9

Challenges in Water Management in Intensively Used Catchments in the Himalayan Region

Juerg Merz[1], Rolf Weingartner[1], Pradeep M. Dangol[2], Madhav P. Dhakal[2], Bhawani S. Dongol[2], Gopal Nakarmi[2]
[1] Hydrology Group, University of Berne, Switzerland
[2] ICIMOD, Kathmandu, Nepal (PARDYP-Nepal)

Abstract

The middle mountain catchments of the Hindu Kush-Himalayan region suffer from water scarcity, flooding, landslides, and soil erosion. This PARDYP study found that water scarcity is the issue of most concern. This scarcity is caused mainly by the seasonality of water resource availability. Precipitation is highly seasonal with 75 to 80% of rainfall occurring during the monsoon season and 10 to 15% during the pre-monsoon season. The remaining time is virtually dry. Evapotranspiration rates peak during the pre-monsoon season, making March to April the driest time of the year as runoff is also at its minimum during this time. Water supply for domestic use is also at a minimum and many households face great hardships. This period also is the time of lowest water quality when most contamination occurs. Local water use for agriculture is generally well adapted to the seasonality of supply. Still, farmers experience water shortages at this time as they are not able to grow any additional crops. Farmers at the tail end of irrigation systems receive inadequate supplies even during the wet seasons. The time of highest risk for farmers is the time between the first pre-monsoon rains and the onset of the monsoon as this is when maize is planted and the rice nurseries are prepared in anticipation of the rains arriving. The other time when agriculture is vulnerable is the winter season when wheat and potatoes are grown. Dry conditions can lead to damage to rainfed crops and one less crop on irrigated lands. In addition, the growing number of farmers producing cash crops is putting additional stress on water resources. This paper contributes to the further understanding of water availability and supports a future focus by researchers on the improved management of irrigation systems, the catchment-based management of water resources, improved water quality management, and appropriate technologies to reduce water demand and increase water availability during the dry season.

Introduction

The Hindu Kush-Himalayan (HKH) region is the largest storehouse of freshwater in the lower latitudes (Chalise 2000). It also contains the largest mass of ice and snow outside the Polar Regions. This mountainous area supplies freshwater to its 150 million inhabitants and to 500 million people in the adjacent plains and downstream basins. Such mighty rivers as the Indus, the Ganges, the Yarlung-Tsangpo, the Brahmaputra, the Nu-Salween, the Yangtze, the Yellow River and the Mekong originate in these mountains. Some of these rivers, such as the Huang He (the Indus) are the lifeline for lower areas. The Indus feeds the largest irrigation system in the world (Liniger et al. 1998).

The main water related issues facing the people of the HKH region are floods, soil erosion and water availability.

Floods – Each year about ten thousand people are seriously affected by medium to large flood events. These are most destructive in the adjacent plains with great human and economic losses. In Bangladesh, flooding happens every year with an average of 20% of its area affected (Hofer 1998). Bangladeshi farmers have adapted their agricultural calendar to get the most benefit from this flooding. Every 33 to 50 years catastrophic floods hit the country (Miah 1988). Floods also occur in the inner Himalayan valleys in India (Agarwal and Narain 1991, Subba 2001), and in Nepal (Chalise and Khanal 2002).

Soil erosion – Soil erosion in the foothills of the HKH is a hot topic in land degradation research (Scherr and Yadav 1996). The main issue concerns the loss of topsoil through surface erosion with subsequent declines in soil fertility. This is a serious concern for agriculture and food security and is believed to be a major ecological crisis facing the HKH region (Chalise et al. 1993). However, nutrient leaching is a more important mechanism for the loss of soil nutrients (Gardner et al. 2000). Mass wasting accounts for much of the sediment load in rivers, but is only marginally responsible for soil fertility decline. Galay et al. (2001) have shown the often very damaging impact of high sediment loads on downstream infrastructure. These lead to sedimentation in reservoirs and the build-up (aggradation) of riverbeds. The 1993 storm in the Kulekhani area in central Nepal is one example, where the water storage capacity of an important large reservoir was greatly reduced by an immense sediment input from mass wasting and stream bank erosion.

Water availability has been identified by Merz et al. (2003) as a major concern of people in midhills Nepal. Water for irrigation and domestic use are in short supply. Water pollution is becoming an increasing concern in some catchments. A number of authors (compiled in Merz et al. 2004) report water scarcity from across the HKH. Chalise et al. (1993) reports the drying up of local groundwater resources due largely to changes in local land use. Due to these changes women and children are forced to walk longer distances to collect water. These authors further report on cases from Nepal's Midhills where men are finding it difficult to find brides because of the drudgery involved for hill women to collect water.

The middle mountains are one of the most fragile and vulnerable areas in the HKH region. This zone is characterised by high rainfall, high rates of specific runoff (Alford 1992) and high population densities (over 75 people/km^2). These densities lead to high pressure on, and intensive use of, natural resources with resource degradation in many places.

The study reported in this paper asked the following questions:

- are farmers in upland catchments responsible for floods downstream?
- is soil loss a problem in the selected study catchments?
- is water scarce in middle mountain catchments?

Water availability is an issue of great concern in many parts of the world. This problem is the most frequently mentioned issue in the catchments of the People and Resource Dynamics in Mountain Watersheds of the Hindu Kush-Himalayas Project (PARDYP) in Nepal (Merz et al. 2003), and in China, India, and Pakistan (Merz et al. 2004). This paper discusses this issue in detail. The two other important issues of downstream floods and soil loss are discussed in more depth in Merz (2004) and are addressed in the papers by Jehangir et al. and Dangol et al. in this volume (2005).

Study Site and Methodology

This study is mainly based on data collected in the Jhikhu Khola (JKC) and Yarsha Khola (YKC) catchments in Nepal. An introduction to these two catchments is given in the introductory paper in this volume (The PARDYP Teams 2005). Both are headwater catchments of the middle mountains with elevations of between 790 and 2200 masl in the Jhikhu Khola and 990 to 3040 masl in the Yarsha Khola. They are purely rainfed with the exception of a couple of days of snowfall per year in areas above 2800m. They have high population densities with, in 1996, 437 people/km^2 in the Jhikhu Khola and 386 people/km^2 in the Yarsha Khola. More recent figures show the density in the Jhikhu Khola as having risen to up to 550 people/km^2.

