaries and it is important to be able to deal with this. For example, a water scarce area with sufficient money, may decide to import some (or all) of its basic food requirement, thereby negating the need to use catchment water supplies to grow food. This has been referred to as importing ‘virtual water’ (Allan, 1908 a,b) and is discussed further by Rijsberman (this issue). The key point is that an interaction between internal catchment water resources and external economics needs to be understood and introduced into the catchment management.

Legal issues can arguably be the most dominant factor in determining how water is managed. For example, who owns water and what price should be paid for it are major issues that are usually determined through legislation. However, how much hydrological and ecological information is used in setting and enforcing water laws? Furthermore, how well is legislation matched to catchment boundaries and how do you deal with catchments that cross legal boundaries (e.g. the Danube in Europe and the Mekong in Asia, etc.). The interface between water and law is clearly another major challenge that needs to be met for the successful implementation of good water resources management. Finally there are many complex social aspects to water. These range from cultural and religious beliefs that affect the use of water to modern societies expectations of water resources for recreation and aesthetic value.

Societal priorities for water need to recognise that huge numbers of people throughout the world are today still suffering the burden of poverty. Any new approach to water management must explicitly address this problem, since a typical characteristic of poverty is lack of access to adequate water supplies. Since the proportions needed for domestic requirements are relatively small, accounting only for some 3 - 4 % of total per capita requirements (Falkenmark, 1997), this suggests that losses resulting from small adjustments in allocations to other uses will have a more than proportionate impact on domestic water supply. Bringing about more effective redistribution of water to reduce poverty is therefore very possible. By demonstrating the small degree of change needed to achieve real impacts on poverty alleviation, policy makers may be persuaded to adopt both the appropriate political will, and the necessary finance needed to bring about real change

Taking the water management problem as a whole however, allocations between sectors need to be examined, with the potential goal of highlighting current inefficiencies and inequities in sectoral water use. By highlighting such inefficiencies, attention can be drawn to weaknesses in existing systems, and the opportunities to improve water management through its more equitable reallocation. There is little doubt that water allocations for effective ecosystem health are important to the maintenance of the ecological integrity of human life support systems. As a result, we need to work out how best to share water between people and nature. While it is vital that adequate water be reserved for the maintenance of ecological services, the quantities needed for this are not yet fully understood. However, it is likely that ecological requirements will represent a significant proportion of the available water resource, although this will mostly be non-consumptive use. In order to incorporate this ecological allocation into water management, new approaches are needed to quantify the effects of non-optimal supply on ecosystems. When these are better known along with human requirements and the efficiencies of the different sectors, a more equitable approach to the sharing of water between society and nature should be possible.

5. Concluding remarks

Despite the abundance of water on the Earth, it is becoming clear that the relatively small proportion that is fresh and accessible is coming under increasing pressure as the world population rises. Human requirements for water have greatly increased in the past 50 years and look set to continue to increase for at least another 50 years. These requirements are dominated by the water used in irrigated agriculture, where significant productivity gains (yield per unit of water used) are required to limit the water allocation to this sector to acceptable levels. On the other hand, basic human requirements for drinking and other domestic purposes is a very small proportion of the total water used and hence it should be possible to meet these vital needs without much impact on other sectors.

As human water requirements grow, the water left to support ecosystems is reduced and the already considerable ecosystem impacts will continue to rise. However, it is now widely recognised that supplying sufficient water to ecosystems is essential to maintaining the very essence of life on Earth. Ecosystems provide direct support of humans through natural resources and hydrological functions and they are a fundamental part of the social structure of many rural communities. In line with the principles of sustainable development, there is also a growing acceptance that we have a moral and ethical duty to maintain our fellow species on the planet. Science can provide a fundamental insight into the principles of ecosystem functioning and its interactions with water. We are beginning to gain a better understanding of the water requirements of species and communities and about the thresholds that define critical levels of water supply to maintain ecosystem health. Nevertheless, in many parts of the world, ecosystems have become highly managed and it is not possible, or even in many cases desirable, to return them to a natural state and only small areas will ever be conserved as true wilderness. The desired state of our ecosystems will inevitably be guided primarily by social choice. Scientific principals can then be employed to define the necessary water requirements. Whether these requirements can be met will depend upon a complex interaction between law, policies, economics and politics.

