

5 THE MESO-SCALE (CATCHMENT-SCALE CASE STUDIES)

5.1 INTRODUCTION

In Section 4, trends in climate and anthropogenic change were identified at a regional scale. In Section 5, these trends are investigated at the catchment scale, whereby the impact of global climate change is considered alongside desakota activity and its associated environmental consequences. Seven case study catchments within the four ESPA regions were chosen and the socio-economic characteristics of these catchments are described in Section 2.F-G. The aim of this section is to provide an environmental background to support these sections, which focuses on the environmental impacts of desakota activity within the context of future climate change. In each case study, the environmental characteristics and key ecosystem services within each catchment are described; the environmental changes induced by climate and anthropogenic activity are considered and the impacts on ecosystem services are assessed, concluding with some catchment-specific research questions.

5.2 CHINA: THE MIYUN RESERVOIR AND THE HAI RIVER BASIN

The Hai catchment provides an interesting example of the conflicting demands between urban and rural water use and illustrates the upstream-downstream linkages in the environmental impacts of desakota development. Within the catchment, the major urban centre is Beijing which, facing a crisis in water supply, has attempted to restrict development in the upstream areas, to ensure an adequate, clean water supply. This case study also illustrates how policy interventions may impact desakota development.

5.2.1 Environmental Context and Services

The Hai river basin (Figure 5.1) is situated in western China and is the 7th largest basin in China, with a total area of 318 000 km², draining into the Bohai Sea. It drains the districts of Hebei, Tianjian and parts of Shandong, Henan, Shanxi and Nei Mongol and provides the main water source for Beijing. 60% of the catchment is in mountainous terrain, whilst 40% is in the lowlands of the North China Plain. Rainfall in the catchment is from summer monsoons (July and August), which account for 70% of annual rainfall. Monsoonal rainfall exhibits high inter-annual variability and there has been a drought in the catchment since 1999 (Peisert and Sternfeld 2005). This is exacerbated by the high temperature regimes in the plains, which coupled with strong winds, results in high evapotranspiration rates (Qian 2007).

In response to the precipitation regime, the highest flows in the Hai are in summer (60-70% of annual total), with less than 10% of flow in the winter months. There are two broad types of rivers within the basin: mountainous and lowland (Jiasan 1983). The upper reaches of the Hai are situated in mountainous areas and the rivers are characterized by eroding channels with steep gradients and deeply incised beds. There is perennial flow and the source of flow changes seasonally - during the flood season, flow is mainly from surface water, whilst flow in the dry season is from subsurface seepage of waters stored in the wet season (Jiasan 1983).

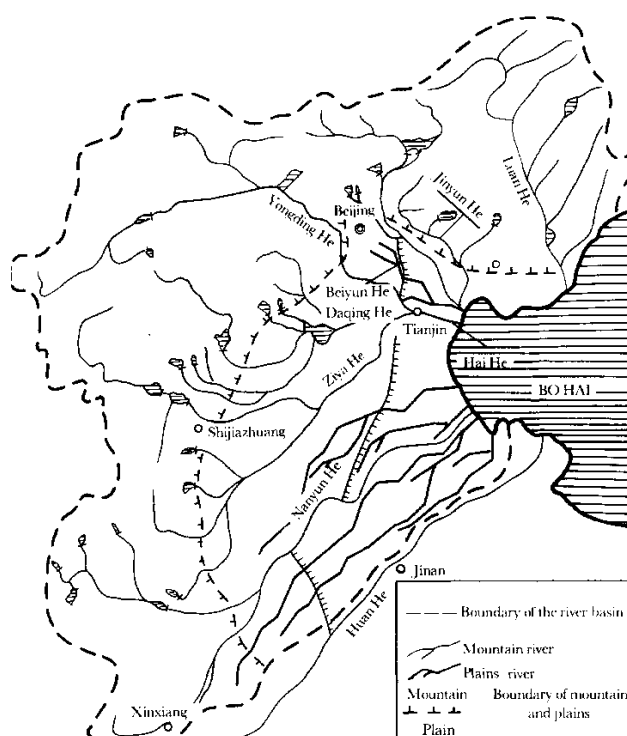
The lower reaches of the river, located on the plains, have a lower gradient, with wide, shallow channels. Here, river flow recharges groundwater and the riparian area through seepage, irrigation diversions and floodwater breaches. However, the level of recharge has been reduced by flood protection and diversion schemes. Many of the river channels in these lower reaches are

artificially excavated to drain excess water in the flood season (Jiasan 1983). The lowlands also support a number of wetlands, but these have suffered drastic decline due to reduction in water availability as a result of human use. As a result, the wetland area in the catchment has decreased from 10 000km² at the beginning of the 1950s to 1000 km² in 2007 (Xia et al., 2007).

Since the 1970s, the Hai River has frequently dried up in its lower reaches. The extent of this desiccation is increasing in extent and duration, so that in total, 4000 km of the Hai river, which constitutes 40% of its length, has been affected (Xia et al., 2007). This has been attributed to increasing upstream water use and decreasing reservoir storage (Lui and Xia 2004). The Hai river currently has a negative water balance and is the most water stressed in China, possessing 1.5% of China's water resources but 10.2% of its population, 11.2% of its farmland and 11.3% of its GDP (Nickum and Lee 2006). As a result there is considerable water stress for both the environment and human population, with Beijing having less than 300 m³ water per person per year (Peisert and Sternfeld 2005).

Water quality is also a problem in the Hai River, with 80% of reaches categorized as polluted (many of these are in the 'worst polluted' category). Over 20% of the total runoff is sewage, which, through influent seepage renders 50% of the groundwater undrinkable.

Figure 5.1: Sketch map of the Hai catchment (from Jiasan 1983)



The Hai catchment has a number of major reservoirs, which have been constructed to store surface water. Guanting reservoir was built in 1954 for flood control and to provide surface water to Beijing. Water demand in the region is high and subsequent reservoir construction upstream (17 medium and 248 small reservoirs, Peisert and Sternfeld 2005) has reduced flow into the Guanting reservoir. Demand has been so high that, although the reservoir has a capacity to store 2.3 billion m³, the actual stored volume has been reduced to less than 220 million m³ (Duan 2003, cited in Peisert and Sternfeld 2005). Sedimentation has also reduced water storage capacity of the reservoir, with 640 million tonnes of sediment already intercepted and more being added each year (Peisert

and Sternfeld 2005). Reservoir water quality is also a problem as a result of widespread use of pesticides and chemical fertilizers. Upstream discharges of untreated/inadequately treated water account for one third of input (approximately 100 million m³ a year) and have reduced water quality to the extent that it ceased to be an urban water supply to Beijing in 1997 (Peisert and Sternfeld 2005).

The Miyun reservoir was built in 1958-60 to provide water to agricultural areas downstream (Tianjin and Langfang 1983) and is the focus of the study. In the 1980s, the poor water quality of the Guanting reservoir led to the Miyun reservoir becoming an increasingly important drinking water source (Peisert and Sternfeld 2005). It now provides most of Beijing's surface water and is the main source of drinking water, with the city having exclusive rights over water supply (Nickum and Lee 2006). The reservoir bestrides the main paths of the Chao and Bai river, which runs through the Hebei province. Due to a drought in this region in 1999, inflow to the reservoir decreased from 400-800 million m³ to 73 million m³ and this has not been replenished.

Water quality is also a problem in the reservoir as a result of upstream mines, which cause water pollution and soil erosion, particularly in the rainy season (Su et al., 2005). There have been a number of attempts to try and improve the quality of the Miyun reservoir through legislation, particularly in relation to controlling land use in the immediate surrounding area (lakeside and 4km from shoreline) and controlling fisheries (Peisert and Sternfeld 2005). This is considered in more detail in Section 5.2.2.

The surface and groundwater catchment areas are similar and groundwater is an important resource. Groundwater has also been over-exploited and water table levels have declined by up to 11.78 m observed between 1980 and 2000 (Peisert and Sternfeld 2005). This has created cones of depression in the aquifers affecting an area of 2200 km² (Peisert and Sternfeld 2005)

The catchment supports several broadleaf and grassland ecosystems, shown in Figure 5.2. Much of the southern lowland catchment is characterized by Huang He plain mixed forests, where broadleaf forests grow due to the moist, warm summers and cold winters (Olson et al., 2001b). The other major ecoregion in the catchment is the Central China loess plateau mixed forest, which forms a transition between forests and steppes and deserts. In this ecoregion, natural vegetation (mixed deciduous broadleaf forests) has been replaced over many centuries by agriculture, which exploits the rich nitrogen, potassium and phosphorous levels in the loess, and has resulted in high rates of erosion, affecting 45% of the area (Olson et al., 2001b). The upland areas of the catchment are characterised by Mongolian-Manchurian grassland, which provides important grazing for livestock (particularly goats). The climate in this region is temperate, with low winter temperatures from the 'continental monsoon effect' induced by low pressure systems over the South China Sea. The ecoregion includes marshes and reed beds, which provide important breeding sites for birds and ecosystem services such as reed-cutting, hunting, egg collection and fishing. The mouth the Hai river, in Beijing, supports Bohai Sea saline meadow, a periodically flooded grassland maintained by river silt deposition. The vegetation communities in this ecoregion are heterogenous and form a gradient from saline meadows (inundated at high tide) to grass and sedge marsh, which surround freshwater lake systems. This ecoregion has been heavily impacted from agriculture and industry and is currently very degraded.

The ecoregions of the Hai catchment provide a wide range of ecosystem services. Principally, the catchment is a major water source for many people, although the increasing demand currently outstrips supply. Water is also used for food production: the region is one of the most important bases for the production of commercial food grains (wheat, rice and maize) and economic crops (soybean, sugar beet) (Lin and Yang 2005). There are extensive areas of cultivated land on the lowlands and much of these are dependant on groundwater for irrigation. Upland areas also provide provisioning services such as hunting, fuel from brushwood and grass and mining (Olson et

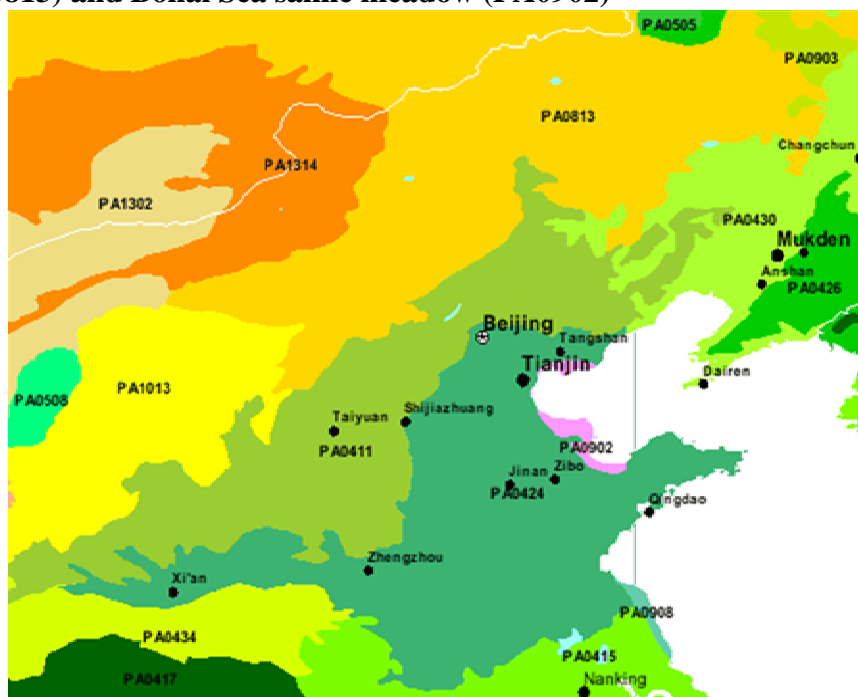
al., 2001b). Wetlands within the catchment provide an important food source, although these are under strain. For example, the Miyun reservoir has been very important for commercial fish farming. In 2003, associated water pollution raised concerns over drinking water for Beijing, which resulted in the prohibition of cage fishing in 2003. Despite this, the reservoir is still an important food source, which has prompted informal development along its margins (Peisert and Sternfeld, 2005).

5.2.2 Environmental Change

Regional Climate Change: As described in Section 4.2.1, climate change models predict increases in mean temperature in the Hai catchment, with increases in precipitation amount and intensity. This will increase water availability in the catchment, but may also increase flood risk. Changes in climate will have significant impacts on the vegetation. Temperature increases will extend the growth period (Chen et al., 2005), whilst the northward movement of accumulated temperature belts and decrease in cold stress will change the distribution of ecoregions (Lin and Yan 2005). In general, this may result in an increase in the extent of forest biomes within the region, with a reduction in the extent of grassland (Yu et al., 2006). However, the heavy fragmentation of important transitional zones, such as the Central China loess plateau mixed forests, may hinder adaptation to these changes (Olson et al., 2001b)

Changes to climate are likely to affect agricultural production. Zhang (2005) predicts longer growing days and a better condition for vegetation growth in the Beijing area (Zhang 2005), which may benefit agriculture. However, increases in water stress and extreme events are also predicted: Tao et al. (2003) suggest a decrease in precipitation and increase in soil-moisture deficit that will cause major challenges to rain-fed crops.

Figure 5.2: Map of the Hai catchment, showing the major ecoregions: China loess plateau mixed forest (PA0411); Huang He plain mixed forests (PA0424); Mongolian-Manchurian grassland (PA0813) and Bohai Sea saline meadow (PA0902)



source: (from Olson et al., 2001b).

A well-documented hydrological impact of climate change is sea-level rise. In the Hai catchment, this may have adverse impacts on the Hai Delta/Bohai Sea wetlands. Predicted impacts include increased beach erosion, landward retreat of the coastline, wetland loss, saltwater intrusion into groundwater and land salinisation (Olson et al., 2001b)

Catchment-Scale Anthropogenic Change: Within the Hai catchment, an increase in agricultural demand, coupled with rapid urbanisation, has increased water scarcity (Beilingshi Shuiliju 2002, cited in Peisert and Sternfeld 2005; Tao et al., 2003). The rapid rate of urbanisation has caused a lag in infrastructure development, such as water supply and wastewater treatment, and water shortages have resulted (Nickum and Lee 2006). Furthermore, the growth of Beijing has furthered water resource problems in the region, which was already water scarce.

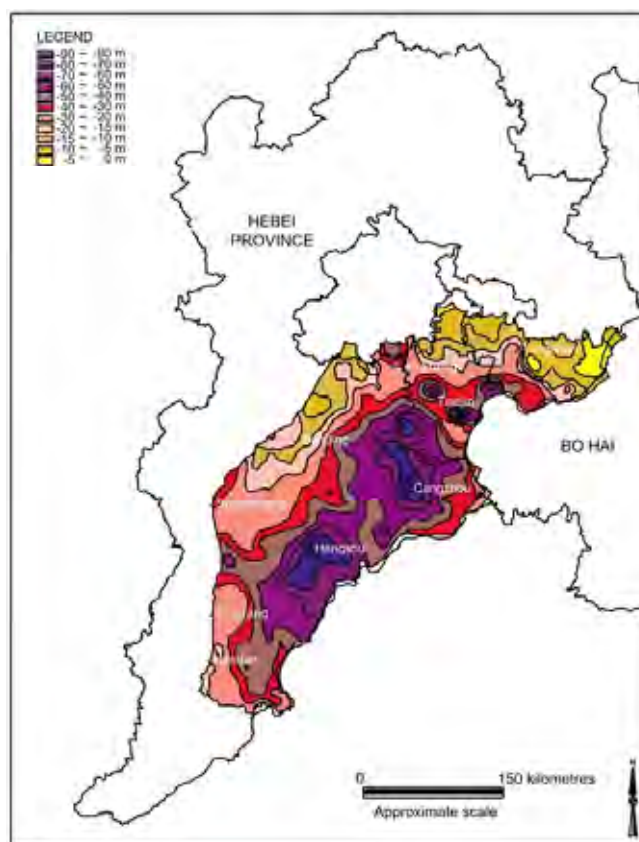
Anthropogenic activity in the catchment has also been responsible for a decline in water quality, which has furthered the water problem. In urbanising areas, domestic sewage and industrial wastewater have caused water pollution problems, although the leading source of water pollution in China is from non point sources in agricultural and rural areas, particularly from fertiliser use (Wang 2006). Some officially forbidden pesticides are still used in rural areas and have huge health and ecotoxicological risks (Zhang and Lu 2007).

To meet the water demand, groundwater resources have been used, with current abstraction estimated at $26 \text{ km}^3 \text{ year}^{-1}$, considerably more than the $9 \text{ km}^3 \text{ year}^{-1}$ that are thought to be sustainable (Han 2000, 2003). Coupled with over-abstraction, natural groundwater recharge in the catchment has been limited by flood protection schemes (Peisert and Sternfeld 2005) and this has resulted in extensive, severe declines in the groundwater table (Figure 5.3), which was identified as a regional problem in Section 4.5.3. According to Duan (2003, cited Peisert and Sternfeld 2005), the groundwater table in the urban area fell by 11.78 metres between 1980 and 2002. The decline in water from the Hai river and from groundwater sources has raised the importance of the Miyun reservoir as a water source to Beijing. This has caused tensions between the Beijing and Hebei governments, as Beijing has attempted to restrict development in the Miyun region, to protect the reservoir quality.