The Jhikhu Khola catchment is one of the most intensively cultivated rural areas in Nepal's middle mountains. It is therefore not representative of other catchments in the region, but does represent the condition that many other areas in the region are tending towards. Its irrigated areas cover 1838 ha or 16.5% of the total catchment. Rainfed agricultural land covers 4266 ha or 38.3% of the total area. On irrigated land two to three, and in some cases four, crops are grown with rice during the monsoon season and potato and tomato during dry seasons. Other vegetables increasingly cultivated include cauliflower, cabbage, bitter gourd, cucumber, capsicum, and chilli.

The Yarsha Khola catchment has a total irrigated area of 744 ha (14% of its area) with rice during the monsoon season and wheat or potatoes during the dry season. On the 1996 ha of rainfed agricultural land (37% of the catchment area), maize is grown during the dry season followed by millet in the post-monsoon season as a relay crop, and wheat or potatoes during the dry season.

In both catchments the PARDYP project has run dense hydro-meteorological monitoring and research networks (Merz 2004). The study reported in this paper used data covering 1993 to 2000 for the Jhikhu Khola and 1998 to 2000 for the Yarsha Khola. The data was substantiated with data collected from household surveys, water quality surveys, and other measurements.

The study follows the approach described in Merz (2004). The conditions and dynamics of the biophysical and socioeconomic processes that govern local hydrological regimes in the HKH are changing in many places due to the pressures of land use change, population growth, and climate change. It is very important to understand the current conditions and the related processes to be able to plan to accommodate these changes.

Water Availability Study

Farmers say that the availability of irrigation and domestic supplies has decreased over the last 5 to 25 years (Merz et al. 2002). Farmers and scientists also perceive that flows out of the two catchments have decreased over the last 10 to 15 years (Merz et al. 2002). However, this could not be proven from the streamflow data due to inadequate data accuracy at the low flow level. The question therefore remains of whether or not it is true that water resources are really scarce or whether it is more an issue of shortcomings in water management and distribution. This study explored the actual water availability and the issues related to this on the basis of a water balance approach that looks at the water inputs (precipitation), the water outputs (evapotranspiration, outflow, human consumption), and water storage in the groundwater and the soil. This paper first discusses the main parameters of precipitation, evapotranspiration, runoff, storage and human consumption before this information is synthesised in a water-accounting exercise below.

Precipitation Dynamics

The two catchments are headwater catchments and precipitation is therefore the only input into their water cycle. Most precipitation occurs as rainfall with occasional snowfall in upper areas of the Yarsha Khola. The Jhikhu Khola catchment receives about 1295 mm areal rainfall per year and the Yarsha Khola 2206 mm per year. The minimum annual rainfall in the Jhikhu Khola catchment was measured in 1993 with 1082 mm, while the maximum of 1628 mm was measured in 1999.

Most of the rainfall in the Jhikhu Khola catchment falls in the monsoon season accounting for about 79% of the total. The pre-monsoon season receives 13% of annual rainfall while the remaining 8% occurs in the dry season which runs from October to May. The values in the Yarsha Khola catchment are similar with 81% of rainfall in the monsoon season, 15% in the pre-monsoon season, and 4% in the dry season. The seasonal variability of rainfall is highest during the October to May low rainfall season (Figure 9.1) indicated with coefficients of variation between 0.9 and 1.3 in the post-monsoon season, 0.5 to 1.6 in winter, and 0.3 to 0.8 in the pre-monsoon season depending on station location.

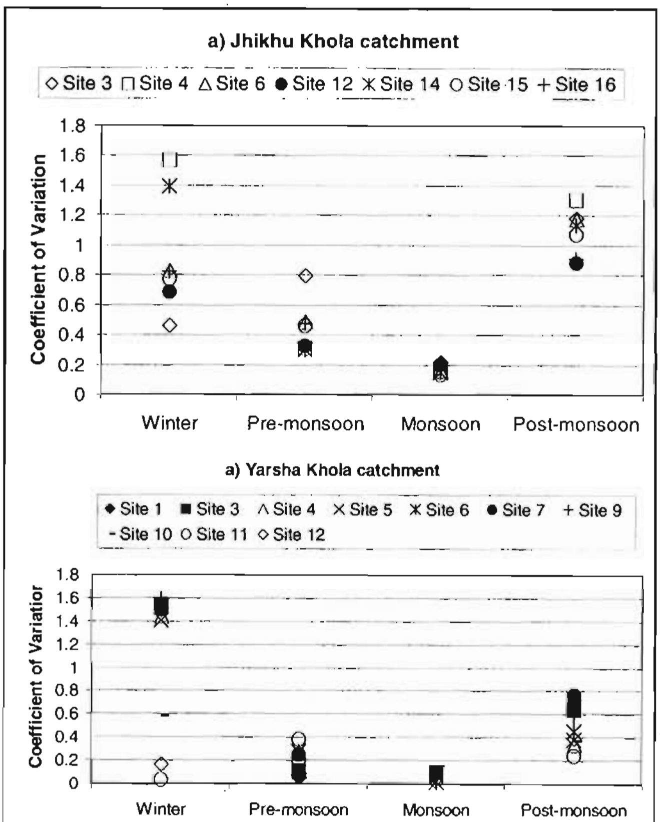

Figure 9.1: **Seasonal rainfall variability in the Jhikhu Khola (1993-2000) and Yarsha Khola (1998-2000) catchments**

In the Yarsha Khola, rainfall variability shows a similar trend as the Jhikhu Khola; but these values should be treated with caution due to the short time series of the data.

Rainfall only occurs occasionally during the dry season. The number of dry spells of 15 subsequent days without measurable rainfall (Mosley and Pearson 1997) in the Jhikhu Khola catchment ranged from nine to thirteen in number in the 1993 to 2002 period. These dry spells most frequently lasted between 25 and 50 days. The longest dry spell recorded was 144 days. The period from 1998 to 2000 was particularly dry with most dry spells lasting between 50 and 100 days. The Yarsha Khola catchment has fewer dry spells per year (about 8 to 11 in number), but they were longer. From 1998 to 2000 most dry spells lasted between 50 and 100 days.