Equity has become an important concept in water allocation in the past decade. As pressure on water resources increases, ensuring equity between economic, social and environmental sustainability will become a major challenge. Over the past 100 years, economic development has been dominated by infrastructure, with water allocation focused on intensive agriculture, hydropower generation and industrial and domestic supply. There has been a repeated tendency to neglect the needs of the rural poor, who, more than any others are dependent on natural resources and functions of ecosystems. More equitable allocations of water for poor peoples' needs have to be met by redistribution from other sectors, although the quantities involved are relatively small. At the same time, conservation of ecosystems and rare species has often had the lowest priority. It has now become clear that the long-term survival of human and biological diversity on Earth will be dependent on a new paradigm of equitable allocation between our economic, social and ecological needs. More equitable sharing of water resources between society and nature will require values to be placed on both human and ecosystem requirements. These values will need to be incorporated into macroeconomic policies so that more rational decision-making about water allocations can be made, not only to meet the needs of our current population, but also to meet the needs of the continually growing future generations.

Catchment based integrated water resources management (IWRM) provides a framework within which water resources can be managed more holistically. This makes it possible for human and ecosystem water needs to be better understood, highlighting areas where water use efficiency can be improved or where limited water is best used. More effective natural resource accounting in general, and water accounting in particular, would provide a solid foundation on which more sustainable and equitable policies can be built. The development of these types of accounts have been resisted by many large-scale enterprises, as they anticipate the associated cost implications. However, through a process of continued institutional strengthening, it will become more likely that better representation of different groups will be achieved in decision-making, enabling a wider range of views to be considered. There is little doubt that such institutional development is crucial to the water sector, and by contributing to this process, catchment based co-management can ensure that more effective ways of representing the interests of both people and nature can be achieved.

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Table 1. Correlations between economic performance and sectoral water use in selected countries

Countries with less than	Correlation between agricultural water use (%) and contribution to value added to GDP from agriculture	Correlation between industrial water use (%) and contribution to value added to GDP from industry	Correlation between value added to GDP from agriculture and Human Development Index score	Correlation between water withdrawals and HDI value	Correlation between water withdrawals and GDP per capita value
Countries with high GDP per capita (1)	-0.03	-0.07	-0.06	0.51	0.47
Countries with low GDP per capita (2)	0.21	0.69	-0.51	0.11	0.27

Notes:

1. Countries with per capita GDP over US$10,000, and per capita water withdrawals of less than 0.5 Km^3 per year, (Barbados,Cyprus, Czech Rep.Denmark, Ireland,Kuwait, Netherlands, Norway, Singapore,Slovakia, Slovenia, Sweden)

2. Countries with per capita GDP less than US$10,000, and per capita water withdrawals of less than 0.1 Km^3 per year. (Benin, Botswana,Burkina Faso.Burundi,Cambodia,Chad, Côte d'Ivoire, Ethiopia,
Eritrea, Ghana,Haiti, Kenya, Lesotho, Malawi, Mozambique,Niger, Nigeria,Tanzania, Togo Uganda)

3 In the higher GDP countries, no country has less than 0.1 Km3 per capita, whereas in the low income group, all the countries have less than 0.01 Km3 freshwater withdrawals.

Data sources:
Population: World Resources Institute, 2000 Tables HD.1 and SCI.1 and Human Development Report, 2001
Water Resources: World Resources Institute, 2000 Table FW.1, and Gleick, 2000
GDP and sectoral contributions: Human Development Report 2001

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Table 2. Ecological management classes (DWAF, 1999)

Class	**Description**
A	Negligible modification from natural conditions. Negligible risk to sensitive species.
B	Slight modification from natural conditions. Slight risk to intolerant biota.
C	Moderate modification from natural conditions. Especially intolerant biota may be reduced in number and extent.
D	High degree of modification from natural conditions. Intolerant biota unlikely to be present.