The upstream areas of the Miyun catchment have recently seen an expansion of economic activity. Small enterprises, such as iron mines, sawmills and quarries have increased, along with settlements and light industry, such as food processing (Peisert and Sternfeld 2005). This has resulted in a deterioration of the water quality, from wastewater discharges and accelerated soil erosion. In addition, in upstream rural areas, nitrogen and phosphorus contamination (Wang et al., 2001) and high soil erosion rates from deforestation and over-tilling have further contributed to the problem (Peisert and Sternfeld 2005). Miyun reservoir is also important for commercial fishing, which expanded rapidly in the 1980s and 1990s. However, the environmental impact of this was substantial – at peak times, 1500 tons of fish were produced each year from cage fishing, generating 2250 tons of waste, nitrates and residues, which were directly dumped in the reservoir (Peisert and Sternfeld 2005).

In an attempt to preserve the water quality of the Miyun reservoir, a number of measures have been taken to restrict development in the catchment. In 1995, land surrounding the lake was divided into three water protection zones and economic activity was restricted. Mines were closed, chemical fertiliser use was reduced in favour of organic fertiliser and, in 2003, and commercial cage fishing was prohibited (Peisert and Sternfeld 2005). The water protection zone immediately surrounding the lake had the highest population density and, despite restrictions, a strong alternative economy, based on mining, intensive fish farming and breeding of aquatics has grown, which has resulted in further water quality decline (Peisert and Sternfeld 2005).

Figure 5.3: Groundwater declines in the Hai catchment from 1958 – 1998



source: FAO: <http://www.fao.org/docrep/005/y4495e/y4495e08.jpg>

Concerns have also been raised over declines in lake storage, which have resulted from high rates of abstraction and droughts. The Beijing government attribute this to the high number of dams upstream of the reservoir, which were constructed to support industry (Peisert and Sternfeld 2005). Research also predicts problems for the reservoir from an increasingly dry climate that will cause a reduction in lake volume (Li et al., 2007) and also increased phosphorous release from lake sediments due to temperature increases, which will further reduce the water quality (Xu et al., 2005).

A number of measures have been introduced to conserve water in the catchment. In 2001, the Miyun government announced a program to reduce cereal growth in favour of perennial cultures, to save groundwater. In addition, the Beijing government has announced a program to better use water resources including the closure of 1000 groundwater wells, construction of 4000 small water storage dams, implementation of water saving irrigation systems and planting of 4667 ha forests to protect water resources (Peisert and Sternfeld 2005). There are also proposals to transfer water from the Yantze river into northern China, as part of the 'South-North Water Transfer Project' (Peisert and Sternfeld 2005).

These impacts are detectable downstream from the reservoir. In particular, the Bohai Sea is very polluted, impacting on important fisheries. In response, the Chinese government prepared the 'Bo Hai Blue Sea Action Plan' and the 'Water Pollution Prevention Program of Hai River Basin', which concentrated pollution prevention in the large urban centres of Beijing, Tianjin and Shijiazhuang. Although pollution from these large point sources has decreased, water quality has

continued to decline from much smaller scale urban centres and industries, largely because there are limited pollution control and wastewater facilities in these areas (Global Environment Facility 2002).

5.2.3 Impact on Ecosystem Services

Within the Hai catchment, water supply is the principal ecosystem service which has been stressed by a rise in anthropogenic activity and which may inhibit future development. This case study provides a good example of the tensions between urban and rural water usage and the upstream-downstream linkages in the impacts of *desakota*, as the metropolis of Beijing is heavily dependent upon the Miyun reservoir, which is being impacted by *desakota* activity. It is also apparent that, due to the informal nature of *desakota* development, that legislation has not been successful in restricting economic development in Miyun County.

Climate change may increase water availability in the catchment, although increased demand may hinder any opportunity that this may provide (Lin et al., 2005). One of the major issues in the catchment is water scarcity and changes to El Nino and monsoon systems may increase variability of precipitation, which may exacerbate the situation in particular years. This threatens water supply to urban areas and agriculture, particularly if policy prioritises urban water use over rural demands (Cai and Rigler, 2007).

Changes to the precipitation regime and increases in demand will impact many water-based ecosystem services. For example, flood risk may increase from reduced river flows, as the reduced sediment carrying capacity will cause significant in-channel sediment deposition. This has been noted in the Yellow River, where river bed aggradation has been seen to increase flood risk (Liu and Xia 2004) and may be a potential problem in the Hai catchment. Declines in water availability will also reduce fish stocks, particularly as fish populations depend on high flows during April (flood season and fish spawning season) and require 20% of the flow in August and spring (Sun and Yang 2005).

Water quality is one of the main threats to ecosystem service provision in the catchment. If current policy is not successful, the decline in water quality of the Miyun reservoir may threaten water supply to Beijing, in addition to the consequences for fisheries and human health in Miyun County. In addition, pollution of soils from fertiliser use threatens natural habitats and agricultural land (Luo et al., 2007).

In summary, there appears to be a growing water crisis in the Hai catchment, driven by Beijing's water shortages and Miyun's conservation problems (Peisert and Sternfeld 2005). In order to sustain a water supply, measures need to be taken to conserve usage and preserve water quality. The Chinese government has proposed a number of initiatives to do this, although Peisert and Sternfeld (2005) suggest a number of ways in which this needs to be improved.

5.2.4 Research Questions

- The hydrological regime in the catchment has experienced rapid changes in recent years. There is a need to better understand whether the cause of these changes is climate or increased human activity (Liu and Xia 2004)
- Further to this, the impact of human activity on water-cycle processes needs to be accurately quantified (Liu and Xia 2004)

- Liu and Xia (2004) believe it is important to identify where capacity exists to save water in the agricultural and urban/industrial sectors to try and mitigate against water scarcity
- A better understanding is needed of how changes to the vegetation, either from climate change or desertification activity, impacts on the annual and seasonal water balance.
- Groundwater resources are under extreme pressure as a result of overexploitation, but there is insufficient information on the functioning of the groundwater store, including recharge sources and rates and the likely impacts of climate change.

5.3 SOUTHERN ASIA: GUJARAT, WEST INDIA (THE AHMEDABAD – SATLASANA CORRIDOR)

The Ahmedabad - Satlasana corridor in Gujarat demonstrates some contrasting impacts from desertification development. From an ecological perspective, a decline in agriculture from livelihood change has resulted in reforestation, which may have an environmental benefit in increasing the extent of natural forest habitat and mitigating against some of the effects of climate change. However, the dual stresses imposed on the groundwater resource from agricultural and industrial demands have resulted in severe water pollution and associated health impacts, which may increase with climate change.

5.3.1 Environmental Context and Services

This case study considers a corridor, approximately 175 km in length, from Ahmedabad to Satlasana in Gujarat, western India. Average temperatures in the region range between 25°C and 27°C, with hot summers (March to June) and slightly cooler winters (November to February), due to cold northerly winds. The region is arid, generally being dry for 8 months of the year and depends upon monsoon rainfall (Gupta and Deshpande, 1999). Nearly 95% of the rainfall falls in the monsoon season (mid-June to mid-September), which averages between 555-700 mm a year (Pandey and Devota, 2006). Monsoon rainfall is variable and shows large inter-decadal variation, with epochs (ca 3 decades) of above and below average rainfall (Kripalani and Kulkarni 1998). This variability in rainfall results in extreme hydrological events, such as major floods and droughts (Mall et al., 2006). Analysis of precipitation data from 1875-1998 showed that Gujarat has a 21% likelihood of drought in any year, a 2% likelihood of two consecutive droughts and a 1% chance of more than two consecutive droughts (Mall et al., 2006).

The Sabarmati River runs through the corridor and is the main source of surface water in the region (Pandey and Devota, 2006). The Sabarmati River has its source in the Aravalli mountain range in Rajasthan and flows in a south-westerly direction, draining 21 674 km² (see Figure 5.4) (Pandey and Devota, 2006). The river has five main tributaries, the Rivers Sei, Wakal, Harna, Hathmati and Watrak (Pandey and Devota, 2006), the average annual flow from the catchment is estimated at 3.81 km³/year, of which 1.93 km³/year is utilisable (Kumar et al., 2005). The river's discharge is dependant upon the monsoon, with 75% of total discharge occurring during the monsoon period (Gurunadha et al., 2000), often causing flooding. The flow regime has been altered by construction of the Dharioi Dam in 1978, which maintains current flows at an annual average 600 million litres, through controlled releases (Gurunadha et al., 2000).

The Sabarmati catchment is based on alluvium, which provides an important groundwater source. Groundwater supplies nearly 63% of the water requirements in the basin and 80% of the irrigation demand (Kumar et al., 2005). Natural groundwater recharge estimates for the catchment are 64 mm/year (median) and 82 mm/year (mean) (Rangarajan and Athavale 2000). This provides a

total resource of 20.38 km³/year (as on 31 March 2003), of which 16.38 km³/year is replenishable from natural recharge, with a further 4.00 km³/year from canal irrigation (Kumar et al., 2005)

The ecoregion of the catchment is Khathiar-Gir dry deciduous forests (see Figure 5.5), which is classified as both tropical and subtropical dry broadleaf forests (Olson et al., 2001a). The forest is very diverse, supporting 300 bird species and 80 species of mammals many of which are endemic (Olson et al., 2001b). This diversity reflects the intermediate position of the ecoregion between dry forest and thorn scrub and also Afrotropical and South Indian floras (Olson et al., 2001b). The forest is sustained from monsoon rainfall and the composition of the forest is determined by moisture levels. In moister areas, Teak (*Tectona grandis*) is the dominant species, whilst *Anogeissus pendula* and *Acacia catechu* grow in drier areas (Olson et al., 2001b). The total forest area in Gujarat is 1855 km² and this plays an important role in regulating the hydrological cycle (Pandey and Devota, 2006). However, the extent of the natural vegetation in the catchment is not high, with forest only accounting for 24% of the catchment area and agriculture dominating 57% of the catchment area (see Section 2.F.2).

Figure 5.4 Map of the Sujarat catchment (from Pandey and Devota, 2006)



The catchment provides key provisioning services to population of the Ahmedabad to Satlasana corridor. Water availability in the area is one of the lowest in India, at 300m³ per capita per annum (Kumar et al., 2005) and the river provides an important water source. However, with most of the catchment receiving rainfall during the monsoon season, the river frequently dries up in the summer months (March to June) (Pandey and Devota 2006). Therefore, groundwater is a key

resource and is the principal water source for many rural communities. Groundwater is accessed using standpipes, although these can be unreliable in terms of water quality and quantity (Gupta and Deshpande 1999).

Water is also essential for food production and irrigation currently uses 83% of available water (Mall et al., 2006). Much of the forest in the catchment has been cleared for agriculture, with 744 km² used for permanent pastures and 12 310 km² used for cultivation (of this, 10 000 km² is under irrigation and 2310 km² is rainfed) (Pandey and Devota, 2006). The remaining forest provides supporting services such as wood for fuel and for timber (Olson et al., 2001b).

The catchment is also important for mining for marble and minerals, with many rich resources. Currently, industrialists are lobbying for areas of protected Khathiar-Gir deciduous forest to be denotified for mining development (Olson et al., 2001b)

Figure 5.5: Map of the Sabarmati catchment showing the major ecoregion; Khathiar-Gir deciduous forest (IM0206) (from Olson et al., 2001b)



5.3.2 Environmental Change

Regional Climate Change: Climate change is predicted to have a significant impact on water resources within the region (Section 4.4.3). Predictions indicate an increase in temperature (Kothyari and Singh 1996; Kumar et al., 2006) and decrease in precipitation (Singh 2005). Precipitation will become more variable, with an increase in the frequency and magnitude of extreme events (Kumar et al., 2005; Goswami et al., 2006; Kumar and Sahai 2006). This may

increase the occurrence of extreme floods, droughts (Kumar et al., 2005; Goswami 2006) and landslides, which may increase damage to crops (Goswami et al., 2006).

Changes to the precipitation regime are likely to intensify drought, which will impact vegetation and land use within the region (see Section 4.4.3). The vegetation will also be impacted from a rise in potential evapotranspiration rates, caused by temperature increases. Whilst model simulations of changes in the water balance of the Sabarmati River predict a 40% decrease in precipitation levels in 2041-2060 from 1981-2000 levels, resulting in a 35% decrease in actual evapotranspiration (Gosain and Rao 2003, cited in Mall et al., 2006), potential evapotranspiration will increase with a 1% increase during the monsoon season (June to September) and 4% increases during the rest of the year.

Changes to temperature, precipitation and evapotranspiration will result in a decrease in runoff. Mall et al.(2006) predict runoff will decrease to two-thirds of current levels, although they recognise uncertainty in this estimate. Model simulations of changes in 2041-2060 by Gosain and Rao (2003, cited in Mall et al., 2006) predict a 70% decrease in runoff, which will result in decreases in reservoir levels and in soil moisture storage (Kumar et al., 2005), which will impact vegetation and decrease the recharge of groundwater.

Catchment-Scale Anthropogenic Change: In recent years, water demand in India has tripled (Chakraborty 2004) and this is predicted to rise with increases in industrialisation. In India, industry currently uses 15 km³ of water per annum, but this is predicted to increase to 103 km³ in 2050 (Kumar et al., 2005). Much of the demand in the Gujarat region is met from groundwater abstraction, which has dramatically increased due to improvements in the availability of electricity, diesel, fertilisers and government funding, so that 55% of the groundwater resource has been developed (Mall et al., 2006). In the Subarmati catchment, groundwater usage exceeds demand (Kumar et al., 2006), and this groundwater mining has resulted in a steady fall in groundwater levels of between 3m to 50m in the last few decades (Gupta and Deshpande 1999). Groundwater decline has also been responsible for an increase in low flows in rivers (Kumar 2005). There have been some community-based movements to promote groundwater recharge through rainwater harvesting, check dams and recharge tubewells, although these have had limited success due to lack of hydrological understanding (Kumar et al., 2006).

Agriculture in the catchment is widespread, and has recently seen an intensification (particularly of in dairy and alcohol production), with associated hydrological impacts, Deforestation of the catchment to clear land for agriculture has decreased catchment water storage, making the area more prone to drought (Mall et al., 2006). This exemplifies the trends in hydrological impacts from land use change discussed in Section 4.5.2. To try and improve the ecological status of the catchment, the government has initiated a number of programmes to increase the extent of forest in the catchment (see Section 2.F.2). Furthermore, a recent shift towards urban livelihoods has resulted in declines in agriculture, resulting in reforestation in some areas (Shashikant Chopde, personal communication), a global trend associated with economic development (Rudel et al, 2005). Whilst this may help attenuate against low flows, Pandley and Devota (2006) predict an increase in evapotranspiration from an increase on forest cover, based on forest water demands of 19.6×10^8 , which may exacerbate water scarcity in the region. However, this provides an interesting example of how desakota activity may have a positive impact on the environment.

Agriculture in the catchment has also increased water demand (Mall et al., 2006) and much of the land is irrigated to meet this. This increase in irrigated agricultural land has increased the use of deep tubewells, irrigation dams and electronic pumps, which has depleted groundwater resources (Mall et al., 2006). Irrigation has resulted in problems of soil salinisation, compaction, and

waterlogging, which results from inadequate drainage, over-irrigation and seepage from canals and ditches (Kumar et al., 2005).

There has been a rapid increase in industry in the region, which has furthered water demand in the catchment. Industry and domestic use currently accounts for 15% of groundwater use and has resulted in the pollution of surface and groundwater sources (Gupta and Deshpande 1999; Olson et al., 2001b). The urban areas of Ahmedabad, Duff-nala of Shahibaug and also slum dwellings around the river have been identified as the major pollution sources (Rao and Gupta 1999; Gupta 2006). A major cause of water pollution has been the lack of storm- and waste-water drainage systems, which have failed to keep pace with the growth of the population. This has also resulted in increases in flood risk in Ahmedabad during the monsoon season, as the inadequate drainage systems cannot cope with the high storm rainfall (Gupta 2006).

The groundwater resource currently faces dual pressure from industry and agriculture and, in addition to high rates of abstraction, water quality has deteriorated. The groundwater has been contaminated from nitrate runoff from agricultural areas (see Section 2.F.2) and from pollution in urban areas. These problems have been worsened by the lack of surface water, which results in over-exploitation of groundwater, depleted water table levels and the migration of contaminants into the groundwater system (Rao and Gupta 1999; Gurunadha and Gupta 2000). As a consequence of water pollution, there has been an increased incidence of waterborne diseases in the catchment, such as malaria, filarial, falciparum and cholera, amongst others, (Gupta and Deshpande 1999). Fluoride contamination of groundwater is a particular problem and has had major health implications for the local population (Chinoy et al., 1992; Chinoy et al., 1994). Waterborne disease epidemics have been prevalent in Ahmedabad during the flood season, due to the inadequate drainage systems (Gupta 2006). This has also been a problem in rural areas, where wastewater is commonly used as a fertiliser and a replacement for higher-quality irrigation water.