Spatially the precipitation pattern is erratic during the dry season and no distinct pattern can be seen. Elevation provides a good relationship for annual and monsoon data and in months where exceptionally high rainfall events occur. In the Yarsha Khola catchment the elevation-precipitation relationship is consistent throughout the year, but inadequate during the dry season. As a rule of thumb there is generally higher rainfall in the upper areas of the two catchments.

In summary, there is plenty of annual rainfall for human needs in both catchments, but its distribution is skewed towards the monsoon season. At the same time the little rain falling during the remainder of the year is highly variable, which means that farmers cannot rely on it. Rainfall occurrence is also spatially variable and no distinct relationship with elevation was observed.

Evapotranspiration

In the absence of physical evaporation measurements and other sophisticated data for estimating evapotranspiration, the temperature based FAO Penman-Monteith evapotranspiration calculation approach (FAO 1998) was applied. The reference evapotranspiration values ET_0 in the Jhikhu Khola catchment range from 1.7 mm/day at different sites both in January and December up to about 5 mm/day in May (Figure 9.2). In the Yarsha Khola catchment the minimum daily ET_0 was calculated at between 1.0 and 1.5 mm/day. The maximum is reached in April and May with values ranging from 3 to 5 mm/day. 9

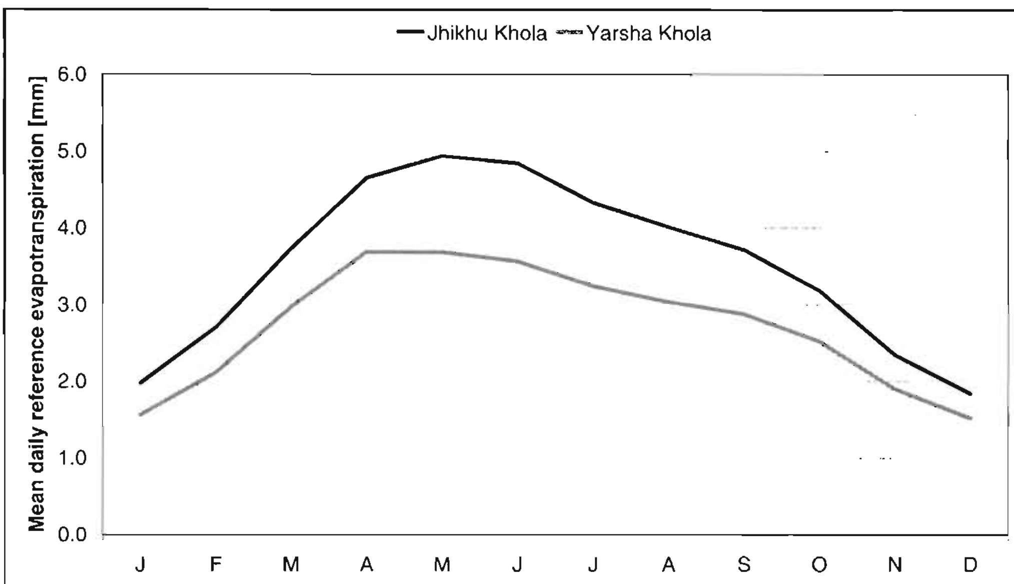

Figure 9.2: **Mean daily reference evapotranspiration at main stations of Jhikhu Khola and Yarsha Khola catchments**

These results were compared with the results of studies in Nepal by Lambert and Chitrakar (1989), MacDonald & Partners (1990), and Tahal Consulting Engineers (2002). The calculated values correspond well throughout the range with the values reported by Lambert and Chitrakar; but are slightly lower in comparison to MacDonald & Partners' values. MacDonald & Partners used the method proposed by FAO (1977), which, according to FAO

(1998) frequently overestimates ET_0. There was a considerable difference with the values reported by Tahal Consulting Engineers (2002). Mainly the values of sites higher than 1500 masl differed largely. It has to be noted that Tahal Consulting Engineers' values are all from western and central western Nepal. There is a considerable difference in sunshine duration between the western and eastern parts of the country (Jhikhu Khola and Yarsha Khola lie in the central-eastern part of Nepal). In particular April, May, and June have significantly different amounts of mean daily sunshine (Chalise et al. 1996). These are the months with the highest reference evapotranspiration rates and the differences in amount of sunshine could therefore explain the differences between the two calculations. In general, the values calculated for the study areas seem to be plausible.

On the basis of ET_0, the actual evapotranspiration AET was estimated by using the crop coefficient approach (FAO 1998). The results are presented in Table 9.1. Values of 850 to 886 mm per annum were estimated for the entire Jhikhu Khola. In the Yarsha Khola, AET values were estimated at between 730 and 790 mm per annum in the period 1998 to 2000.

Table 9.1: **Annual evapotranspiration data for the Jhikhu Khola and Yarsha Khola catchments [mm/yr]**

	1993	1994	1995	1996	1997	1998	1999	2000
Jhikhu Khola	850	886	854	873	859	884	878	869
Yarsha Khola	-	-	-	-	-	778	790	732

Flow Regime

The mean discharge of water at the main station at the outlet of the Jhikhu Khola catchment was 1.45 m^3/s in the period 1993 to 2000, ranging from 1.12 m^3/s in 1994 to 1.79 m^3/s in 1996. In this period the daily maximum discharge was about 30 m^3/s and the minimum was below 0.01 m^3/s. However, these extreme values have to be considered with caution due to inconsistencies related to the relationship between the water level of a river and its flow rate (the stage-discharge relationship).

The annual mean specific yields ranged from 10 to 16 $l/s*km^2$ of water. For a catchment area the size of the Jhikhu Khola (111 km^2), these values are very low and suggest a considerable human impact on streamflow conditions. In comparison, the nearby Rosi Khola catchment that lies to the south of the Jhikhu Khola and covers an area of 87 km^2 had a specific yield of 30 $l/s*km^2$ (Alford 1992) in the early 1990s. The main reason for the higher specific yield of this catchment is its higher rainfall that is related to its higher elevations. The catchment extends up to 2,943 masl and receives much more rainfall than the Jhikhu Khola where the highest elevation is only 2,200 masl.