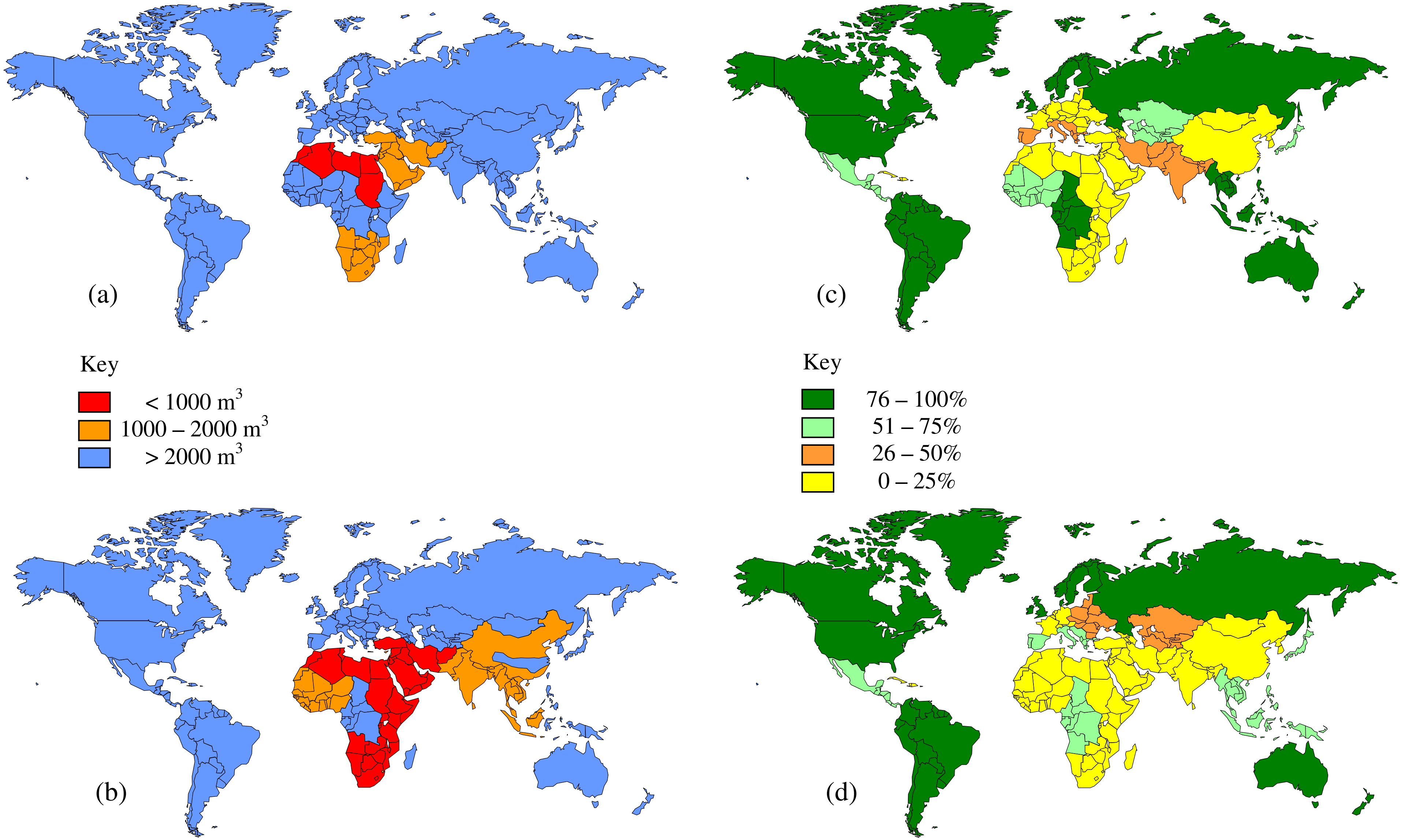


Figure 1. Human water needs (a) now and (b) in 2050, and the residual (% of total available water) for ecosystems (c) now and (d) in 2050.