5.3.3 Impact on Ecosystem Services

In the future climate change will increase water scarcity in the region (Mall et al., 2006), which will affect water availability for domestic use and for agriculture. Increases in demand from an expanding and urbanising population will exacerbate this problem. It is projected that most irrigated areas in India will require more water by 2025 (Kumar et al., 2005). The hydrology of the Sabarmati catchment will change with climate change, resulting in increased runoff during the monsoon season and increased dryness during the summer months. The increase in runoff may be accompanied by a higher risk of landslides, which may in turn increase flood risk due to blockages and changes in river courses (Kumar et al., 2005). Changes to the hydrological cycle will also affect key ecosystem services such as crop production and fisheries (Sathaye et al., 2006). Reforestation of the catchment, which is currently observed, may help mitigate against these impacts, through the regulation of water storage, although this requires further research.

An increase in the extent of forest within the catchment will also increase provisioning services such as fuelwood, fodder and timber. This may be impacted by climate change, which may change the species composition of the forest. Reduced moisture may favour *Anogeissus pendula* and *Acacia catechu* forest over teak (Olson et al., 2001b), which is a major economic product. At present, joint forest management initiatives have encouraged the planting of teak (Patel 2006), but this may not be sustainable in the long term due to unfavourable climate conditions.

One of the major concerns within this case study is the increase in incidence of waterborne diseases, which are predicted to increase with a rise in temperature and water scarcity (See Section 4.6). Fluoride contamination of groundwater is already causing a major problem of fluorosis in the

catchment (Chinoy et al., 1992, 1994), and this is likely to worsen unless adequate drainage systems are constructed and groundwater usage is reduced.

5.3.4 Research Questions

- An improved understanding of the impact of changing patterns of rainfall on runoff and groundwater recharge is needed (Mall et al., 2006). This understanding needs to encompass the relationship between hydrology and ecology and the need for basin-specific environmental flows (Kumar et al., 2005).
- A better understanding of the relationship between the hydrological cycle and vegetation is needed, particularly the response of the catchment to climate change, reforestation and changes in species composition. This needs to be considered in relation to the ecosystem services that the vegetation provides.
- A better understand of the human impacts on floods and droughts in the context of rapid socio-economic development is needed. This needs to be based on an analysis of recent climate variability and extreme events and their impact on water resources and also identification of key risks and potential adaptation strategies (Mall et al., 2006).
- Consideration is needed of the degree to which conversion to more dry land farming practices might help to mitigate against drought vulnerability and water scarcity. For example, this might include potential choices of plants that have a shorter growing period, produce a high yield, tolerate saline irrigation water, have low transpiration rates and have deep and well-branched roots (Kumar et al., 2005).
- Feedbacks from climate change also need to be assessed. For example, increased aerosols in the atmosphere can change irradiance levels by absorbing and scattering solar radiation, which then impacts on photosynthesis, transpiration and evaporation. This little-understood feedback can affect monsoon dynamics (Niyogi et al., 2007).

5.4 SOUTHERN ASIA: BALOCHISTAN, PAKISTAN

The Balochistan case study illustrates how technological development, associated with desakota, can have severe implications on water-based ecosystems. In this catchment, a movement from karez groundwater irrigation systems to tubewells has severely depleted the groundwater resource, which threatens water supply to the region. This area is also threatened the effects of global climate change, which will increase water scarcity.

5.4.1 Environmental Context and Services

This case study focuses on a corridor between Pischin, Quetta and Mastung in the Balochistan region of Pakistan. The region is characterised by dry winds, cold winters and hot summers (Chaudhry 2000). The average minimum temperature varies from 8-15°C and the maximum temperature varies from 24-31.5°C (IUCN 2006). The area has a variable rainfall, averaging 200 to 280 mm/year, with maximum rainfall occurring from January to April (70%) (IUCN 2006). There is only one climatic station in the region, located in Quetta (IUCN 2006), which recorded an average annual rainfall of 276 mm between 1990 and 1999 (EarthTrends 2003c). A study of precipitation trends in Quetta showed that the cumulative probability of sufficient rainfall for spring sowing is 93% (Rees et al., 2000). Precipitation varies topographically: the plains and lower

highlands receive monsoon rainfall during July and August, whilst the upper highlands receive rainfall from storms arriving from the Persian plateau during February and March (Chaudhry 2000).

According to Chaudry (2000), potential evaporation rates in the region are between 3000 and 5000 mm per year, whereas IUCN (2006) quote potential evapotranspiration rates of 5.5 to 6.0 mm/day. These high potential water loss rates result in salt accumulation in soils (Irshad et al., 2007) and, as a consequence of low precipitation and high evapotranspiration, there is little surface water. Short rivers originate in the hills of Balochistan and drain into shallow lakes or are absorbed by the sandy desert soils, but these have a small capacity (Majeed and Ali, undated). To increase surface storage, the Bund Khushdil Khan reservoir was built in 1890 and enlarged 1914, but this has a drastically reduced capacity as a result of siltation (BSSIP 2007).

Groundwater is an important resource in the region (see Figure 5.6) and this is widely exploited for domestic supply (Khan and Mian 2000) and agriculture (IUCN 2006). Traditionally, the local population relies on ancient *karez* irrigation systems, which tap into high groundwater using horizontal channels and wells. However, increased demand has meant that the Pishin Lora catchment is now the most critically stressed in terms of groundwater exploitation in the northern part of Balochistan (BSSIP 2007).

The catchment supports three ecoregions, which vary in distribution with elevation and precipitation levels (see Figure 5.7). To the east of Quetta, East Afgan montane conifer forests (classified as temperate coniferous forests) dominate, as the area is under the influence of monsoon rainfall (Olson et al., 2001b). Forest composition changes with elevation: at lower elevations, lower rainfall supports dry coniferous species, such as *Pinus gerardiana* and *Quercus baloot*; whilst higher rainfall at higher elevations allows mixing of coniferous and deciduous species (Olson et al., 2001b). North of Pishin, vegetation is classified as Sulaiman Range alpine meadow (montane grasslands and shrublands). This ecoregion is dominated by Alpine steppe forest, with sparse tree cover in gullies, and provides an important floristic transition zone between the Palearctic north and Indo-Malayan areas. Consequently, the ecoregion supports a high diversity of 50 mammal species (one endemic species) and 150 bird species (Olson et al., 2001b). The dominant vegetation in the case study area is Balochistan xeric shrub woodland. This medium-altitude arid to semiarid scrub forest supports a tropical steppe flora at lower elevations (below 1500m) and open xeric woodlands at higher elevations (1500 to 2000m) (Olson et al., 2001b).

The catchment provides many water-based ecosystem services. People are reliant upon water sources for domestic supply and for agriculture. Springs, streams and rivers constitute an important resource (Chaudhry 2000) and a limited area in Pishin and Mastung is supplied from channel flood water (Majeed and Ali, undated). However, surface water has limited reliability and so groundwater is the principal water source (Chaudhry 2000). Karezes are the traditional method for tapping this resource, but a recent move to tubewell installation has resulted in over-abstraction (Chaudhry 2000). Much of this water is used for irrigation and the area of land in Balochistan under irrigation from groundwater has increased from 22% in 1989 to 34.5% in 1998, with tubewells alone accounting for 22.8% (Chaudhry 2000). The main crops are grapes, apple, apricot, cherry, pomegranate, wheat, potato, onion and sunflower (IUCN 2006). There has been a recent increase in apple production, which has high water requirements (1393mm a year in this region, with potential evapotranspiration rate of 2125mm) (IUCN 2006).

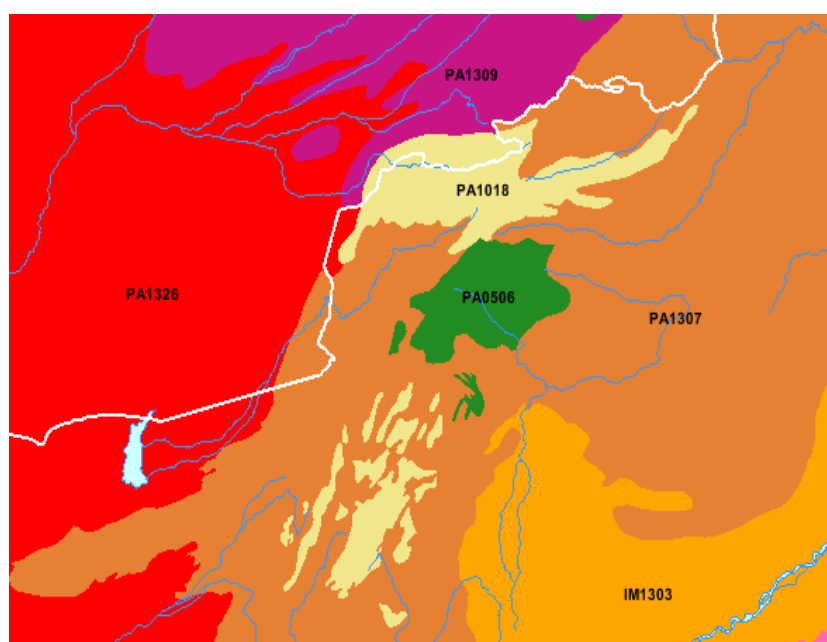
The main agricultural activity in the area is livestock rearing and the natural vegetation provides grazing and fodder (Chaudhry 2000). Where forests and shrublands are able to grow, these provide fuel, timber, charcoal, building materials and food (Olson et al., 2001b). The fauna supported in these habitats also provide important services: brown bears are hunted for their medicinal value and red foxes are hunted for their skin, which has a high economic value (Olson et al., 2001b).

Figure 5.6: Hydrological map of Pakistan, illustrating the potential groundwater resource around Quetta



source: Geological Survey of Pakistan - http://www.gsp.gov.pk/pakistan/ground_water.html

Figure 5.7: Map of the ecoregions of Balochistan, Pakistan: Sulaiman Range alpine meadows (PA1018), East Afgan montane conifer forests (PA0506) and Balochistan xeric woodlands (PA1307)



source: Olson et al., 2001b

5.4.2 Environmental Change

Regional Climate Change: Climate change predictions show a general warming in the region, coupled with changes to the precipitation regime (see section 4.2.2). As the influence of the monsoon is weak in this region, overall rainfall is predicted to decrease. Precipitation will also become more seasonal and decreases in the dry season will increase the risk of drought. Increases in precipitation intensity during the rainy season may increase runoff during January to April, but a decrease in catchment storage will result in water scarcity during the dry season and a possible reduction in groundwater recharge. Increases in temperature will increase potential evapotranspiration rates, which may exacerbate water scarcity during the dry season and increase rates of soil salinisation, reducing the area available for cultivation (Irshad 2007).

Changes to the hydrological cycle from climate change will induce change in the vegetation of the region. Reductions in precipitation will reduce the extent of East Afgan montane conifer forest and possibly the alpine meadows, whilst steppe flora may increase. This may impact the hydrological regime, as water storage and actual evapotranspiration rates may decrease.

Catchment-Scale Anthropogenic Change: Population increases in the region have resulted in significant changes in land use, including an expansion in agricultural production and industrialisation. East Afgan montane conifer forests have seen extensive deforestation from the construction of industrial sites and degradation from overgrazing and woodcutting (Olson et al., 2001b; Majeed 2004). This has caused a huge increase in sheet and gully erosion, resulting in large losses of topsoil and natural nutrients (Majeed 2004). This has caused problems of desertification and has reduced the area of land available for cultivation (Olson et al., 2001b). Deforestation has also caused heavy surface runoff and floods during the rainy season (Majeed 2004). Xeric shrubland has not currently been overexploited, but this ecoregion is very sensitive to land cover attenuation and has a low potential for regeneration (Olson et al., 2001a). Furthermore, degradation of this habitat may have large hydrological implications, as the deep root systems of xeric shrublands facilitate deep drainage and groundwater recharge (Seyfield et al., 2005).

The expansion of anthropogenic activity in the region has resulted in an unplanned increase in the use of groundwater resources (Chaudhry 2000). An increase in tubewell use has prompted an increase in orchard cultivation and a 10% increase in cropping intensities, (Chaudhry 2000). Increases in water demand have resulted in the overexploitation of the groundwater resource, resulting in falls in groundwater levels, shown in Table 5.1. Irrigation is also inefficient and seepage from unlined irrigation channels has caused waterlogging and salinisation in some areas, resulting in loss of potentially productive land.

Although there are currently no significant groundwater water quality problems (Chaudhry 2000), this may become a concern as anthropogenic activity increases. Majeed (2004) notes a degradation of water quality from the disposal of raw and untreated industrial, domestic and municipal wastes into water courses, which is currently common practice. Increasing use of insecticides, pesticides, herbicides and chemical fertilisers on agricultural lands is also polluting aquifers (Majeed 2004), and this may worsen with an increase in agricultural production. Furthermore, increasing shortages of water for irrigation has forced farmers to irrigate vegetables with city sewage water, which has caused a number of problems including weed infestation, soil infertility (Chaudhry 2000), and possible aquifer pollution.

Table 5.1: Average declines in groundwater levels in the Pischin Lora basin (from Chaudhry 2000)

Area	Period	Average Decline in Water Level (m)
Quetta North	1969-1989	4.58
	1989-1996	4.27
	1997-2000	4.39
Quetta South	1967-1988	2.44
	1988-1996	1.83
	1997-2000	2.44
Pishin	1978-1989	3.97
	1989-1996	6.40
	1997-2000	6.71
Mastung	1976-1989	6.40
	1989-1996	2.78
	1997-2000	4.27

5.4.3 Impact on Ecosystem Services

Decreases in water availability as a result of climate change and increases in demand from an increasing population and urban expansion will increase water scarcity in the area. Because rainfall is predicted to become more seasonal, surface water will become less reliable and there will be greater dependence on groundwater. However, the groundwater resource is currently deteriorating and further exploitation will only increase current rates of groundwater table decline. This will drastically reduce water supply for domestic, agricultural and industrial use, which may impact any future development of the area. Future food production in the region may also be affected from soil erosion and salinisation, which will reduce the area of land available for agriculture. These services may also be affected by water pollution, which is increasing in the area.

A reduction in water availability will have adverse consequences on the vegetation of the area and the xeric shrubland may decline. If this vegetation does decline, it will have hydrological implications and may further groundwater depletion. Areas covered by forest are likely to decline in extent, which will result in a drastic fall in the ecosystem services that the forest provides, such as fuel, timber, charcoal, building materials, food and medicine (Olson et al., 2001b). A decline in forest cover will also contribute to increases in runoff rates, which are predicted to increase with climate change, and will increase flood risk in the area.

5.4.4 Research questions

- Groundwater is a key resource in this region, but the impact of climate change on groundwater is little understood. This is partly attributable to lack of understanding of the sources of the groundwater. Thus the sources, pathways and rates of groundwater recharge need to be understood in order to assess how these may be affected by climate change.
- An increase in water scarcity requires adaptation strategies. One option that has been practiced in Yemen and which may be appropriate in Balochistan is water harvesting

schemes (Rapold 2005). However, the success of such schemes relies upon an understanding of rainfall patterns and how these are likely to change with climate change.

5.5 SOUTHERN ASIA: MASTANG TO RUPANDEHI, NEPAL

This corridor illustrates the direct hydrological and ecological impacts of global climate change on the provision of ecosystem services. Desakota development within the area has resulted in severe environmental degradation, from changes in water and land use. Furthermore, the case study provides an example of the health implications of desakota development and climate change.

5.5.1 Environmental Context and Services

This case study focuses on a corridor through central Nepal, running from the provinces of Mustang to Rupandehi. The major river in the corridor is the River (Kali) Gandaki, which has a catchment area of 11 400 km² and an average discharge of 474 m³ s⁻¹. The River Gandaki has its headwaters in the Trans-Himalayan zone of the Tibetan Plateau (Sharma 2005) and runs to Narayani and eventually into India, forming a major tributary of the Ganges. The Gandaki river basin contains 1025 glaciers and 338 lakes, and so is susceptible to frequent glacier outburst floods.

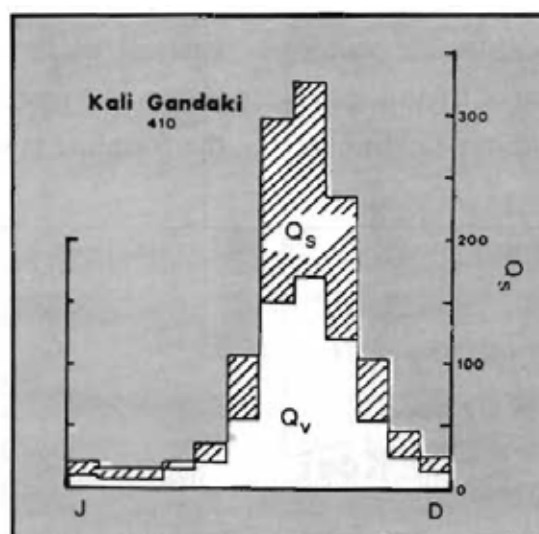
The precipitation regime is controlled by the monsoon systems, which deliver 60-90% of the annual precipitation in the summer months, from June to September (Hannah et al., 2005). The Gandaki catchment is divided into two parts by the Annapurna Himalaya, which acts as barrier to orographic rainfall, resulting in a leeward side in the north and a windward side in the south and thus a very diverse rainfall distribution (Nepal and Regmi 2005). This is superimposed on a general decline in rainfall in Nepal from east to west, as the southwestern monsoon expends most of its precipitation in the eastern region (Olson et al., 2001b).