There is a marked seasonality in the runoff regime of the Jhikhu Khola (Figure 9.3a). The highest mean and median flows were observed during August, followed by the months of July and June. The highest runoff is therefore a month later than the highest rainfall. The absolute minimum flows occur in March closely followed by April, February, and May, indicating the driest time of year in terms of discharge in the river system completely fed by groundwater. With the increasing pre-monsoon showers in May the flow starts to pick up and rapidly increases to the maximum flows in the monsoon season. After reaching maximum flows in the monsoon, flows decline to dry season flows in November, with September and October usually showing intermittent flow amounts.

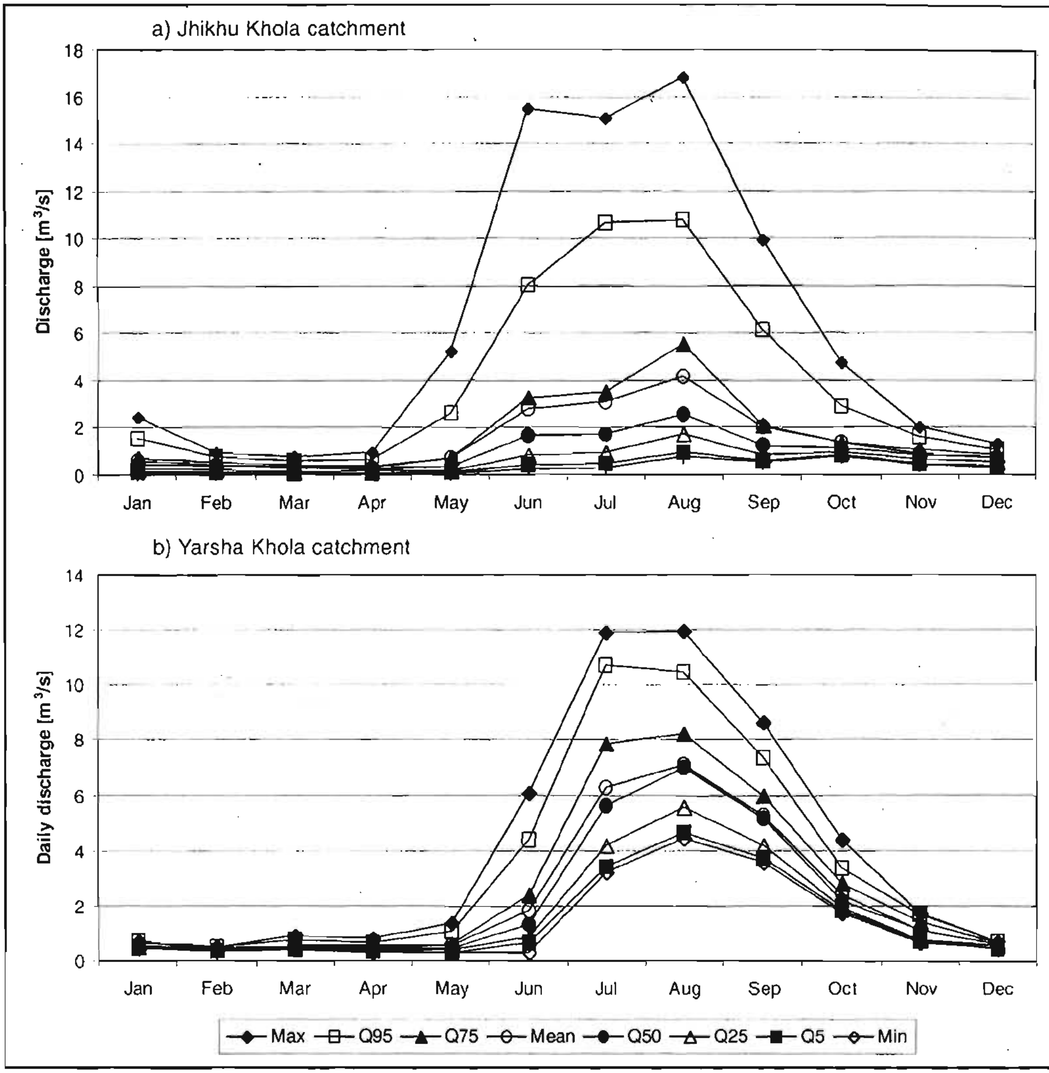

Figure 9.3: **Runoff regime at main stations in the Jhikhu Khola and Yarsha Khola catchments**

The monthly flows in the Jhikhu Khola catchment are generally variable (Figure 9.4). The least variability happens in the monsoon season in July and August. The February flows also have low variability – they were consistently low throughout the measurement period. Generally the pre-monsoon flows in March, April, and May have the highest variabilities as rainfall during this time may be plentiful in some years and erratic in others. They can also be high when intense pre-monsoon rain and extended showers occur.

The highest flow at the main station at the Jhikhu Khola catchment outlet during the year is on average 16 times higher than mean annual flow. The highest daily discharge was on