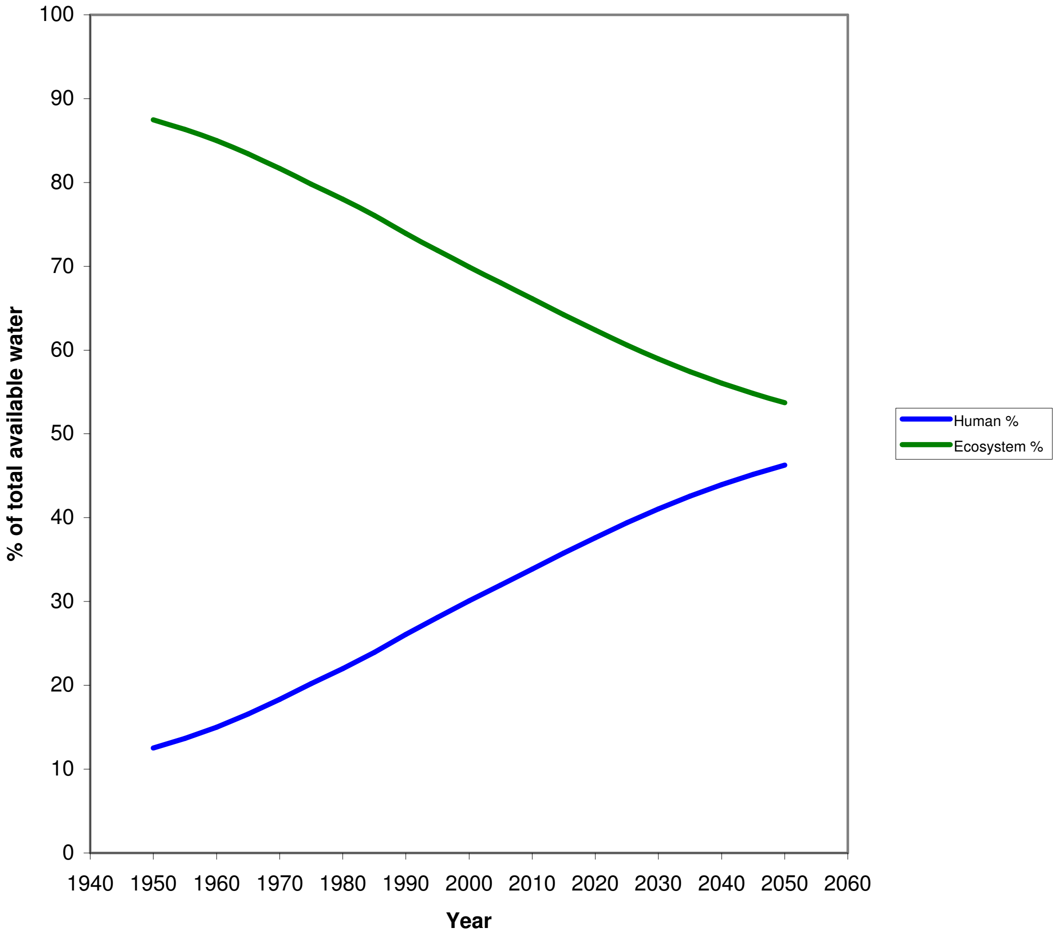


Figure 2. Change in human water use and ecosystem water availability with time.