In response to the monsoonal rainfall, 55-80% of the annual runoff occurs during June to September (Hannah et al., 2005), with high flows that are 10-20 times higher than the corresponding low flows in October to June (Chalise et al., 2003). The high levels of rainfall give an abundant water supply (Sharma 2005). Hydrological patterns in the region are complex and poorly known (Hannah et al., 2005) because there is little available hydrological data. In Nepal, there are only 174 gauging stations and 54 of these were established in 1999 (Chalise et al., 2003).

Hannah et al. (2005) used available hydrological data to conduct an analysis of flow regimes in Nepal. The study considered three sub-basins within the Gandaki catchment, and differences were noted. In the middle mountains near Pokhara, there are high magnitude flow regimes from snowmelt and monsoonal rainfall. The large topographic change over short distances promotes precipitation, resulting in a July-August flood peak with sharp rise and gradual fall. The lower regions do not experience snowmelt, so there is a later flood peak in August to September, with high flows persisting into September because the monsoon ceases later in lower elevations and groundwater recharge contributes to flow. The flood peak in this region is of intermediate magnitude, due to the regular supply of precipitation throughout the summer monsoon region.

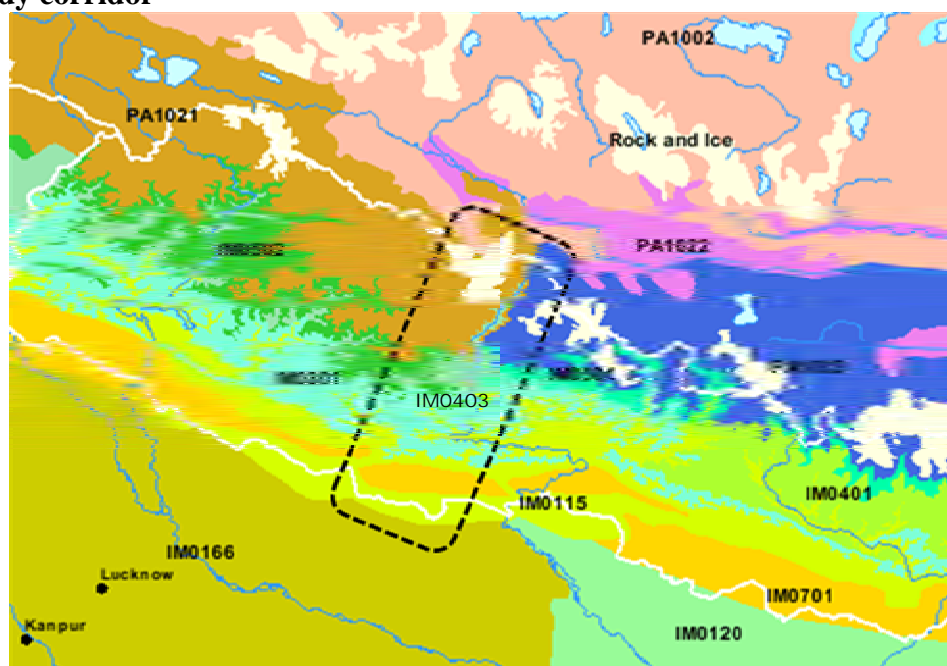
An analysis of the hydrological regime of the Gandaki, from 1964-1985 by Alford (1992) showed the same broad trends noted by Hannah et al. (2005). Figure 5.8 shows the late summer river flow peak and the high proportion of 'specific runoff' from precipitation.

Figure 5.8: The hydrological regime of the Gandaki river during 1964-1985, showing the relative relationship between streamflow volume (Q_v) and specific runoff (Q_s)



source: Alford (1992).

Figure 5.9: Map of the ecoregions of the case study corridor, from Mustang to Rupandehi: western Himalayan alpine shrub and meadows (PA1021), eastern Himalayan alpine shrub and meadows (PA1003), eastern Himalayan subalpine conifer forests (IM0501), western Himalayan subalpine conifer forests (IM0502), western Himalayan broadleaf forests (IM0403), Himalayan subtropical pine forests (IM0301), Himalayan subtropical broadleaf forests (IM0115), Terai-Duar savanna and grassland (IM0701). The dotted rectangle denotes the case study corridor



source: Olson et al. (2001b)

The region has sharp environmental gradients, which result in a high floristic diversity. There is a sharp north-south elevation gradient, from the Terai lowlands to the high Himalayas, and an east-west precipitation rainfall gradient. The west of the region receives less rainfall (1500 to 1900mm) and the treeline is lower than in the east (4500m in east to 3600m in west) (Olson et al., 2001b). Consequently, there are eight major terrestrial ecoregions in the area (Figure 5.9). Connectivity between the ecoregions is very important, as many species exhibit seasonal altitudinal migrations (Olson et al., 2001b).

In the highest part of the region, alpine shrub and meadow vegetation dominates (classified as montane grassland and shrubland, Olson et al., 2001a). Differences in rainfall between the western and eastern Himalayas causes floristic heterogeneity between the east and west of the River Gandaki. Western Himalayan alpine shrub and meadows is situated between 3000-5000 m above sea level and 25% of the ecoregion is covered with bare rock and ice. The area is characterised by cold winters, with blanket snowfall. However, snowmelt in April- May reveals a highly diverse flora, with very localised plant assemblages according to changes in aspect and climate. Shrubs are dominated by rhododendrons and junipers, whilst alpine meadows have low-growing plants (aster, gentian, anemone) and Alpine streams are lined with willows. The area supports over 40 mammal species (including several endangered species) and 130 bird species, including one endemic species. The eastern Himalayan alpine shrub and meadows are also snow covered in winter, with high plant growth in spring and summer, supporting a rich alpine flora. The ecoregion supports over 7000 species (many which are endemic) and 100 mammal species, including several endemic and threatened species, such as the snow leopard (Olson et al., 2001b). Subalpine conifer forests grow at lower elevations and these also show east to west differences.

The eastern Himalayan subalpine conifer forests represent the edge of the treeline (3000-4000 m) and occur on steep, rocky slopes. These forests represent the transition from the treeless alpine meadows to forested Himalayan habitat and are an important wildlife corridor, supporting 88 species of mammal, including the Himalayan musk deer (*Moschus chrysogaster*) and Asiatic black bear (*Ursus thibetanus*), and 200 bird species (6 endemic to the ecoregion) (Olson et al., 2001b). The composition of the forest changes with moisture levels: forests are generally composed of fir (*Abies spectabilis*), larch (*Larix griffithii*), hemlock (*Tsuga dumosa*), *Juniperus recurva*, and *Juniperus indica* with a fir understory, whilst Hemlock (*Tsuga dumosa*), is much more prevalent in wetter areas.

The western Himalayan subalpine conifer forests are drier than the eastern forests and consequently have more extensive conifer coverage. Forest composition changes with elevation, with Cypress (*Cupressus torulosa*) and deodar (*Cedrus deodara*) above 2400m, and Fir (*Abies spectabilis*) between 3000 and 3500m. This forest supports 285 bird species, 9 of which are endemic, with 58 species of fauna, with one endemic rodent and several threatened species (Olson et al., 2001b). Western Himalayan broadleaf forest borders the Gandaki river and forest composition changes with moisture. Evergreen broad-leaved forests are found on the slopes and vary according to aspect, whilst deciduous broadleaf forests are distributed in riparian areas. This ecoregion supports 315 bird species (7 endemic) and 76 mammal species (2 endemic and several threatened species) (Olson et al., 2001b).

At lower elevations, forest composition changes and this shows east-west variation. Himalayan subtropical pine forests are more prevalent in the western regions and show differences in forest structure either side of the River Gandaki, with drier conifer forest in west and wetter, richer conifer forest in east. This ecoregion is dominated by Chir pine (*Pinus roxburghii*), with a little developed understory from frequent fires and supports 120 mammal species and 480 bird species (11 endemic). To the east of the River Gandaki, Himalayan subtropical broadleaf forest

dominates at the same elevation. Forest composition in this region is diverse, reflecting the east-west moisture gradient and changes in the complex topography and soil type. This ecoregion supports 97 mammal species (1 endemic) and 340 bird species (1 endemic) (Olson et al., 2001b).

The most southerly part of the case study corridor is characterised by Terai-Duar savannah and grassland, which is the only ecoregion classified as tropical and subtropical (Olson et al., 2001a). This ecoregion supports the world's tallest grasslands, which indicate wet and nutrient-rich conditions. There is a wide range of habitat types, such as savanna grassland, evergreen forest, deciduous forest, thorn forests and steppe, and their distribution corresponds to different moisture conditions. Many of the habitats are dependant upon inundation and silt deposition from monsoon floods, which create a range of disturbance conditions that support different communities and a very diverse fauna assemblage (Olson et al., 2001b).

There is also a high diversity of aquatic habitats in the case study region. Aquatic plant diversity and species richness of lakes exhibits a linear decrease with increasing altitude, due to changes in water temperature, substrate quality, altitude, pH, transparency and conductivity (Lacoul and Freedman 2006).

The diversity of this case study environment provides a range of different ecosystem services, some of which are general to all ecoregions (such as water supply) and some which are ecoregion specific. Forests are a very important resource, providing about 79% of the energy consumption and 50% of the fodder for livestock of the country (Mood et al., 2001). At the highest elevations, Himalayan alpine shrub and meadow provide livestock grazing and wood for fuel. This is increasingly being exploited, as habitats at lower elevations have reached carrying capacity, forcing pastoralists into the higher meadows. These ecoregions also provide a number of medicinal plants, which are now threatened by overgrazing and overharvest (Olson et al., 2001b). The sub-alpine conifer forests also provide important services, such as fuel, medicinal plants, food from edible mushrooms and several economically important tree species (*Daphne bholua*, *Arundinaria* spp, *Betula utilis*). The musk deer and Asiatic black bear inhabit these ecoregions and both of these are hunted for their medicinal properties. In addition, the forest provides land for cultivation and this area is increasingly being cleared for food production (Olson et al., 2001b). Similarly, much of the Western Himalayan broadleaf forest has been cleared for agriculture and logging. Livestock are grazed at higher elevations and the area is often set on fire to promote plant growth, which destroys the understory and retards forest regeneration (Olson et al., 2001b).

The lower elevations have a higher population density and the ecoregions are extensively exploited for their services. Himalayan subtropical pine forests have seen widespread forest clearance for agriculture and terraced agricultural plots have replaced nearly all of the natural forest between 1000-2000m (Olson et al., 2001b). The remaining forest is used for grazing, fuelwood, fodder, shifting cultivation and the lower slopes have been quarried for their mineral resources. The soils of the Himalayan subtropical broadleaf forests are erosion prone and not suitable for agriculture, so most of the forest remains intact and is used for fuelwood and livestock grazing.

There has been a widespread conversion of the Terai-Duar alluvial grasslands to agriculture and much of the surface water is used for irrigation. The forests produce fuelwood and are a major area for logging. There has recently been an expansion of the wood industry and the number of sawmills in the region has increased (Olson et al., 2001b). The rivers in the region are important for power generation, irrigation and drinking water (Sharma 2005). The alluvial sediments of this area provide a good groundwater supply, which is used for drinking water, irrigation and industry (Sharma et al., 2005). The use of shallow tubewells has increased which has enhanced irrigation (Bhandari 2001) and serves 11 million people (Atreya et al., 2006). However, the water quality from the tubewells is low as they are often shallow and located close to toilets (Atreya et al., 2006).

5.5.2 Environmental Change

Regional Climate Change: Climate change is predicted to cause a general warming of the region, with high rates of warming at high elevations and low warming at lower elevations (Shrestha 1999). Temperature records in the case study area reflect this trend, with an increase in temperature observed between 1980 and 1993, particularly at higher elevations (see Section 2.F.4).

As discussed in Section 4.2.2, temperature increases will result in a reduced snow cover (IPCC 2001) and glacial retreat (Chalise et al., 2003), with associated hydrological consequences. Recent study has suggested that most of the glaciers in the Himalayan region will vanish within 40 years as a result of global warming (Pearce 1999). The meltwater generated from the retreating glaciers will cause glacial lakes to grow, with the potential to increase the frequency of meltwater outburst floods (Mool et al., 2001; Chalise et al., 2003; Chalise et al., 2006). Glacier retreat will have significant hydrological impacts, as many of the rivers in the region are dependent upon seasonal meltwater, particularly in areas where precipitation is low, such as the western Himalayas (Rees and Collins 2006). As a consequence of glacial retreat, river flows will initially increase and then decline in the long-term, leading to reductions in river flow and water availability in the dry season (Chalise et al., 2006; Rees and Collins 2006).

The region is also dependant upon monsoon rainfall and this is predicted to change with global warming. Duan et al. (2006) predict a reduction of precipitation in the Himalayas as the transportation of water vapour from the Indian Ocean to the Himalayas will decrease with decreasing thermal contrast between the Tibetan Plateau and the tropical Indian Ocean. The monsoon will also become more variable and the strength of the monsoon is likely to change (IPCC 2001). However, it is difficult to predict how this will impact the case study region, as precipitation is very variable due to altitude and topographic barriers which induce local rain shadows and precipitation hotspots (Kansakar et al., 2004).

Important linkages exist between monsoon rainfall and geomorphic processes, which may be affected by changes in monsoon rainfall patterns. Currently, erosion in low- and mid- elevation areas of the Himalayas is dominated by annual reoccurring monsoonal rainfall, whilst high-elevation areas are more affected by abnormal monsoon years (Bookhagen et al., 2005). It is uncertain how these will change with climate change.

Section 4.4 described how vegetation may shift in response to changes in climate. This has been observed within the study corridor, where new species have been recorded although these are mostly poisonous and may impact agriculture (see Section 2.F.4).

Catchment-Scale Anthropogenic Change: The Himalayan region is geo-dynamically unstable and ecologically sensitive (Tiwari 2000), so changes to land use can have drastic consequences for the natural environment. Increases in the population have resulted in increases in agricultural production and both deforestation and overgrazing are widespread problems.

At higher elevations, the alpine shrub and meadows are threatened by development and increasing tourism (Olson et al., 2001b). Over 70% of the Western Himalayan alpine shrub and meadow has been cleared or degraded, threatening the medicinal plants that grow there. The steep slopes are increasingly being used for cultivation, although terracing is used to reduce soil erosion (Olson et al 2001).

An increase in population pressure has pushed agriculture into forested areas, destabilising fragile mountain slopes, disrupting the hydrological cycle and increasing soil erosion in all Himalayan basins (Tiwari 2000). Deforestation is extensive in broadleaf forests, where logging, agriculture and tourism development are expanding. Furthermore, pastoralists frequently start fires to promote plant growth, which destroys the understory vegetation. The Himalayan subtropical pine

forests have also undergone deforestation from shifting cultivation, quarrying, agriculture and road construction (Olson et al., 2001b). Road construction leads to destabilisation of mountain slopes, destruction of forests and wildlife, disruption of drainage and production of colossal amounts of sediment (Tiwari 2000). Road construction may also affect the hydrological regime by intercepting rainfall, concentrating flow and diverting or rerouting surface runoff (Merz et al., 2006). Fodder demand has also increased in the forests, as animal husbandry is increasingly practiced over crop farming, which has degraded the forest environment (Tiwari 2000). As agriculture moves to less fertile areas, fertiliser use has increased, which may have implications for water quality (Collins and Jenkins 1996).

Terai-Duar savannah and grassland is widely cultivated, and surface water is frequently diverted for irrigation (Olson et al., 2001b). Brick production has increased in the area, to meet construction demands. Bricks are constructed in the dry season, using the same soils used for agriculture (namely rice cultivation) in the wet season. This has resulted in declines in the groundwater, as soils have been removed and water is used to wet the bricks (Haack and Khstiwada 2007).

The extension of cultivation, deforestation and overgrazing in the Himalayas has disrupted the hydrological regime by reducing groundwater recharge, increasing runoff and soil erosion (Ives and Messer 1981; Tiwari 2000; Gardner and Gerrard 2003). Furthermore, Collins and Neal (1998) noticed that the irrigation canals associated with terraced agriculture reduces infiltration and increases runoff, further affecting the hydrological regime. However, there is debate surrounding these relationships, with some studies arguing that Himalayan deforestation has not been responsible for downstream flooding in the region (Ives and Messer 1981; Ives 1991; Hofer 1993).

Although the hydrological impact of land use change may be contested, the hydrological cycle of the region has undergone undeniable change from the rapidly increasing demand for water for domestic needs, agriculture and industry (Sharma et al., 2005). Changes in water use may also have impacts on the geomorphology of the region. In Nepal, the extraction of sands and gravels from rivers has recently increased, with many people migrating from upland areas and establishing illegal settlements on riverbanks (Sharma et al., 2005). However, the impact of this activity on the aquatic environment has not been studied. Pokharel (2001) also note that the Gandaki river is a potential source for hydroelectric power development, with 50 billion m³ of water a year flowing through it, it has the potential to generate 20 650 MW. However, the potential environmental impacts of such developments include; flooding, loss of valuable habitat, disruption of fish migration, possible increase in the incidence of water-borne diseases and risk of devastating floods from landslides and seismic activities (Pokharel 2001; Thapa 2005).