9

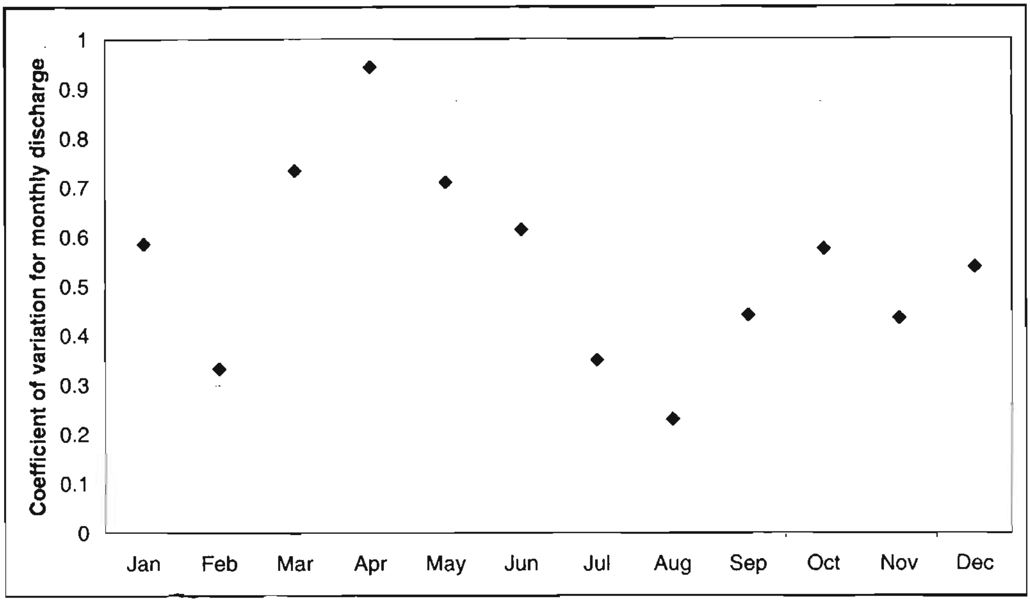

Figure 9.4: **Temporal variability of monthly flows for the Jhikhu Khola catchment**

average about 1500 times larger than the minimum daily flow throughout the study period and the mean flow was 83 times larger than the lowest annual flow.

Data monitoring in the Yarsha Khola catchment started in 1997 and complete annual data is only available from 1998 to 2000. In this period the mean discharge ranged from 1.9 to 2.9 m^3/s and the maximum discharge from 11.6 to 14.3 m^3/s. The minimum recorded value was below 100 l/s in 1998 and about 250 l/s in the other years. The same reservations regarding extreme low flow data quality have to be made here as for the Jhikhu Khola data.

The mean specific yield in the Yarsha Khola catchment (area 53 km^2) was considerably higher ranging up to 50 $l/s*km^2$ in 2000 and 40 $l/s*km^2$ in 1998 and 1999. This matches the values observed in the Rosi Khola that has a similar size and similar elevation, but more human activity.

The absolute minimum flows in the Yarsha Khola happen in May (Figure 9.3b). However, when there are strong pre-monsoon rains or the monsoon started early the smallest range of flows happened in April and February. Flows were consistently low from December through to the onset of the monsoon. The maximum flows were recorded in July and August followed by September and June, with irregular flows in October and November. The observed flows during August ranged from 4 to 12 m^3/s. The lowest flows were recorded in February with a range of annual values from 0.36 to 0.52 m^3/s.

The variability was not assessed for the Yarsha Khola as three years of data is not enough to carry out a variability analysis. The intra-annual variability can however be shown in terms of the ratio between the highest, lowest and mean flows at the outlet of the catchment. The highest flows were on average about 6 times bigger than the mean flows and about 64 times bigger than the lower flows. The lowest flows were on average only about a tenth of mean flows.

A comparison of the daily runoff at the hydrological stations at the outlets of the two catchments shows that the Yarsha Khola catchment generally carries much more water per unit area than the Jhikhu Khola (Figure 9.5). The baseflow – the flow derived from ground and soil water storage – in particular is higher in the former catchment.

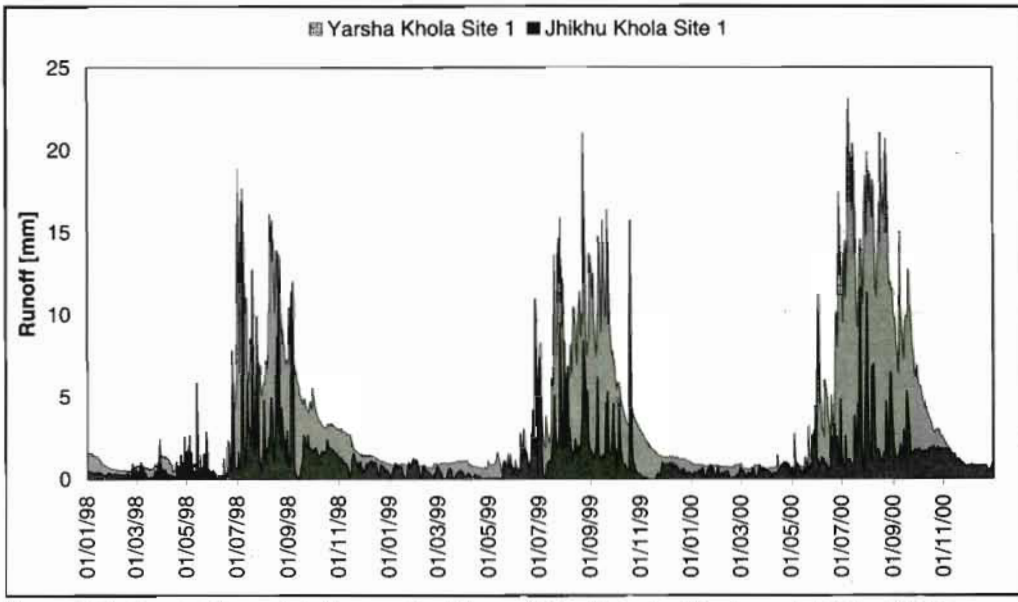

Figure 9.5: **Comparison of daily runoff at the outlets of Yarsha Khola and Jhikhu Khola**

The above analysis can be summarised as follows:

- both catchments have a distinct wet season-dry season regime with the lowest water flows in the pre-monsoon season (March/April) and the highest in July/August;
- the mean specific yields are about 12 l/s*km² in the Jhikhu Khola and 40 l/s*km² in the Yarsha Khola;
- annual runoff ranged from 300 to 500 mm during the 1993 to 2000 period in the Jhikhu Khola catchment and from 1200 to 1600 mm in the Yarsha Khola catchment for the period 1998 to 2000; and
- highest flow variabilities were recorded in pre-monsoon season flows.

Storage

While the flow during the monsoon season is governed by the distribution of rainfall, the flow in the post-monsoon and winter season, and often to a large extent also in the pre-monsoon season, is dependant on the emptying out of stored water from the catchment. These storages and their capacities are important to consider when assessing the potential availability of water. Some of the best forms of storage are glaciers, snow, and lakes. These delay the flow of water by a year or even years in the case of glaciers. None of the studied catchments contains any of these and so rainfall is stored as groundwater and soil water storage. In general these storage systems are believed to hold rainfall for up to one year. Kansakar (2001) mentions three main types of geological settings where groundwater can be expected in the hills of Nepal:

- thick unconsolidated fluvial, glacial and lacustrine sedimentary deposits in river and tectonic valleys;
- thick weathering mantles with coarse debris over bedrock; and
- fractured bedrock.