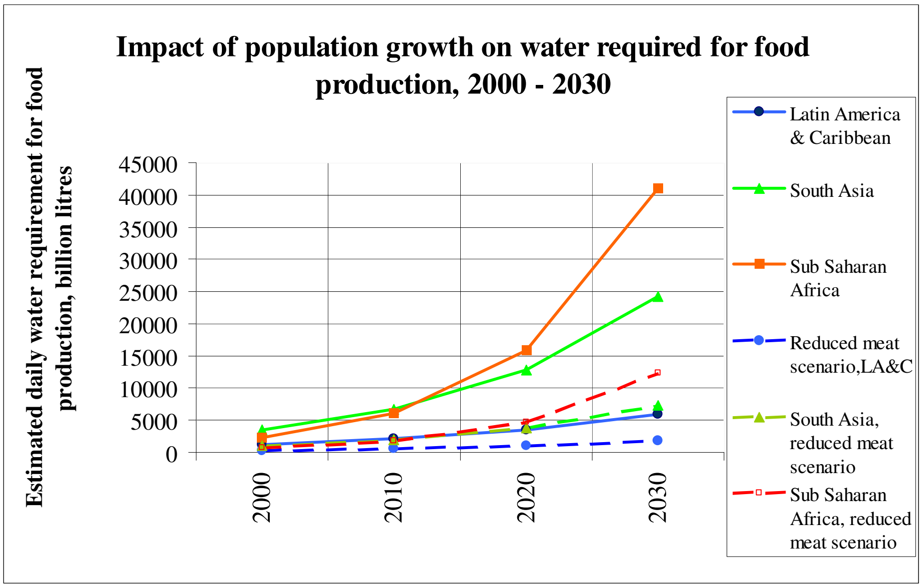
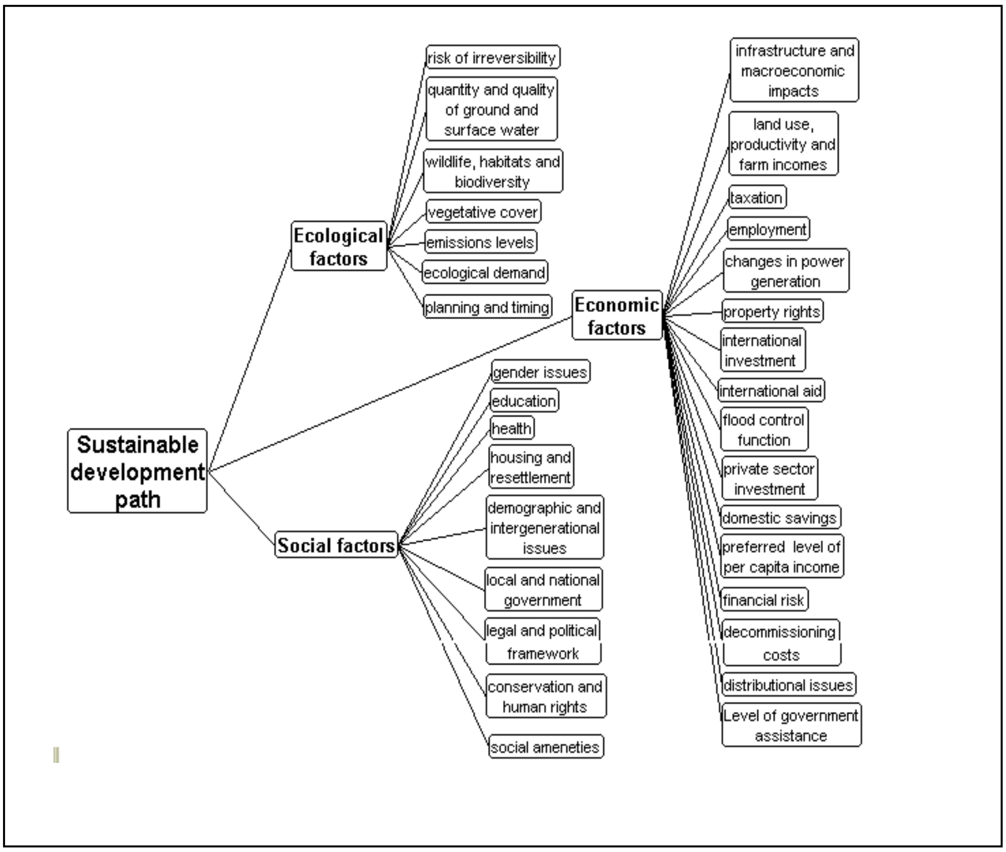
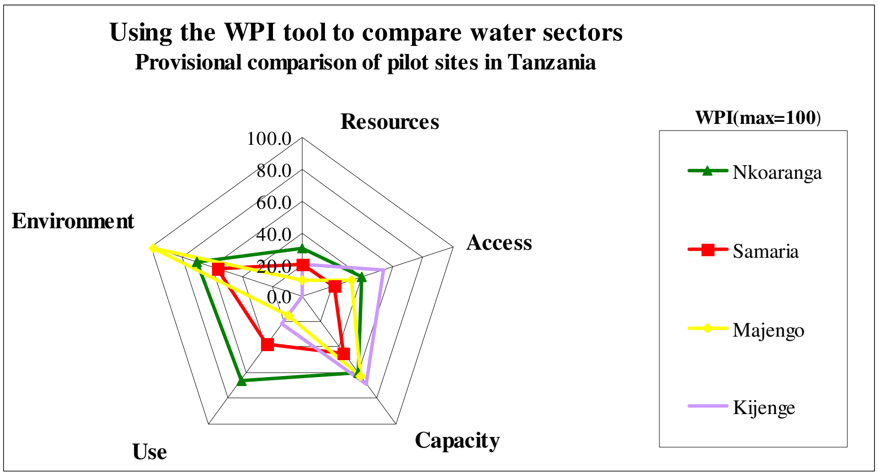


Figure 3. How water for food production may be influenced by consumer choices.