Anthropogenic activity has also decreased the water quality of the catchment. A study of surface water quality of the Gandaki river in the Upper Mustang (upper reaches), revealed a downstream deterioration in water quality that was attributed to anthropogenic and animal wastes (Collins and Jenkins 1996). The absence of sewage systems means that water sources are frequently contaminated by human and animal fecal matter (Boselli et al., 2005) and poor sanitation around wells has resulted in groundwater contamination (Dongol et al., 2005). The consequences of this are severe: only 34% of the population of Nepal has access to safe drinking water and 67% of children have stunted growth from water-borne disease (Sharma 2005). Collins (1998) predicts that increases in population will increase anthropogenic nitrogen deposition, which will increase the potential for eutrophication of surface waters.

Increases in agriculture and industry have resulted in the contamination of groundwater from chemical fertilisers, pesticides, pathogenic bacteria, nitrate and industrial effluent (Dongol et al., 2005; Sharma et al., 2005). Much of this has been attributed to desakota development, as fertiliser and pesticide use is unregulated. Collins and Jenkins (1996) noted that tillage agriculture alters the

chemistry of rivers through fertiliser runoff and also from the exposure of fresh soil material to weathering, which increases base cations and metals in the water. Paper mills have been identified as the main pollutants in the Narayani River, discharging untreated effluent (Sharma 2005). Effluent from paper mills has resulted in decreases in species richness of fish, decreases in abundance of macroinvertebrates, decreases in dissolved oxygen and increases in alkalinity (Edds et al., 2002).

The geomorphology of the river has also changed as a result of anthropogenic activity. Sediment input into rivers has increased from deforestation, excessive firewood collection, overgrazing and road construction (Olson et al., 2001b; Merz et al., 2006). This has resulted in the siltation of reservoirs and rivers and study has shown that the beds of the Terai rivers are rising at the rate of 15-30cm annually (Olson et al., 2001b), reservoir capacity is reducing the incidence and severity of flooding is increasing (Tiwari 2000).

Through changes to the quantity and quality of water within the catchment, anthropogenic activity has altered the aquatic environment. In a survey of streams in Nepal, Manel et al., (2000) observed that streams draining terraced catchments differ significantly from other streams in habitat structure; they have more physical modifications, wider channels, fewer cascades, finer substrata and simpler riparian vegetation with fewer trees. The survey also showed that, after taking into account altitude, land use significantly affected stream habitat structure, stream chemistry, aquatic invertebrate abundance and the occurrence of river birds.

5.5.3 Impact on Ecosystem Services

Anthropogenic activity has had widespread consequences throughout the region. The over-exploitation of natural forests and meadows threatens key ecosystem services, such as fuel, timber, logging, medicinal plants and fodder. Furthermore, future decreases in water availability from climate change may reduce the potential of these areas for cultivation and livestock grazing. Moreover, the area of land currently used for agriculture may decrease from rapid soil erosion. Associated changes in vegetation distribution and crop diseases from climate change may place further pressure on agriculture in the region.

Changes in precipitation patterns and increases in water demand threatens to reduce river flows and water availability, which may hinder future development (Pearce 1999). This may be exacerbated by an increase in irrigation from changes to rainfall patterns. Furthermore, contamination of water sources may reduce water supply. Despite reduced flows in rivers, the increased incidence of meltwater outburst floods may increase flood risk to the area (Pearce 1999).

Although future water availability is a concern, water quality in the region is perhaps the greatest threat to the future of the population. Water pollution from desakota activity threatens the health of the population, due to increases in the incidence of waterborne disease. This may be exacerbated by the increase in floods and low flows and from an increase in temperature, which may promote habitat for disease vectors (see Section 4.6). Furthermore, malaria may be an increasing problem in the Terai region as a result of climate change.

Tiwari (2000) believes that the Himalayan region is currently under environmental stress:

“The Himalayan Mountains are on the verge of a major ecological crisis threatening the collapse of the very life-support system. The impact of unscientific and irrational resource-development processes and the resulting deteriorating environmental conditions in the Himalayas are not confined to the region itself but also adversely affect the environment and

economy of the adjoining plains of the entire Indian sub-continent through the disruption of the hydrological cycle of the region” (pg. 100)

5.5.4 Research questions

- There is currently very little monitoring of river levels in Nepal, particularly in the High Himalayas. Consequently, there is limited understanding of the hydrological regimes which severely hinders any predictions about the impacts of climate change. Specifically, improved understanding is needed of high altitude snowfall and melt patterns (Winiger 2005) and snow- and icemelt-driven hydrological regimes (Rees and Collins 2006).
- There is sparse data on river flows and little knowledge of regional variation in flow regimes in Nepal. Most research has looked at Nepal as a whole, but there is large variation due to large spatial variations in topography and variations in precipitation, temperature and snowmelt. Such data is crucial to improving water resource management (Hannah et al., 2005).
- There is currently no water quality monitoring in Nepal (Sharma et al., 2005). Such data is fundamental to understanding the impacts of anthropogenic activity on the aquatic environment.
- Groundwater is an important resource, but is little understood in the region. Again, data scarcity and process understanding are needed to improve resource management and understand how these may be affected by climate change.
- Vegetation is likely to alter with climate, but improved understanding is needed to interpret the impacts that this may have on the hydrological regime
- Sand and gravel extraction from rivers is an increasing desakota activity, but the impacts of this have not been considered. This should be studied if we are to appreciate the impacts of human activity on the natural environment

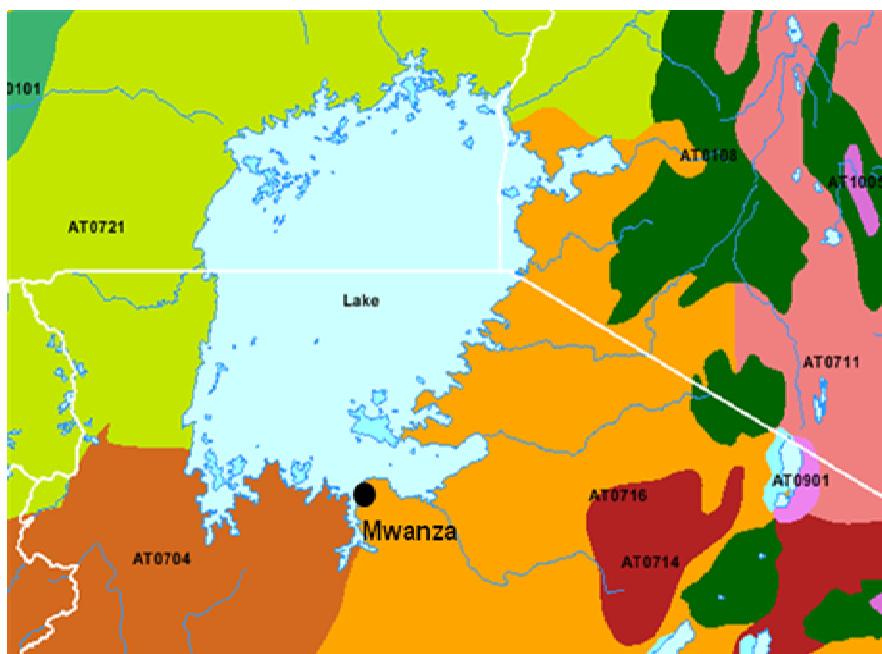
5.6 SUB-SAHARAN AFRICA: MWANZA, TANZANIA

Desakota activity within Mwanza has been concentrated around Lake Victoria and the surrounding wetlands, which provide key ecosystem services. This case study illustrates the increased stress that rural and urban uses place on the environment and how this may threaten future service provision. In addition, the case study highlights issues of vegetation degradation and increases in disease prevalence, which shows the inter-linkages between global climate change and desakota activity.

5.6.1 Environmental Context and Services

The Mwanza district lies to the north of Tanzania. The population is concentrated around the southern shores of Lake Victoria, which is Africa's largest lake and the world's second largest freshwater lake. Lake Victoria has a surface area of 68 800 km², a water storage capacity of 2760 km³ and a catchment area of 258 700 km². 85% of the inflow to the lake is from direct precipitation (Global Environment Facility 1996). Average rainfall is 600-800 mm/year, although this is unpredictable and exhibits a strong bimodal distribution, with rains falling from March to May and November to December and a long dry season (Olson et al., 2001b). This results in fluctuations in the lake

Figure 5.10: Map of the Mwanza case study region showing the major ecoregions: central Zambezan Miombo woodlands (AT0704), southern Acacia-Compiporo bushlands (AT0716) and Lake Victoria forest savanna mosaic (AT0721).



source: Olson et al. (2001b)

Lake Victoria crosses several international boundaries and is shared between Kenya (6%), Tanzania (51%) and Uganda (43%). It is outside of the scope of this review to provide a comprehensive review of the environmental situation of Lake Victoria, which would consider a much wider geographical area than the case study site. Thus, Lake Victoria will be considered within the context of the case study area only, and any relevant environmental issues will be raised if they directly affect the case study area and associated desakota activity.

The vegetation of the case study region is sub-tropical grassland, savanna and shrubland, distributed across three ecoregions (Figure 5.10). The central Zambezan Miombo woodlands and Southern Acacia-Compiporo bushlands are widespread and patches of Victoria basin forest savanna mosaic occur in the moister areas (Olson et al., 2001a).

Central Zambezan Miombo woodlands occur in the west of the area and are characterised by broadleaf, deciduous savannahs and woodlands with occasional wetlands. The area is prone to drought and has a well-drained, highly leached, nutrient poor soil. The region has a high floral richness, which supports a high diversity of mammals, birds, with many endemic species. Fires are frequent after the dry season, occurring both naturally and through human activities such as land clearance for cultivation or for cultural beliefs (Olson et al., 2001b). The area is also characterised by South Acacia-Comiporo bushlands, which provide an important migration corridor for animals. The soil here is also poor and is vulnerable to erosion (Schrumpf et al., 2006). In wetter areas, the characteristic ecoregion is the Victoria basin forest savanna mosaic, which is characterised by very high diversity due to its position at the junction between eastern and western Africa. This ecoregion supports many wetlands, which are dependent upon the two annual rainy seasons for replenishment (Olsen et al., 2001b).

The Mwanza area provides many key ecosystem services to the local population. The lake and associated wetlands are an important water supply for domestic, agricultural and industrial use.

The environment is important for food production and the wetlands and surrounding areas provide important grazing areas for livestock (Hongo and Masikini 2003). The lake area also provides fisheries and wild game for food, whilst the drier woodland areas support hunting for bushmeat (Olson et al., 2001b). Fisheries are particularly important in the area, with over 2 million people directly dependent upon fishing-based livelihoods.

The economy of the area is dominated by agriculture and the natural vegetation is increasingly being cleared for cultivation, both for food production and economic crops, such as tobacco (Olson et al., 2001b). The natural vegetation which remains provides important supporting services, such as timber, fuelwood, building materials and charcoal, which is used for fuel and tobacco drying (Olson et al., 2001b). Many of the natural plants are collected for medicinal purposes and many of the large animals are hunted for food, medicine and economic purposes, although this is largely illegal (Olson et al., 2001b).

5.6.2 Environmental Change

Regional Climate Change: The region is predicted to experience a general warming of 2°C by 2080-2099 (relative to 1980-1999 levels), particularly in the summer months of June to August (3°C) (Christensen et al., 2007). Precipitation is also predicted to increase by 10% (Christensen et al., 2007), although this is likely to show high variability (Magadza 2000). These changes are highly likely to have notable impacts on the natural environment.

Lake Victoria is vulnerable to climate change due to its relatively shallower depth (average 40m) in comparison with the other African Great Lakes, limited inflow and large surface area. The temperature of the lake is likely to increase (Ogutu-Ohwayo et al., 1997) and increased evaporation may lead to reduction in lake levels over the next two decades (Tate et al., 2004) and possible changes in the lake's thermal stability (Ogutu-Ohwayo et al., 1997). These warming effects may be associated with a reduction in the productivity of the aquatic ecosystem as suggested for Lake Tanganyika (O'Reilly et al., 2003; Verburg et al., 2003). The lake level is influenced by El Nino events. As an example, the 1997/1998 El Nino event caused the level of Lake Victoria to rise by 1.7m (Conway et al., 1005), which flooded the surrounding rivers and wetlands (Williams et al., 2007). Thus, any changes in precipitation and the El Nino may have serious implications for the surrounding littoral and riparian environment.

An increase in rainfall variability may have adverse effects on the woodland, bushland, forest savanna in the larger area surrounding the lake. Such vegetation is highly sensitive to changes in rainfall amount and seasonality (Hely et al., 2006) and changes in woody vegetation cover will affect the hydrological behaviour of the landscape, affecting runoff rates, soil moisture retention (e.g. Munishi 2005, Magadza 2000).

Catchment-Scale Anthropogenic Change: Anthropogenic activity in the region has had significant environmental consequences through land use change, water demand and pollution. These will increase with an expanding and urbanising population.

Increased population pressure has resulted in widespread deforestation and expanding agriculture, which threaten all of the ecoregions in this area (Olson et al., 2001b). Trees and scrub have been cleared principally for agricultural expansion, but also for fuel wood and energy supplies (Mandulu 2004), which has increased in recent years due to electricity shortages. As discussed in Section 4.5.2, vegetation clearance can have severe hydrological consequences and study elsewhere in Tanzania has shown increases in runoff and soil erosion and reductions in water availability during the dry season as a result of vegetation clearance (Munishi and Shear 2005). Many of the

remaining forests are overgrazed and increasing anthropogenic fires at the end of the dry season, which coincides with the seed dormancy period, have reduced forest regeneration (Chidumayo 1996). These processes have caused severe soil erosion and loss of soil fertility (Mandulu 2004). The hydrological and land degradation consequences of native vegetation removal are a growing concern throughout Tanzania (see Section 4.4.2 more a broader discussion).

Mining is also important within the region (see Section 2.G.1) and this can have serious environmental consequences in terms of sediment runoff, soil erosion, vegetation destruction and water pollution (Mandulu 2002).

An increase in commercial agriculture, especially tobacco production, in wetland areas has reduced the extent of the wetlands and damaged the forest vegetation, as charcoal is frequently used for tobacco drying (Olson et al., 2001b). The severe consequences of increases in water use for irrigation and livestock grazing of river-margin wetlands are demonstrated on the Great Ruaha River, central Tanzania. Here severe reductions in river levels, including seasonal drying out of the river are associated with a shift from wet to dry vegetation communities (Mtahiko et al., 2006) and major damage to the river ecosystem, notably large-scale fish deaths when the river gives way to isolated unshaded water holes in the river bed during the dry season (Epaphras et al., 2007). An increase in grazing pressure in the fringing wetlands of Lake Victoria near Mwanza, exacerbated by recent drought, has resulted in vegetation loss as well as clearance and soil erosion (Hongo and Masikini 2003).

Anthropogenic activity surrounding Lake Victoria has had dramatic impacts on the lake environment. One of the most reported impacts from man has been the change in the fish populations in the lake. In the 1950s, a decline in fisheries prompted the introduction of the Nile perch (*Lates niloticus*) and *Oreochromis niloticus* into Lake Victoria (Henry and Kishimba 2006). The population of these species grew and, as a consequence of their predation on native species, over 200 endemic fish species (which originally formed 90% of the lake fish biomass) have become extinct (Getabu et al 2003). As a consequence of the Nile perch introduction, an expanding fishing industry has grown around the lake shore in Tanzania (Henry and Kishimba 2006) at the expense of a huge decline in biodiversity. The fisheries produce over 500 000 tonnes of fish annually (Getabu et al 2003) and over-fishing, particularly of native fish species, is an increasing concern (see Section 2.G.1). The socio-economic consequences of the fishing industry are discussed in more detail in Section 2.G.1.

Pollution of Lake Victoria from increasing agriculture, industrial expansion and urban development (Ogutu-Ohwayo et al., 1997), provides a classic illustration of environmental stress from the mixed urban and rural land uses of desakota areas. Small industries, such as breweries, tanning, fish processing, agroprocessing (sugar, coffee, abattoirs) and mining have expanded, releasing organic and inorganic suspended solids, dissolved nutrients, effluent, heavy metals and compounds from smoke into local watercourses (Olson et al., 2001b; Kishe and Machiwa 2003; Global Environment Facility, undated) and unplanned urban development generated by the rapidly increasing population has contributed to water quality problems as a result of poor sanitation and inadequate waste disposal (Mandulu 2004). Agriculture and overgrazing on the lake shore have also been responsible for phosphate and nitrate contamination (Hongo and Masikini 2003) and pesticide contamination in fish (Henry and Kishimba 2006). Eutrophication is an increasing problem in Lake Victoria (Katereggia and Sterner 2007, Global Environment Facility, undated) with frequent algal blooms (Goudswaard et al., 2002) and reductions in water transparency and oxygen levels (Ogutu-Ohwayo et al., 1997).