In the Jhikhu Khola the main valley is filled with alluvial deposits forming a potential aquifer of the first type. Adhikari et al. (2003) showed that spring yield is closely correlated with rock type in the eastern part of the Jhikhu Khola indicating a potential aquifer of the third type. They reported that 75% of the high spring yields were related to carbonate rocks such as limestone, dolomite and marble beds. These are highly fractured and contain interconnecting holes and fissures. In contrast the metamorphic rocks in the area such as phyllite, schist, quartzite and gneiss showed moderate to low discharge. The highest yields were further observed in the base of the syncline fold in the Jhikhu calcareous beds.

In the Yarsha Khola catchment, massive sedimentary deposits and thick weathered mantles are largely missing. Subsurface water that feeds base flows therefore probably mainly come from aquifers in the fractured bedrock and soil water storage.

In general the Yarsha Khola catchment shows a higher storage capacity than the Jhikhu khola catchment. This is reported in Dangol et al's paper in this volume (2005) as the base flow index (BFI). The base flow index is the proportion of a river's runoff that derives from stored sources. It varies from 0.1 for a river that is very prone to flash floods to near unity for a very stable river with a high proportion of base flow (Gustard et al. 1992). The base flow index for the 1998 to 2000 period was 0.46 for the Jhikhu Khola catchment and 0.68 for the Yarsha Khola showing a higher proportion of the annual runoff sustained by base flow in the Yarsha Khola.

To assess the storage capacity of the two catchments the flow recession curves were determined after the monsoon rains at the hydrological stations at both catchment outlets (Figure 9.6). For the Yarsha Khola the fit of a logarithmic curve with base e was very good with an r2 of 0.93 in the 1998/1999 dry season and 0.95 in the 1999/2000 dry season. Following the curve to the point of intercept with the x-axis, a theoretical storage capacity of about 310 days (304 days in 1998/1999, 321 days in 1999/2000) was determined. In the Jhikhu Khola catchment the fit was not as good. This was the case especially in 1999 when it was poor (probably partly due to a measurement error after a very large rainfall event). The theoretical storage capacity was determined at 299 days in 1998/1999 and 305 days in 1999/2000, with an average of about 300 days.

These values indicate that in both catchments the complete exhaustion of the groundwater has not occurred as in both cases the storage is refilled by the onset of the monsoon rains before it is exhausted. The longest possible theoretical dry season is 240 days.

Human Consumption

Water consumption by people in the rural catchments of Nepal's middle mountains comes from demands for crop production, livestock, and domestic needs. Industrial demands are negligible. For the Jhikhu Khola area demands from the tourism industry could become a major water use if this industry continues to grow.

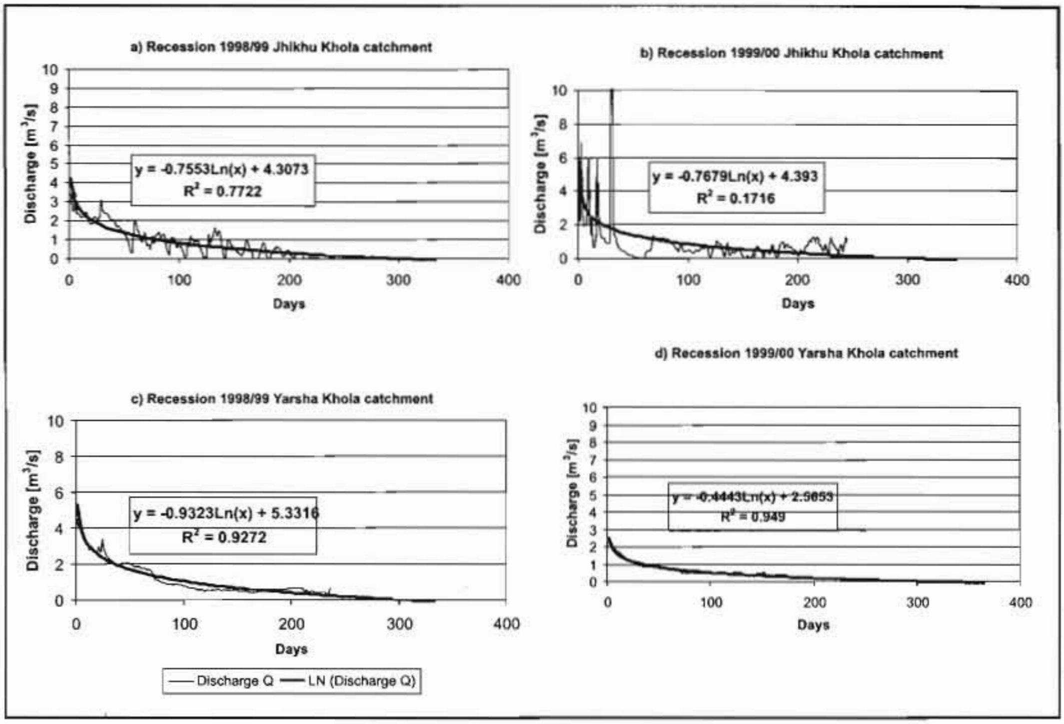

Figure 9.6: **Flow recession curves in the Jhikhu Khola catchment: a) 1998/1999 dry season, b) 1999/2000 dry season; and for the Yarsha Khola catchment: c) 1998/1999 dry season, and d) 1999/2000 dry season.**

Water demand for domestic use is low in the study catchments. On average respondents in the Jhikhu Khola only use 23.2 litres per day of water (Table 9.2). In the Yarsha Khola catchment water use was estimated at 21.1 litres per person per day. These demands are about half of the 45 litres of water per person per day as estimated by HMGN's Department of Water Supply and Sewerage (RWSSSP 1994). This value includes 20% for losses and wastage. On the basis of these water use values, overall water demand for domestic use per year was calculated at about 413,000 m³ (~4 mm) of water in the Jhikhu Khola and 159,000 m³ (~ 3 mm) of water in the Yarsha Khola catchment.