Source: McCartney, M.P., Sullivan, C. A., and M.C. Acreman (1999)

Figure 4. Using a multi-criteria approach for management of large dams.



Source: Sullivan, Meigh and Fediw, 2002

Figure 5. An illustration of the Water Poverty Index applied to communities in Northern Tanzania.

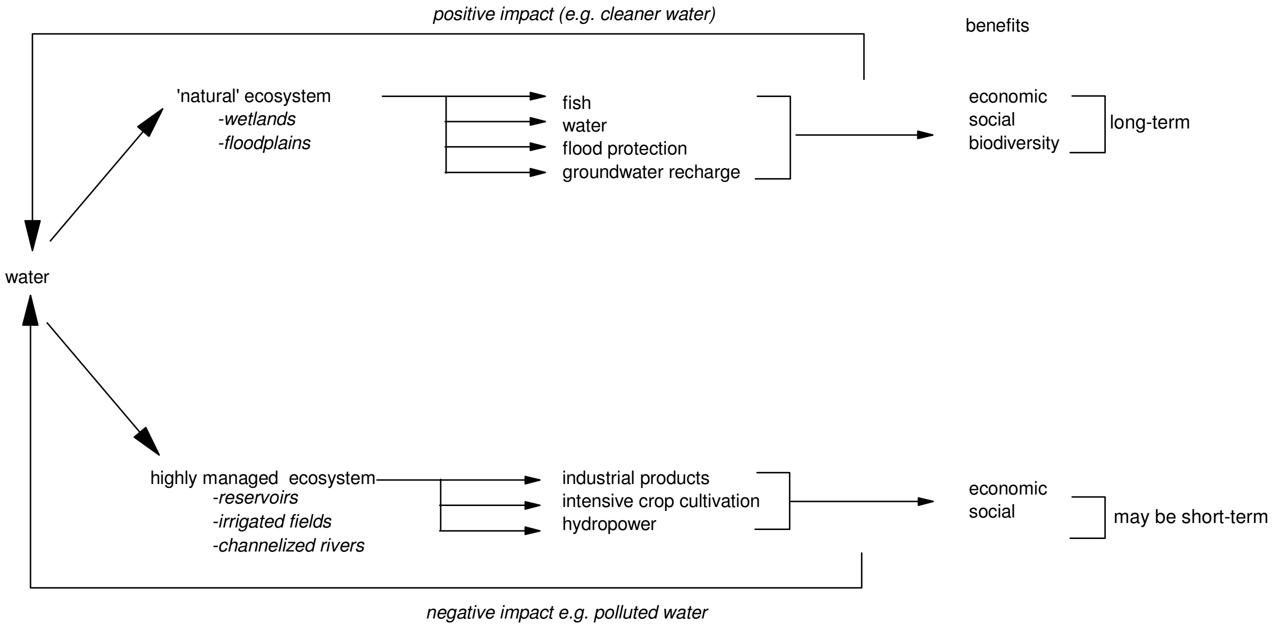


Figure 6. Natural and non-natural ecosystem benefits.