The lake environment also suffers from the invasive water hyacinth (*Eichhornia crassipes*), the growth of which has been attributed to abundant nutrients in the lake (Katereggia and Sterner 2007). This species has several detrimental effects, increasing suspended, decaying organic matter,

deoxygenating the water (Global Environment Facility, undated), and inducing declines in biodiversity. According to the Lake Victoria Environmental Management Project (1999, cited Kateregga and Sterner 2007), some major impacts of the water hyacinth include: a reduction in fish through deoxygenation of water in bays; interference with fishing and transportation; impeding urban and rural water supply, and providing habitat for organisms such as the mosquitos, snakes and bilharzias-associated snails. Furthermore, evapotranspiration losses from the water hyacinth, can be 3.5 times that of a free water surface (Ogutu-Ohwayo et al., 1997)

5.6.3 Impact on Ecosystem Services

In the Mwanza region, Lake Victoria and its surrounding wetlands provide a number of key provisioning services, which are threatened from over exploitation and climate change. In the surrounding catchment, native land cover may change in response changes in precipitation (see Section 4.4.3) exacerbated by widespread vegetation degradation and clearance and leading to significant, adverse hydrological impacts, such as an increase in surface runoff and a reduction in water storage (see Section 4.5.2 for a broader discussion). An increase in rainfall variability in the region is predicted. Changes in vegetation are likely to amplify both drought and flood risk and also to adversely affect ecosystem services such as livestock grazing, timber, fuelwood, building materials, charcoal and medicine (Olson et al., 2001b; Hely et al., 2006). The wetland areas surrounding Lake Victoria are also being overexploited, leading to important ecosystem services, such as crop and livestock production and pollutant buffering being potentially threatened (Hongo and Maskini 2003), and regional climatic changes may exacerbate these problems through a marked change in lake levels.

Much of the population expansion in Mwanza has been supported by the fisheries of Lake Victoria. However, changes to lake levels, temperatures and stratification, pollution, eutrophication, marginal vegetation (particularly the water hyacinth), fish species diversity as well as overfishing, threaten the ecosystem services on which these livelihoods depend. Changes to lake levels may also impact the distribution of water hyacinth, which saw a drastic decline partially in response to high lake levels in the El Nino year of 1997/1998 (Williams et al., 2005; 2007).

Anthropogenic activity and climate change may reduce the regulating services of the lake environment and serious health impacts are predicted. Increases in temperatures may increase disease outbreaks, from increases in disease vectors such as mosquitoes (Magadza 2000). Cholera epidemics around Lake Victoria show a relationship with increasing temperatures and may increase further with climate warming (Olago et al., 2007). Furthermore, there may be health implications from the discharge of sewage (Senzia et al., 2003) and heavy metals (Machiwa 2005) into rivers and wetlands, and the prevalence of water hyacinth within the lake may encourage populations of disease carrying vectors (Lake Victoria Environmental Management Project, 1999, cited Kateregga and Sterner 2007).

5.6.4 Research Needs

- There is a need for integrated studies on the ecosystem functioning of Lake Victoria (Bootsma and Hecky, 2003). A better understanding of lake function will enable a more accurate interpretation of impacts of climate change and anthropogenic activity.
- There is a need for further understanding of the functioning of the wetlands in relation to the hydrological regime, as this habitat is critical in terms of the ecosystem services that it provides. The wetlands provide provisioning services, such as fisheries, fiber and water,

and also help mitigate against the environmental problems in the catchment, such as eutrophication and surface runoff increase.

- This region remains one of the least-studied areas in terms of ecosystem dynamics and climate variability (Hely et al., 2006). The forest has recently undergone degradation and there is a need for a better understanding of the engineering function of the trees in this habitat and the ecological and hydrological consequences of increased patchiness. There is also a need to understand the ability of the habitat to cope with stress and the conditions at which threshold conditions in this habitat will occur, whereby the engineering function of the vegetation will cease. There is also a need for a better understanding of how vegetation will respond to climate change and how this may affect hydrological processes.
- Groundwater dynamics need further study, with an emphasis on likely changes induced by climate and vegetation change. In this context shallow groundwater along seasonal water courses, lake shores and within wetlands are crucial to ecosystem services and are also highly susceptible to relatively small hydrological changes.
- Invasive species, such as the water hyacinth, threaten Lake Victoria and many other waterbodies. Limited understanding of the ecology of these species hinders the development of effective management strategies.
- The area is very sensitive to El Nino events, which are predicted to increase in frequency and intensity. A better understanding of this phenomenon would aid forecasting and the development of appropriate responses.

5.7 AMAZONIA: THE FUQUENE CATCHMENT, COLOMBIA

The Fuquene case study highlights how the environmental impacts of desakota activity can be spatially separated. The case study area is impacted from upstream development and, in turn, desakota activity within the case study area has had downstream consequences. Further, the case study shows how the impacts of climate change can exacerbate the impact of changes in land use.

5.7.1 Environmental Context and Services

The Fuquene catchment, situated in central Colombia, 80 km northeast of the capital city, Bogota (Condesan, undated), has a catchment area of 1750 km², which supports a major waterbody, Fuquene Lake. The lake covers 3260 ha, stores 50 million m³ of water and is shallow, with a mean depth of 1.5m and a maximum depth of 5.5m (Montenegro-Parades 2004).

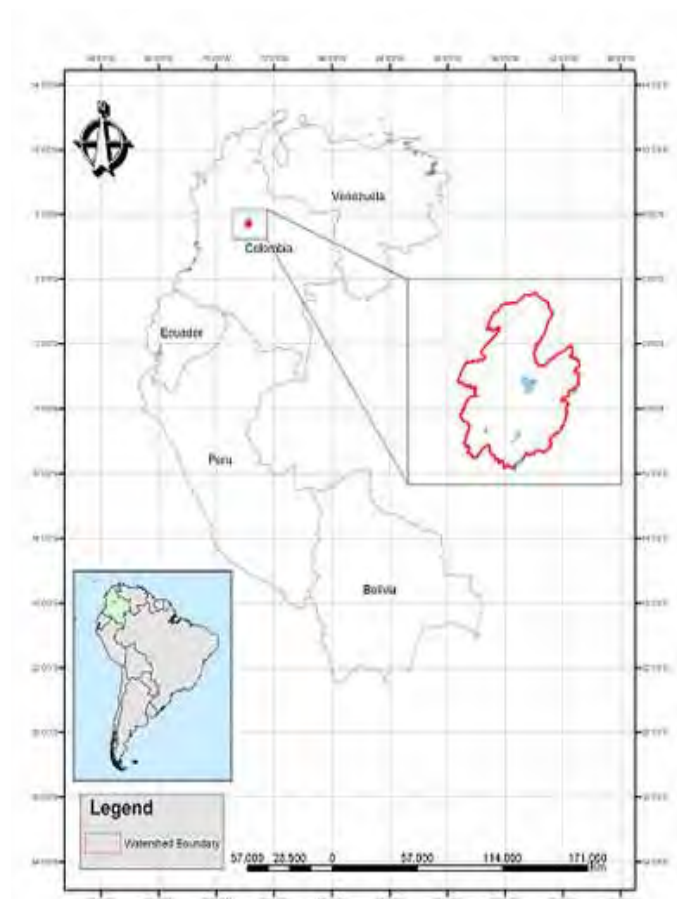
Fuquene Lake drains the Ubate and Fuquene watersheds and the major outflow is the Suárez River (Montenegro-Parades 2004). Lake levels remain constant, maintained by the Tolón floodgate located 18km downstream (Montenegro-Parades 2004). The lake is situated at 2539m above sea level (Global Nature Fund 2008) and its shores are characterised by non-consolidated silts, aquatic beds and swamps of emergent vegetation, including rushes, reeds and sedges (Montenegro-Parades 2004).

The catchment has stable temperatures (ca 12-13°C) with little seasonal fluctuation. Mean monthly humidity varies between 70 and 80%. The watershed has two dry seasons (Dec-Feb, June-Aug) and two wet seasons (March-May, Sept-Nov), with 700-1500 mm of rain annually (Condesan, undated). The evaporation does not exhibit seasonal variation and monthly ranges are between 66.7-98.6 mm (Montenegro-Parades 2004). The region is affected by El Nino and, whilst associated reductions in precipitation during El Nino periods have been observed (Poveda et al., 2005;

Buytaert et al., 2006), the hydrological response of Colombia to El Nino is highly complex and non-linear (Marin and Ramirez 2006).

The watershed is characterised by Magdalena Valley Montane Forest (see Figure 5.12), which is classified as Tropical and Subtropical Moist Broadleaf Forest (Olson et al., 2001a), with a very high floral and faunal diversity, and many endemic and endangered species (Olson et al., 2001b). Within these wet montane forests, cloud forests usually form at high elevations.

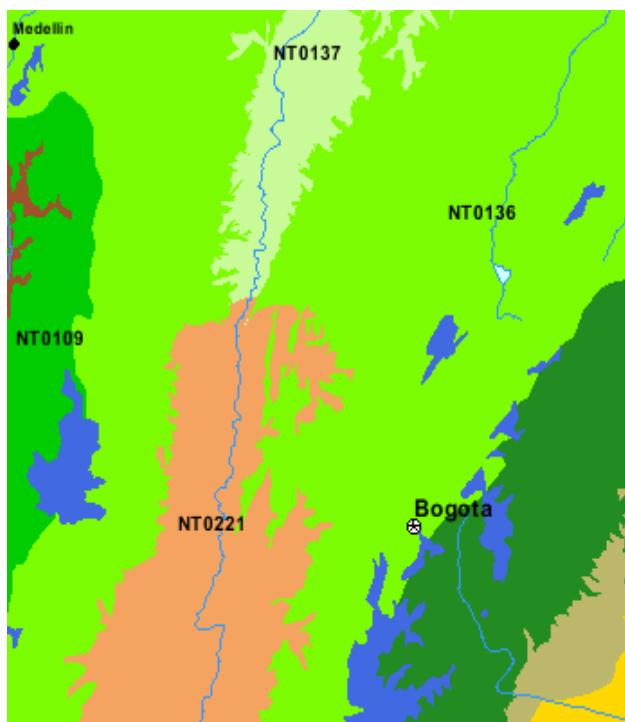
Figure 5.11: Map of the Fuquene catchment, Colombia.



source: Condesan (<http://www.condesan.org/andean/fuquene.htm>)

Fuquene Lake supports a variety of different ecosystem services and over 200 families, fishermen and basket makers are directly dependent upon the lake (Global Nature Fund 2008). The lake provides a number of key provisioning services, such as drinking water and food, from fisheries and wildfowl (Montenegro-Parades 2004; Global Nature Fund 2008). The lake also supports a handicrafts manufacturing industry, which is the main livelihood for many local people (Montenegro-Parades 2004). Other provisioning services include transport and fuel from riparian trees. The wider catchment is important for food production and much of the plains and the forested upland areas have been cleared for agriculture. Increasingly the slopes are being used for coffee (Olson et al., 2001b; Montenegro-Parades 2004), potato and grain cash crop production. In the lowlands, water from the lake is used for irrigation of crops (Montenegro-Parades 2004) and the littoral area is used for livestock grazing, to support an extensive and rapidly increasing dairy industry (Hoeck, undated).

Figure 5.12: Map of the Fuquene catchment, showing the major ecoregion, Magdalena Valley Montane Forest (NT0136)



source: (from Olson et al., 2001b)

The catchment also provides a number of regulating services. In the upland areas, the paramo vegetation regulates water resources and the montane forest mitigates climate change and supports carbon storage in biomass and soils. Water resources are also regulated by Fuquene Lake, which provides downstream flood control (Montenegro-Parades 2004).

5.7.2 Environmental Change

Regional Climate Change: Analysis of temperature records from 1961-2003 indicates a trend of general warming of the region (Aguilar et al., 2005), which will continue to 2080-2099 (Christensen et al., 2007). Christensen et al. (2007) predict an increase in the seasonality of temperature, with higher rates of warming between June and August (see Section 4.2.4). Precipitation will also increase, particularly in December to February (Christensen et al., 2007), with predicted increases in rainfall intensity and the number of wet and very wet days (Aguilar et al., 2005). However, Colombia is influenced by El Nino, which causes deficits in rainfall in the mountainous regions and drought in the rainforest (Laurance and Williamson 2001). Although uncertain, predicted changes to El Nino from climate change are an increase in the length and intensity of events, which would result in more pronounced and drier periods in the upland areas which supply the lake (Buytaert et al., 2006). The El Nino may also impact the forest vegetation, by inducing drought periods (Laurance and Williamson 2001), which may have implications for the hydrological regime. Other predicted impacts of climate change in the region include increases in humidity (Vuille et al., 2003) and changes to evapotranspiration rates (Vuille et al., 2003)

These predicted changes will have impacts on the natural vegetation. Cloud forest is very prone to the effects of climate change due to its location on steep, topographically controlled climatic gradients (Mulligan and Burke, 2005). Primary productivity in the forest may change as a

result of elevated carbon dioxide levels (Clark 2004; Beerling and Mayle 2006), although this is uncertain (Chambers and Silver 2004; Clark 2007). The vegetation composition of the catchment may change as a result of boundary changes to the forest-savanna transition (Marchant et al., 2006) and the migration of species to higher elevations (Weng et al., 2007). The susceptibility of the forest to climate change may also be enhanced if there are high rates of deforestation (Laurance and Williamson 2001.) In addition, increased temperature and evaporation rates may cause a drying of Lake Fuquene and changes in the aquatic environment.

Catchment-Scale Anthropogenic Change: Anthropogenic activity, including changes in land use. Direct changes to water consumption and pollution of the aquatic environment, has impacted the natural hydrological functioning of the catchment. Extensive deforestation of the upper catchment has altered the hydrological cycle, with an increase in overland flow and changes in the streamflow regime (Mulligan and Burke 2005). The paramos (valleys and plains with a large variety of lakes, peat bogs and wet grasslands intermingled with shrublands and low forest patches, Buytaert et al., 2006) form important sources of water to Fuquene Lake. The paramos have a naturally high water retention (see Section 4.5.2), but increased cultivation has reduced this water retention capacity. Further increases in cultivation of the paramos may affect the Fuquene watershed through an altered hydrological input, particularly the reduction of sustained base flows (Buytaert et al., 2006). This provides an example of the processes described in Section 4.5.2.

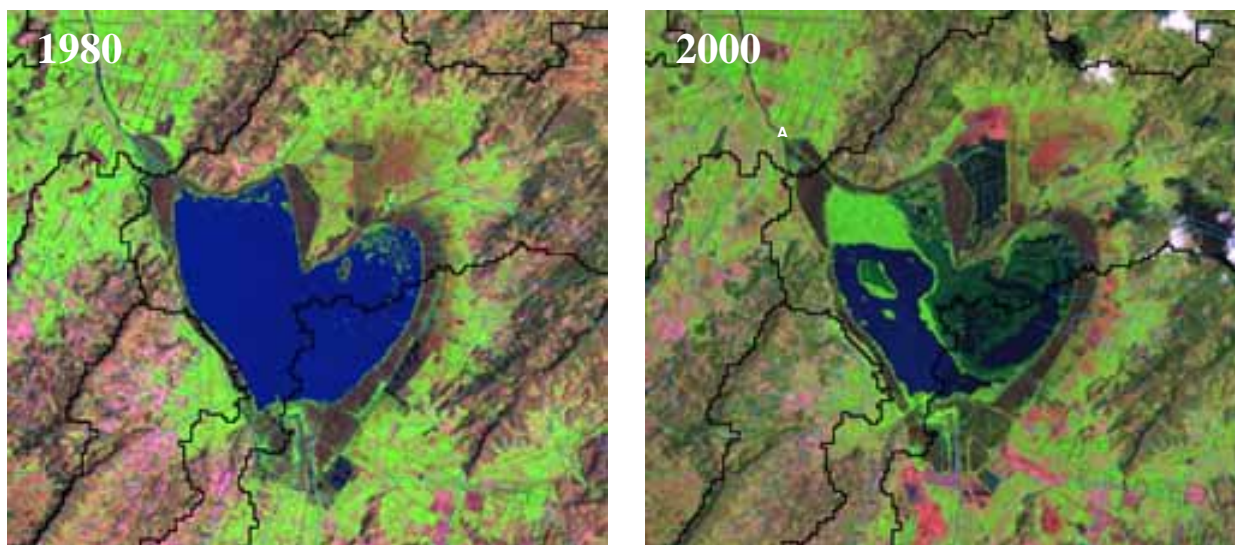
Deforestation, coupled with inappropriate agricultural techniques and planting of monocultures, has also caused large increases in soil erosion. Currently, there are 13000 ha of land in the catchment that are seriously eroded and 40 000 ha are threatened (Condesan, undated). Slopes with less than 50% vegetation cover can produce soil erosion rates of 16 tonnes/ha in a single rainfall event because of the high rainfall intensities (Condesan, undated), which are predicted to increase with climate change.

The increase in soil erosion has caused sedimentation in Lake Fuquene, estimated at 6700 tons/year (Condesan, undated), which has caused the lake to shrink in size. However, this impact has been minor relative to the infilling of the lake from dairy farmers, to increase available space for agriculture. As a consequence of this activity, the lake area is shrinking by 39.9 ha/year, which is reducing its storage capacity (Figure 5.13). These major changes in lake extent and depth are undoubtedly having major impacts on the aquatic ecosystem, as physical properties such as light and temperature will inevitably be changing. Furthermore, the decrease in lake storage has altered the downstream hydrological regime, causing problems of low flows and flood risk (see Section 2.G.3).