This amount of water use is above average in comparison with the estimated average figures for Nepal of 12 litres per person per day (Gleick 2000). These amounts mainly include water for drinking, cooking, and food preparation. Other water related activities such as washing and personal hygiene mostly happen directly at watercourses or taps. RWSSSP (1994) estimated the water demand at 45 litres per person per day for areas where piped water is available (usually at tap stands). The estimated amount of water used in areas with difficult access to

Table 9.2: **Annual domestic water needs in the Jhikhu and Yarsha Khola catchments**

Catchment	Population (1996)	Daily water use (litres/person/day)	Annual water use	
			(m³)	(mm)
Jhikhu Khola	48728	23.2	412,629	3.7
Yarsha Khola	20620	21.1	158,805	3.0

water and collection times of more than 15 minutes is 25 litres and in local towns 60 litres per person per day. Gleick (1996) has calculated that individuals need 50 litres of water per day including 5 litres for drinking, 20 litres for sanitation, 15 litres for bathing, and 10 litres for cooking.

The quality of water is equally important as the amount. Schaffner (2003) and Merz et al. (2004) report that hardly any of the water sources in the Jhikhu Khola area are free from microbiological contamination. In addition nitrate and phosphate levels although still below World Health Organization guideline values (WHO 1993), are approaching levels of concern due to increasing fertiliser application.

The yearly cropping cycle in the two catchments are described in Merz et al. (2002). The following water demands were calculated on the basis of these cropping cycles. The theoretical water demand of different crops differs tremendously depending on climatic conditions. The following values assumed average climatic conditions based on the 1993-2000 data from the Jhikhu Khola and 1998-2000 data for the Yarsha Khola catchment. It is important to note that these water requirement values were calculated for maximum yields. It is therefore understood that crops may often use less water leading to lower yields. The impact of water stress on yields can be estimated by using a yield response factor to calculate the actual expected yield on the basis of the estimated yield at times of optimum water supply conditions (Doorenbos et al. 1979). Here optimum water conditions are assumed for maximum growth and yield.

Rice is by far the most demanding crop on irrigated land needing 1400 mm of water per crop. This value corresponds with the values of 1200 to 1800 mm/crop given by ILACO (1981). The impact on annual water resources availability is however limited as this crop is grown during the monsoon season. The recently introduced cash crop tomatoes is the next most demanding with 345 mm. The other main cash crop potatoes, however, requires less water – mainly due to its shorter growing season – than the wheat that was traditionally grown at the same time of the year. It is however important to note that potato crops actually use more water than wheat under the current management practices in irrigated land. This happens due to the drought resistance of wheat compared to potatoes' relative sensitivity to soil water deficits. This causes farmers to keep the soil moist for potatoes, whereas only one to two irrigations are applied to wheat (Doorenbos et al. 1979). On rainfed land the monsoon crop maize has the highest water demand followed by wheat and tomatoes.

A number of different crop rotations exist in the Jhikhu Khola. Pujara and Khanal (2002) identified 10 different crop rotations on irrigated land and 13 on rainfed agricultural land. All the rotations on irrigated land included a rice crop whilst all the rotations on rainfed land included a maize crop. Water use is therefore only given for the major crop rotations identified during this study's water demand and supply survey.

The calculation shows that 1898 mm water is required per $1m^2$ of irrigated land (Table 9.3). Given the 11,141 ha extent of the catchment area, the annual demand for the 1838 ha of irrigated fields is therefore about 313 mm/year. The water demand of the 4267 ha of rainfed areas was calculated at about 349 mm/year.

In the Yarsha Khola the main crops on irrigated land are rice, wheat, and potato. The highest water demanding crop is rice followed by potato and wheat. On rainfed land the traditional crops are maize, millet, wheat and potato with maize demanding the most water. Millet is

Table 9.3: **Water demand of main crop rotations in the Jhikhu Khola catchment**

Rotation	Annual	Monthly
1. Irrigated land		
Rice-potato-maize	1897 mm/12 months	158 mm/month in 12 months
Rice-wheat-maize	2018 mm/12 months	168 mm/month in 12 months
Rice-potato-tomato	1931 mm/12 months	161 mm/month in 12 months
Rice-wheat	1706 mm/10 months	171 mm/month in 10 months
Irrigated land average	1898 mm/yr	165 mm/month in 11.5 months
2. Rainfed land		
Maize-wheat	837 mm/10 months	84 mm/month in 10 months
Maize-tomato	848 mm/7 months	121 mm/month in 7 months
Maize-potato	808 mm/9 months	90 mm/month in 9 months
Maize-mustard-wheat	1050 mm/12 months	88 mm/month in 12 months
Rainfed average	912 mm/yr	96 mm/month in 9.5 months

relayed with the maize crop and requires about 340 mm per crop. The total water demand for the 742 ha of irrigated cropping land in the Yarsha Khola catchment is estimated to be 249 mm/year on the basis of the entire catchment area (Table 9.4). The demand for the 1996 ha of rainfed areas is estimated to be 295 mm/year.

Table 9.4: **Water demand of main crop rotations in the Yarsha Khola catchment**

Rotation	Annual	Monthly
1. Irrigated land		
Rice-wheat	1774 mm/12 months	148 mm/month in 12 months
Rice-potato	1801 mm/11 months	164 mm/month in 11 months
Irrigated land average	11.5 months = 1794 mm/yr	156 mm/month
2. Rainfed land		
Maize-millet	738 mm/yr in 8 months	92 mm/month in 8 months
Maize-millet-wheat	987 mm/yr in 11 months	90 mm/month in 11 months
Maize-potato	672 mm/yr in 10 months	67 mm/month in 10 months
Rainfed land average	789 mm/yr	83 mm/month in 9.5 months

Livestock are a very important part of HKH farming systems and an important factor in calculating water demand. Traditionally livestock were taken to water sources to drink. However, increased stall feeding, especially of buffaloes, but also sometimes goats and cows, means that they are now watered on-site (Merz et al. 2002). The water demand for the animals in Table 9.5 was estimated from a survey conducted in the Jhikhu Khola and the Kathmandu Valley of 23 farmers. The results were verified from the literature on the subject (ILACO 1981). In general the values arrived at are slightly higher than the values in the literature, which is appropriate given the hotter conditions in the Jhikhu Khola catchment than the places in the literature. The annual water demand for livestock in the Jhikhu Khola was estimated at 4.6 mm, while in the Yarsha Khola, where livestock plays a bigger role, water demand was estimated at 6.0 mm (Table 9.5).