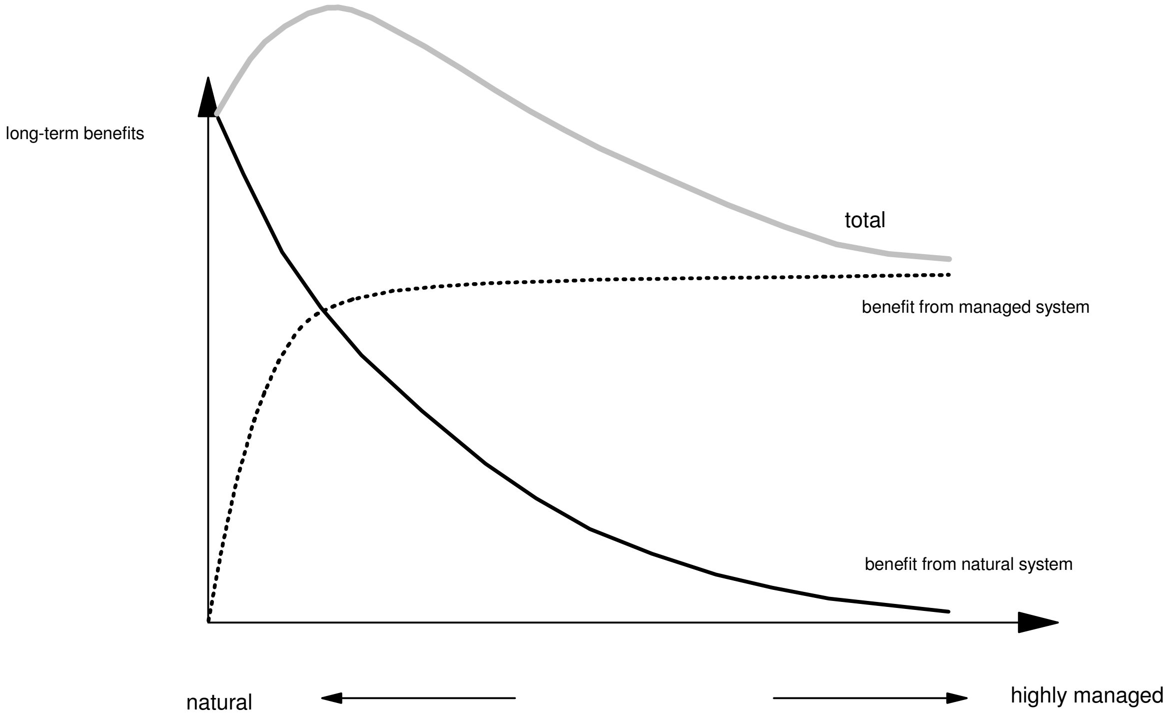


Figure 7. Maximising benefits from freshwater ecosystems.

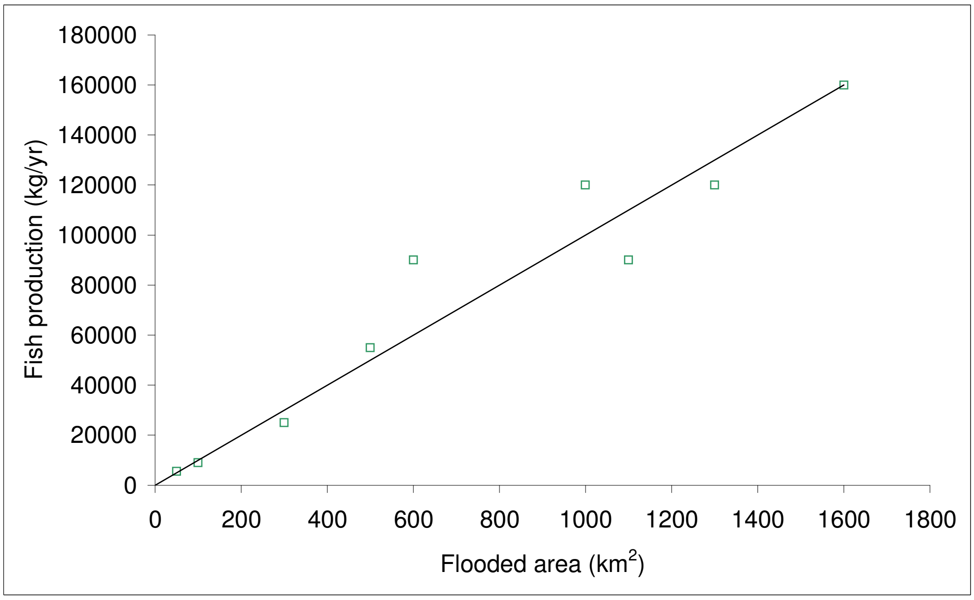


Figure 8. Relationship between flooded area and fish catch (after Welcomme, 1996).