Lake Fuquene has also seen declines in water quality recently. Nutrient runoff from upstream cultivation, fertiliser use, intensive stock breeding and urban sewage discharge has caused problems of eutrophication in the lake (Section 2.G.3; Condesan, undated; Montenegro-Parades 2004). Water quality in the lake has also deteriorated from the invasion of water hyacinth, which threatens the aquatic environment. Increased urbanisation in the catchment will reinforce water pollution problems, as poor sanitation results in the discharge of raw sewage into the lake (Montenegro-Parades 2004).

The littoral habitat of Lake Fuquene is also threatened by anthropogenic activity. The increase in agriculture has resulted in drainage of marshes and cultivation of the lake shores, which has severely degraded the natural habitat (Montenegro-Parades 2004) and invasive species are further transforming the habitat and threatening wildfowl populations, which are also under stress from human population increases and increased hunting (Montenegro-Parades 2004).

Figure 5.13: Aerial photos of Lake Fuquene in 1980 and 2000, illustrating the large declines in lake area and level



Source: Condesan, undated: <http://www.condesan.org/andean/fuquene.htm>)

5.7.3 Impact on Ecosystem Services

The major threat to the environmental services provided by Lake Fuquene has been the shrinkage of the lake area, which is attributable to direct anthropogenic activity and from catchment-wide deforestation. The reduction in lake volume has reduced biodiversity in the area, from habitat degradation, and has reduced the ability of the lake to control downstream flooding during the rainy season and provide a water supply to downstream communities in the dry season. Thus, desakota development around the lake threatens the provision of ecosystem services to downstream communities, illustrating the upstream-downstream linkages associated with desakota activity. Infilling of the lake, coupled with eutrophication will also have an adverse impact on the aquatic ecosystem, although this has not been studied to date.

Development around the lake shore has degraded the littoral wetlands, which will impact agriculture and the availability of material to sustain the handicrafts manufacturing industry (Montenegro-Parades 2004). However, one of the major environmental impacts from desakota activity has been the degradation of the forest vegetation and the associated increases in runoff and soil erosion, which have impacted the lake environment.

Precipitation patterns in the region are predicted to change (Section 4.2.4) with associated changes to the hydrological regime. Runoff is predicted to increase during the rainy season, which may increase the frequency of flooding and landslides. The impacts of this are likely to be exacerbated from deforestation in the area, as study as shown positive feedbacks between forest fragmentation, drought and climate change (Laurance and Williamson 2001). Furthermore, there may be hydrological implications from temperature induced changes in the vegetation composition of the ecoregion, as described in Section 4.4.3. However, the precise feedbacks between changes in vegetation, climate and the hydrological regime, and the impact of on ecosystem services, has not been studied to date and requires further research.

5.7.4 Research Questions

- The paramos have an important hydrological function, although this is not well understood. In particular, a better understanding is needed of the interaction between ecology and hydrology in this habitat and the impacts of human activity on this interaction (Buytaert et al., 2006)
- There is a need for more research into the hydrological and vegetation community responses to El Niño.
- A better understanding of the ecological functioning of invasive species would help to develop management and mitigation techniques.

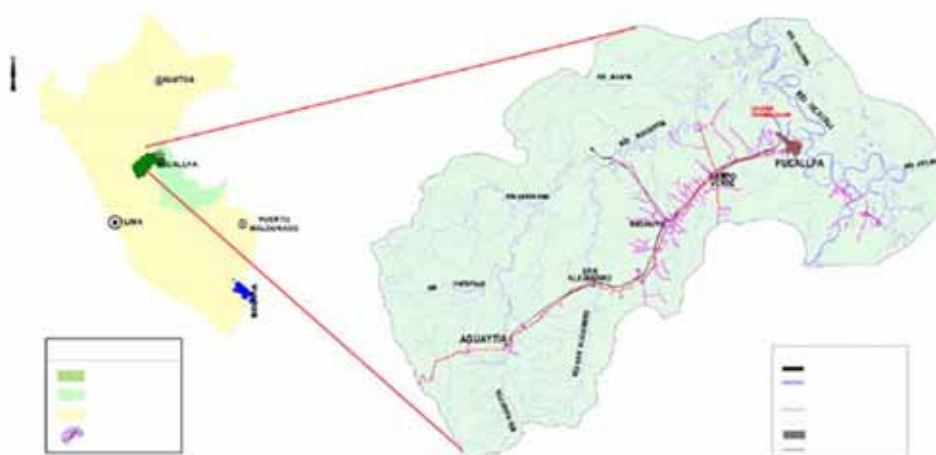
5.8 AMAZONIA: UCAYALI, CENTRAL PERU

This case study region illustrates the ecological and hydrological impacts that land use change, from widespread cultivation and deforestation, can have on a catchment scale. Furthermore, this case study highlights that catchment-scale anthropogenic activity can have regional and global consequences.

5.8.1 Environmental Context and Services

The Ucayali region in central-west Peru is situated within the Aguaytia river catchment close to the Brazilian border (Figure 5.14). The major river system in the Aguaytia watershed is the Ucayali River, which is an upper tributary of the Amazon. The Ucayali River has a meandering, mobile course. The floodplains experience rapid change, with sediment deposits of up to 1m in a single flooding season and channel shifts of up to 50m. The floodplain soils are heterogeneous in both quality and fertility and have varying periodicity and length of inundation, which provides different options for land use (De Jong 2001). However, no data is available on the flows in the Ucayali River, as only one gauging station exists in the entire Peruvian Amazon (Villar et al., 2006).

Figure 5.14: A location map of the Aguaytia catchment



source: ASB: http://www.asb.cgiar.org/regions/amazon/peru/ucayali_site_map.asp

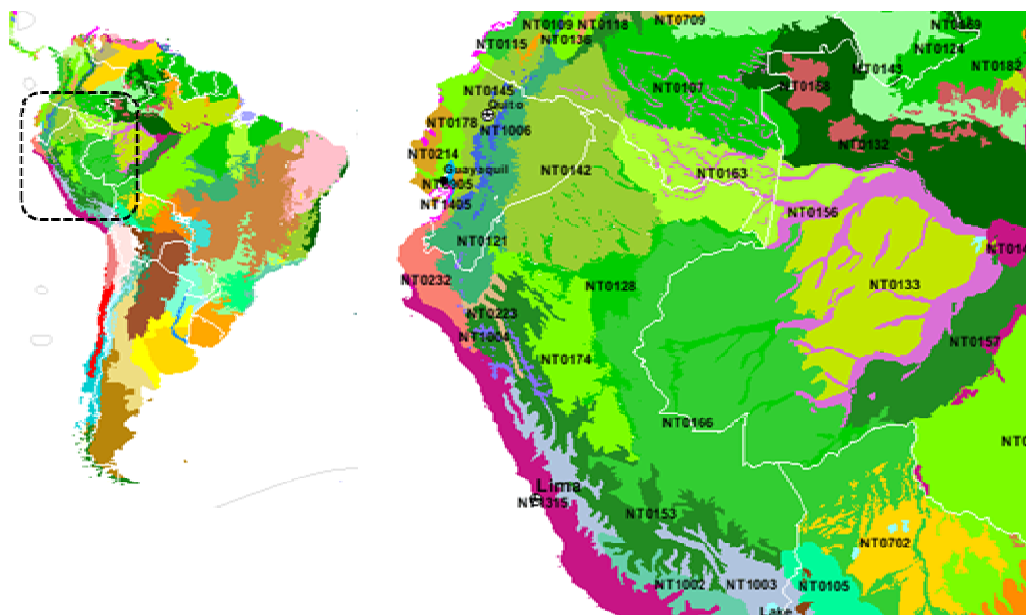
Rainfall in the catchment varies from 1600 to 2500 mm/year (Olson et al., 2001b). These conditions support tropical and subtropical moist broadleaf forests and the ecoregion of the area is classified as Ucayali moist forests (Figure 5.15). These moist forests are characterised by high species diversity including a large number of tropical hardwood species, such as mahogany, tropical cedar and kapok, and over 188 mammal species and 600 bird species (Olson et al., 2001b)

Palms and swamp forests grow along the corridors of the river. These are characterized by high diversity and have adapted to the hydrological regime (Godoy et al., 1999), being very sensitive to both the timing and magnitude of the flood (Lamotte 1990). The forests have a mosaic structure in accordance with inundation levels, which gives rise to a high diversity of forest types. Lamotte (1990) distinguished four broad forest types based on flood inundation: occasional flooding, annual short flooding, annual long flooding and annual submersion. Variation in flooding also supports a variety of different swamp types: herbaceous swamp, shrub swamp, palm swamp and forest swamp (Kalliola et al., 1991)

The forested wetlands support a large population (Lopez Parodi and Freitas 1990), who have adapted land use to the hydrological regime (Kvist et al., 2001a; Kvist and Nebel 2001). A shifting cultivation mosaic is practiced, whereby rotational stages of crops such as rice, cassava, plantain or beans are grown. The riparian area is particularly appropriate for this and the choice of crops is dependent upon flood frequency and duration (Coomes et al., 2004)

The Ucayali River and the surrounding tropical forest provide a rich array of ecosystem services. The river provides water supply and fish, which are a staple food source. The lowland areas are prone to flooding, which supports fish productivity (Coomes et al., 2004). In addition, speciality fish (diverse aquarium species, paiche, carachama, shrimp, turtle and turtle eggs) have a high economic importance (Coomes et al., 2004). The river is also very important for transport (Kvist and Nebel 2001; Coomes et al., 2004).

Figure 5.15: Map of the region, showing the occurrence of Ucayali moist forests (NT0174) in the Aguaytia catchment



reflects floodplain landforms. Particular crops are grown in different areas to take advantage of the inundation regime on an annual or multi-annual basis (De Jong 2001). For example, short-cycle crops are grown in frequently-flooded areas, whilst plantain is grown on higher elevations (e.g. the top of levees) where flooding is much less frequent (De Jong 2001). The lowland forest is frequently flooded and agriculture depends upon the flood regime for fertile soil. The forest is also important for hunting (Kvist and Nebel 2001; Coomes et al., 2004), medicine (Kvist et al., 2001a; Gavin 2004) and for providing material for construction, technical uses and commerce (Kvist et al., 2001a). The extraction of forest products, particularly palm products (morange palm fruit, *Mauritia flexuosa*, heart of palm, *Euterpe precatoria*), is important for subsistence food production and also as an income source (Kvist et al., 2001b; Coomes et al., 2004). This has expanded in recent years and directly supports over 300 families in the region (Swallow et al., 2007).

The forests also provide regulating services, such as carbon storage in biomass and soils (Foley et al. 2007), which may help mitigate against climate change. In addition, the riparian forests protect river water quality (McClain and Cossio 2003).

5.8.2 Environmental Change

Regional Climate Change: Analysis of temperature records from 1961-2003 show a pattern of general warming in the region (Aguilar et al., 2005) and this is predicted to continue to 2080-2099 (Christensen et al., 2001). Precipitation trends from 1961-2003 show no change in total rainfall (Aguilar et al., 2005), although analysis by Christensen et al. (2001) suggests that precipitation will show slight increases in the future. Both analyses show an increase in the seasonality of rainfall. Aguilar et al. (2005) show that rainfall intensity is increasing, with more frequent wet and very wet days. These changes will affect the hydrological regime, with increases in flood magnitude and a possible reduction in low flows. As the composition of the forest is related to the hydrological regime, changes in forest composition and structure are likely, although the exact extent of changes is unknown. Further to this, study has suggested that the Amazonian rainforest is very sensitive to climate change, which may induce changes in species composition and net primary productivity (see Section 4.4.3). The area is affected by the El Nino phenomenon, which causes a reduction in rainfall in the area and drought conditions in the forest (Laurance and Williamson 2001). Climate-induced changes in the frequency and intensity of this may also impact the forest vegetation.

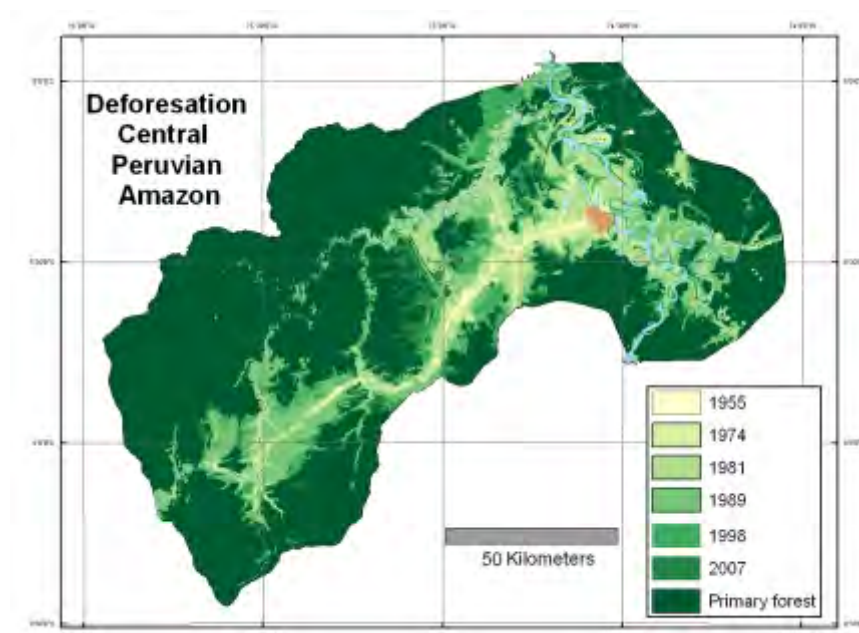
Catchment-Scale Anthropogenic Change: The catchment has seen an increase in population in recent years, which has resulted in large scale changes in land use. There has been widespread deforestation and fragmentation as a result of forest exploitation, logging and clearance for agriculture (Olson et al., 2001b). In particular, there has been a widespread conversion of floodplains to intensive agriculture (Kvist and Nebel 2001) and small scale cattle pasture (Olson et al., 2001b). Oil palm plantations have increased in extent, now covering 200 hectares and supporting over 300 families. Road construction has also increased resulting in further forest loss. The extent of deforestation is shown in Figure 5.16.

These widespread land use changes has undoubtedly had marked impacts on the hydrological regime (Luijters et al., 2000), increasing surface runoff and flood magnitude (see Section 4.5.2). The increased exposure of soils may increase rates of soil erosion, which will impact the form and function of the river channel, affecting the flood regime and aquatic environment, threatening fish populations. The changes to the hydrological regime will combine with climate-induced changes to affect the structure of the riparian forest and patterns of shifting cultivation. This is dependent upon the scale, pattern and intensity of deforestation in the catchment

(see Section 4.5.2) and the extent of deforestation in the region (and the extent to which the catchment is approaching threshold conditions, whereby fundamental changes to the hydrological regime are observed) requires further study.

The existing riparian forest is also endangered from increases in the human population and its need for monetary incomes (Kvist and Nebel 2001). The river channel is a principal transport route and meander bends have traditionally been cut off to reduce travel distances (Abizaid 2005). An increase in population density may expand this practice, having further implications for the hydrological regime and the riparian forest. The river is also threatened from a reduction in water quality as a result of agricultural intensification and pollution from expanding urban areas and a reduction in the riparian forest will reduce the river's capacity to buffer such water quality changes (McClain and Cossio 2003).

Figure 5.16: Map of the Aguaytia catchment showing the extent of deforestation from 1955 – 2007



Source: ASB: http://www.asb.cgiar.org/regions/amazon/peru/ucayali_site_map.asp

5.8.3 Impacts on Ecosystem Services

The Ucayali moist forest is threatened from anthropogenic activity, which will impact significantly on the ecosystem services that the catchment provides. The habitat is threatened from the widespread conversion of forest to agriculture, which threatens key services such as forest products, timber, medicine and hunting. Furthermore, the relationship of the forest to a changing hydrological regime will affect the species composition and age stands of the existing forest, which may affect key ecosystem services as a result of changes in the canopy structure (Gavin 2004). Flood risk may also increase downstream, affecting local settlements. The effects of forest fragmentation have not been considered in detail, but Foley et al. (2007) showed that deforestation causes damage to surrounding forest through enhanced drying of the forest floor, increased frequency of fires and lowered productivity. Therefore, key ecosystem services from the forest may be affected by fragmentation. Section 4.2.2 discusses the impacts of increasing patchiness on

ecosystem stability and this is something that should be considered in relation to the deforestation of this region.

Intensification of agriculture and increased soil erosion threatens to reduce the water quality of the Ucayali River, although this has not been studied in any detail. Declines in water quality will result in declines in fish populations, which will impact food availability and fish extraction for economic purposes.

A reduction in forest extent will reduce carbon storage, which will reduce any climate regulating service that the forest may provide. Swallow et al. (2007) estimate that primary forest has an above-ground carbon storage capacity of 162 t ha^{-1} , compared to rubber plantations, which have 74 t ha^{-1} and oil palm plantations, which have 41 t ha^{-1} . Moreover, study has shown that deforested areas may encourage a reduction in precipitation, leading to lower humidity, higher surface temperatures and more severe dry seasons (Laurance and Williamson 2001). Thus, if deforestation, observed at a catchment scale in this study, is widespread within the region, there may be large regional and global consequences.

5.8.4 Research Questions

- There is a need for more data on the ecohydrological functioning of this region. Climate change may alter the hydrological regime, which will change the structure of the riparian habitat mosaic and will affect cultivation of the riparian zone. Whilst broad climate trends have been considered, the hydrological response in the Peruvian Amazon remains a research need.
- There is little understanding of the ecohydrology of the swamp vegetation (Kalliola et al., 1991). This provides an important habitat and losses in swamp vegetation will adversely affect the biodiversity of the region. Thus, there is a need for further research in this field.
- There is a need for further research into the impacts of forest fragmentation on the remaining forest ecosystem, including the susceptibility of forest patches to drought and the stage at which a 'deforestation threshold' is reached, whereby the functioning of the ecosystem is fundamentally altered (Laurance and Williamson 2001).
- The Amazon rainforest exhibits enormous ecological heterogeneity and spatial floristic complexity. Further research on the ecology and physical environment of the Amazon is needed to aid understanding of historical and ecological factors which have influenced Amazon biogeography and biodiversity (Tuomisto and Ruokolainen 1997)
- The aquatic environment of the Ucayali river has not been studied, despite the importance of fisheries to the local people. Therefore, it is important to investigate the ecological functioning of the instream environment and the impacts of human activity and climate change.

5.9 OVERVIEW AND CONCLUSIONS

The analysis of seven case-study catchments, located in very diverse regions of the world, has illustrated the impacts of desakota activity and climate change on the environment, and the impact of this on the ability of the environment to provide ecosystem services. Whilst some of these issues were catchment-specific and highlight regional differences in the nature of desakota activity, some real similarities between the areas can be seen, highlighting more general trends.

Water resources were a key theme highlighted in the case studies, with a widespread increase in demand, based on a dual pressure from rural and urban usage. Large-scale water use for

agriculture showed an increase from agricultural intensification and, in addition to this, an expansion of urban activity, which increased demand for domestic and industrial use. This was apparent throughout South Asia, in China and in Tanzania. In many of the catchments, there were extensive and unsustainable abstractions to meet this demand and groundwater mining was observed in catchments in India, Pakistan and China. Groundwater mining threatens the future provision of water and, within South Asia, this will be exacerbated from an increase in water scarcity from climate change.

Within the case study catchments, rural and urban water use also showed negative impacts on water quality. A combination of agricultural intensification and urban expansion resulted in a deterioration of water quality in all of the catchments. In some catchments, the decline in water quality threatened the ecosystem services that the catchment provided. For example, in India and Nepal, poor water quality had caused serious health implications. Again, many of these problems were predicted to worsen with climate change and increase in disease was a concern in many of the regions, illustrating some of the trends described in Section 4.6.

One of the key anthropogenic impacts shown the case studies was land use change. In all of the catchments, natural vegetation had been cleared for agriculture and for urban land use. Furthermore, the remaining natural vegetation showed degradation from an increase in population pressure and exploitation of the natural resources. Whilst most of the catchments showed a decline in the natural vegetation from desakota, reforestation in Gujarat provided an interesting contrast and illustrated that desakota can have potential positive environmental impacts.

In all of the catchments, land use change impacted the hydrological regime and highlighted the linkages between land use, climate and hydrology, which were discussed in Section 4. Further to this, the widespread deforestation shown in Amazonia illustrated some of the climatic feedbacks that vegetation change may have and showed that catchment scale trends can have regional and global consequences. Such spatial linkages were shown in other case studies. For example, China and Peru illustrated the upstream-downstream linkages between desakota activity and showed the spatial separation that may exist between desakota activity and its environmental impacts.

The case study catchments highlighted the environmental effects of anthropogenic activity and how this may threaten ecosystem services. In combination with this, climate change trends were considered, which reinforced the adverse impacts of anthropogenic change as many issues, such as water scarcity, would intensify in future. For example, in South Asia and Africa, decreases in precipitation from climate change will exacerbate the current water scarcity issues. Similarly, changes to the hydrological regime in Amazonia will increase runoff rates and high flows, which will be intensified from widespread deforestation. Climate change also showed some positive impacts, for example, predicted precipitation increases in China are likely to increase water availability in the region. A general observed trend was that desakota activity may reduce the ability of the catchments to adapt to climatic change and may intensify some of the observed environmental impacts from anthropogenic activity.

The analysis highlighted some very important research gaps, which need to be addressed if we are to further our understanding of climate change and develop mitigation strategies in the catchments. Although specific research questions were considered with each case study, some general research needs can be identified. Whilst there is much research considering temperature and, to a lesser extent, precipitation changes, the hydrological impacts of these at the catchment-scale have not been considered in sufficient detail. In particular, understanding how the El Nino and monsoon systems will impact hydrological resources requires research attention, if we are to fully understand how the regions are to be affected by climate change.

Whilst general climatic trends can be identified, specific changes to the hydrological regime and to the groundwater are not well understood. There is a particular lack of understanding of the

linkages between ecology and hydrology, shown in all of the analysed catchments. For example, the response of the vegetation to climate change, the hydrological impacts of this and any possible feedbacks, requires further study. Furthermore, many of the aquatic, littoral and riparian environments which are intimately linked to the hydrology of the catchment, and which provide many important ecosystem services (and in many cases sustain the livelihoods of the surrounding populations) are not well understood.

Anthropogenic activity has increased stress on ecosystems, but the full impact of habitat fragmentation requires further research. Specifically, there is a need for understanding how fragmentation affects the remaining habitat and the stage at which 'threshold conditions' are reached, whereby ecosystem function is fundamentally altered. This will have clear implications for water-based ecosystem services, which will affect future anthropogenic activity.

We need to improve our understanding of the relationship between ecology and hydrology in all of these ecosystems if we can understand how they may be impacted by climate change and by anthropogenic activity. Extensive further research is required in this area if we are to fully appreciate the impacts of climate change and develop mitigation strategies.

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6 SUMMARY OF RESEARCH NEEDS

A number of research needs have been identified in the previous sections. These are combined into a single list below:

Section 2 – complexity and interconnectivity of human impacts at a catchment scale demand a catchment or larger-scale perspective on the management of water-related ecosystem services

Section 3 – global changes in climate and related hydrological processes are at a coarser scale than required by the ESPA programme but provide a backdrop for the regional analyses and case studies provided in sections 4 and 5. In particular, the uncertainties and process-complexities connecting climate, surface and sub-surface hydrology and river flow regimes is revealed, underpinning several important areas of research need:

- There has been enormous research effort towards understanding and forecasting changes in global climate. Models are becoming more sophisticated and there seems to be increasing convergence in the projections based on particular scenarios of change. However, this crucial research area demands continuing and substantial research effort
- An area of particular relevance to the ESPA programme is to improve understanding of linkages and feedbacks between human modification of the earth surface, manipulation of the hydrological system, and climate. Whilst land cover provides an important input to global climate models, research at finer spatial scales is suggesting interesting complexities in interactions between plants and their environment, which are highly relevant to ecosystems and their services. We will revisit this theme in section 4 of this report.
- Interactions between climate and hydrology have received considerable research attention, although the crucial association between climate and river flow regime (which integrates the impact of intervening hydrological flows and stores) is under-researched.
- Finally, the intimate association between river flow-sediment-quality regimes and water-related ecosystems, which have been recognised to some degree at finer spatial scales, remain an important research gap at continental to global scales.

Section 4

- Changes in climate will have major consequences for ice and snow cover and melt-driven catchment systems within the ESPA regions. Whilst broad trends have been estimated, the broader implications of these changes across the entire hydrological cycle (e.g. including groundwater) and across large catchments needs further research.
- Changes in climate also have the potential to cause shifts in biomes and/or their contained ecoregions and changes in the landcover within biomes or ecoregions can induce climate feedbacks
- Relationships between vegetation, whether native or planted, and climate are complex and non-linear. In particular, biome and ecoregion boundaries may be particularly sensitive to changes in climate and *vice versa*. Self-organised patchiness in vegetation cover indicates a landscape close to threshold conditions that is highly sensitive to small changes in resource availability (e.g. climate drying or warming, groundwater extraction) and also small changes in landcover particularly with respect to engineering vegetation patches (e.g. overgrazing, burning, clearance of shrub and tree patches for fuel). These interactions need further research to identify the sensitivity of different landscapes to changes in vegetation and the resources (particularly water) that support vegetation growth.

- Land use, intensity and management can strongly impact on climate-vegetation interactions across space and time scales, with the potential to induce marked changes in climate and water-related ecosystem services that may be extremely difficult to reverse. Whilst broad interactions between vegetation, land use and climate that impact on water-related ecosystem services have been defined, many research gaps remain. Particular research needs include (i) definition of responses to particular types of human land surface manipulation, (ii) the threshold conditions beyond which ecosystem impacts of particular land uses and management become severe, and (iii) the degree to which the spatial layout of human land use and management can moderate these threshold conditions.
- Land use and management along the rural-urban continuum, and particularly within ‘peri-urban’ areas is central to the desakota phenomenon. Peri-urban areas are characterised by a patchwork of intensive land uses. Understanding the impact of mosaics of these land uses is crucial to developing approaches that balance human and ecosystem needs in a sustainable way. It is highly likely that adjustments in the current land use mosaic coupled with the introduction of patches of lower-intensity land uses to buffer the impacts of intense land use could yield dramatic improvements in water-related ecosystem services.
- Direct manipulations of the hydrological system (particularly the over-development of groundwater and the imposition of large surface reservoirs) form the second major group of human impacts on water-related ecosystem services. Much research has been conducted on the exploitation of groundwater and surface water stores, but a greater understanding is needed of how these manipulations fit within their broader environmental setting. Manipulation of both of these stores affects river flow, sediment transport and water quality regimes, yielding adverse effects on river and riparian ecosystems and thus on their ecosystem services. Moreover, the exploitation of both of these types of water store depends upon the spatial and temporal hydrological functioning of the catchments within which they are located. Conceptual, generic and case-study research is needed to investigate ways in which ground and surface water stores can be managed in greater sympathy with their catchment setting and the needs of humans and ecosystems within the catchment.

Section 5

- All of the above research needs can be summarised as new approaches to understanding catchments and integrating their management. The ESPA regions include very large catchments and river systems, where integrated understanding is limited but where management based on sound science, at least at the subcatchment scale, could yield enormous benefits. Each case study is unique and thus the identified research needs are listed with respect to each catchment, below:
- CHINA: THE HAI RIVER BASIN
 - The hydrological regime in the catchment has experienced rapid changes in recent years. There is a need to better understand whether the cause of these changes is climate or increased human activity.
 - Further to this, the impact of human activity on water-cycle processes needs to be accurately quantified.
 - It is also important to identify where capacity exists to save water in the agricultural and urban/industrial sectors to try and mitigate against water scarcity
 - A better understanding is needed of how changes to the vegetation, either from climate change or desakota activity, impacts on the annual and seasonal water balance.

- Groundwater resources are under extreme pressure as a result of overexploitation, but there is insufficient information on the functioning of the groundwater store, including recharge sources and rates and the likely impacts of climate change.
- **SOUTHERN ASIA: GUJARAT, WEST INDIA (THE AHMEDABAD – SATLASANA CORRIDOR)**
 - An improved understanding of the impact of changing patterns of rainfall on runoff and groundwater recharge is needed. This understanding needs to encompass the relationship between hydrology and ecology and the need for basin-specific environmental flows.
 - A better understanding of the relationship between the hydrological cycle and vegetation is needed, particularly the response of the catchment to climate change, reforestation and changes in species composition. This needs to be considered in relation to the ecosystem services that the vegetation provides.
 - A better understand of the human impacts on floods and droughts in the context of rapid socio-economic development is needed. This needs to be based on an analysis of recent climate variability and extreme events and their impact on water resources and also identification of key risks and potential adaptation strategies.
 - Consideration is needed of the degree to which conversion to more dry land farming practices might help to mitigate against drought vulnerability and water scarcity. For example, this might include potential choices of plants that have a shorter growing period, produce a high yield, tolerate saline irrigation water, have low transpiration rates and have deep and well-branched roots.
 - Feedbacks from climate change also need to be assessed. For example, increased aerosols in the atmosphere can change irradiance levels by absorbing and scattering solar radiation, which then impacts on photosynthesis, transpiration and evaporation. This little-understood feedback can affect monsoon dynamics.
- **SOUTHERN ASIA: BALOCHISTAN, PAKISTAN**
 - Groundwater is a key resource in this region, but the impact of climate change on groundwater is little understood. This is partly attributable to lack of understanding of the sources of the groundwater. Thus the sources, pathways and rates of groundwater recharge need to be understood in order to assess how these may be affected by climate change.
 - An increase in water scarcity requires adaptation strategies. One option is water harvesting schemes. However, the success of such schemes relies upon an understanding of rainfall patterns and how these are likely to change with climate change.
- **SOUTHERN ASIA: MASTANG TO RUPANDEHI, NEPAL**
 - There is currently very little monitoring of river levels in Nepal, particularly in the High Himalayas. Consequently, there is limited understanding of hydrological regimes which severely hinders any predictions about the impacts of climate change. Specifically, improved understanding is needed of high altitude snowfall and melt patterns and also of snow- and icemelt-driven hydrological regimes.
 - There is sparse data on river flows and little knowledge of regional variation in flow regimes in Nepal. Most research has looked at Nepal as a whole, but there is large internal variation due to large spatial variations in topography and variations in precipitation, temperature and snowmelt. Such data is crucial to improving water resource management.
 - There is currently no water quality monitoring in Nepal. Such data is fundamental to understanding the impacts of anthropogenic activity on the aquatic environment.
 - Groundwater is an important resource, but is little understood in the region. Again, data scarcity and process understanding are needed to improve resource management and understand how these resources may be affected by climate change.

- Vegetation is likely to alter with climate, but improved understanding is needed to interpret the impacts that this may have on the hydrological regime
- Sand and gravel extraction from rivers is an increasing desakota-related activity, but the environmental impacts of this have not been considered.
- SUB-SAHARAN AFRICA: MWANZA, TANZANIA
 - There is a need for integrated studies on the ecosystem functioning of Lake Victoria. A better understanding of lake function will enable a more accurate interpretation of impacts of climate change and anthropogenic activity.
 - There is a need for further understanding of the functioning of the wetlands in relation to the hydrological regime, as this habitat is critical in terms of the ecosystem services that it provides. The wetlands provide provisioning services, such as fisheries, fiber and water, and also help mitigate against the environmental problems in the catchment, such as eutrophication and surface runoff increase.
 - This region remains one of the least-studied areas in terms of ecosystem dynamics and climate variability. There is a need for a better understanding of how vegetation will respond to climate change and how this may affect hydrological processes.
 - Groundwater dynamics need further study, with an emphasis on likely changes induced by climate and vegetation change. In this context shallow groundwater along seasonal watercourses, lake shores and within wetlands are crucial to ecosystem services and are also highly susceptible to relatively small hydrological changes.
 - Invasive species, such as the water hyacinth, threaten Lake Victoria and many other waterbodies. Limited understanding of the ecology of these species hinders the development of effective management strategies.
 - The area is very sensitive to El Nino events, which are predicted to increase in frequency and intensity. A better understanding of this phenomenon would aid forecasting and the development of appropriate responses.
- AMAZONIA: THE FUQUENE CATCHMENT, COLUMBIA
 - The paramos (an area of valleys and plains with many lakes, peat bogs and wet grasslands) have an important hydrological function, although this is not well understood. In particular, a better understanding is needed of the interaction between ecology and hydrology in this habitat and the impacts of human activity on this interaction.
 - There is a need for more research into the hydrological and vegetation community responses to El Nino.
 - A better understanding of the ecological functioning of invasive species would help to develop management and mitigation techniques.
- AMAZONIA: THE AGUAYTIA CATCHMENT, UCAYALI, CENTRAL PERU
 - There is a need for more data on the ecohydrological functioning of this region. Climate change may alter the hydrological regime, which will change the structure of the riparian habitat mosaic and will affect cultivation of the riparian zone. Whilst broad climate trends have been considered, the hydrological response in the Peruvian Amazon remains a research need.
 - There is little understanding of the ecohydrology of the swamp vegetation. This provides an important habitat and loss of swamp vegetation will adversely affect the biodiversity of the region. Thus, there is a need for further research in this field.
 - There is a need for further research into the impacts of forest fragmentation on the remaining forest ecosystem, including the susceptibility of forest patches to drought and the stage at which a 'deforestation threshold' is reached, whereby the functioning of the ecosystem is fundamentally altered.

- The Amazon rainforest exhibits enormous ecological heterogeneity and spatial floristic complexity. Further research on the relationships between ecology and the physical environment of the Amazon is needed to aid understanding of historical and ecological factors which have influenced Amazon biogeography and biodiversity.
- The aquatic environment of the Ucayali river has not been studied, despite the importance of fisheries to the local people. Therefore, it is important to investigate the ecological functioning of the instream environment and the impacts of human activity and climate change.