Table 9.5: **Water demand for livestock watering in the Jhikhu and Yarsha Khola watersheds**

	Water demand	Jhikhu Khola		Yarsha Khola	
	ltr/day	HH*no. [1]	m^3/day	HH*no. [1]	m^3/day
Buffaloes	61	8002* 1.2	585.7	4362* 1.1	292.7
Bullocks	49	8002* 0.8	313.7	4362* 1.5	320.6
Cows	23	8002* 0.9	165.6	4362* 0.9	90.3
Goats	12	8002* 3.5	336.0	4362* 3.3	1727
Pigs	10	-	-	-	-
Annual water use		511,365 m^3		319,849 m^3	
Annual water use		4.6 mm		6.0 mm	

[1]Number of households (HH) from PARDYP aerial photograph analysis times average number of livestock per household (no.) from Merz et al. (2002)

Working out the domestic, agricultural, and livestock water requirements allowed the study to come up with an overall figure for the amount of water needed in the two catchments. The combined totals give a water demand of 671 mm per annum in the Jhikhu Khola catchment and 553 mm in the Yarsha Khola (Table 9.6). The difference is mainly due to the higher evapotranspiration rates and thus higher crop water requirements in the Jhikhu Khola with a greater demand of about 60 mm/year for its irrigated land and 50 mm/year for its rainfed land. The other components are comparable in the two catchments.

Table 9.6: **Summary of water demands for human consumption in mm**

	Domestic	Agriculture			Total
		Irrigated land	**Rainfed land**	**Livestock**	
Jhikhu Khola	4 (1%)	313 (47%)	349 (52%)	5 (1%)	671
Yarsha Khola	3 (1%)	249 (45%)	295 (53%)	6 (1%)	553

Note: All values are rounded and therefore may add up to more than 100%

Synthesis

The hydrological water balances of the Jhikhu Khola and Yarsha Khola catchments at the catchment outlet points are presented in Figure 9.7. The area monitored at the outlet of the Jhikhu Khola received about 1295 mm rainfall per annum on average during the study period. This amount is depleted by about 869 mm of evapotranspiration and 411 mm of runoff. This means that about 67% of the rainfall is lost through evapotranspiration and 32% by runoff. The balance of 15 mm was probably due to inaccurate measurement of precipitation or runoff, inaccurate interpolation of rainfall or evapotranspiration, or the inaccurate calculation of evapotranspiration. However, the balance only amounts to 1% of the entire rainfall.

In the Yarsha Khola catchment, which receives nearly double the rainfall of the Jhikhu Khola, 2206 mm rainfall was measured on average at the outlet point during the three-year study. Of this input 34% (767mm) was lost through evapotranspiration and 62% (1349 mm) through runoff downstream. The error due to measurement, calculation, or interpolation was 90 mm or 4% of total rainfall.

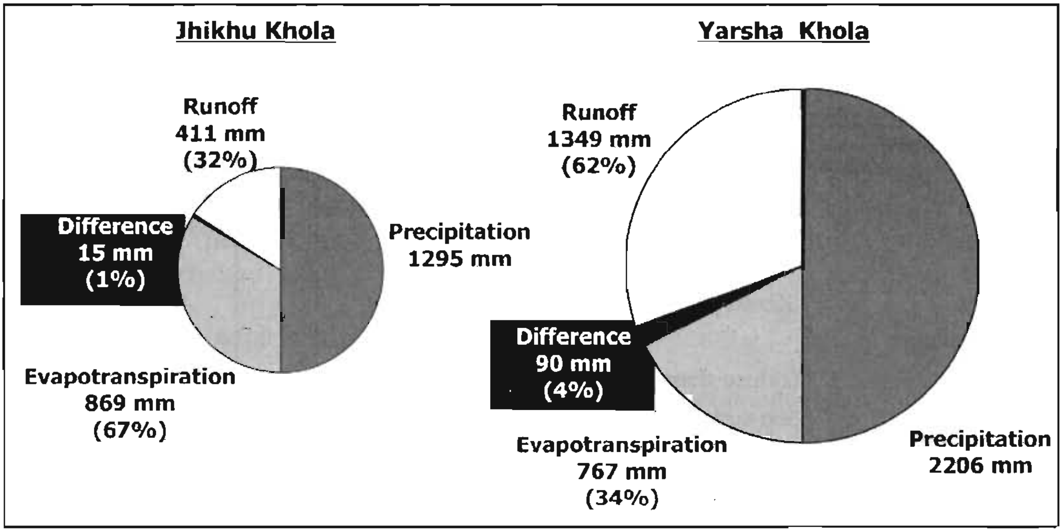

Figure 9.7: **Hydrological water balance of the Jhikhu and Yarsha Khola catchments**

The study found that precipitation accounts for the entire gross inflow in both catchments and it was therefore assumed that there were no ground or soil water storage changes over a one year period.

The results of the water accounting analysis are shown in Table 9.7. Note that the data in this exercise is derived from measured data. Also, the 'available water for agriculture' figure in the calculation is derived from the total water available in the catchment minus the water that is depleted in various ways. Note Box 9.1 provides some useful definitions of the terminology used here.

Box 9.1: **Some water accounting definitions**

- **Gross inflow** is the total inflow into the catchment from precipitation, surface, and subsurface sources.
- **Net inflow** refers to changes in storage in addition to gross inflow.
- **Water depletion** refers to the use or removal of water from the catchment that renders it unavailable for further use, such as through evaporation, flows to sinks, pollution, and incorporation into a product. The water can be process-depleted such as when it is used to produce agricultural crops, energy, or industrial products. Non-process depleted water is the water lost through processes other than for the process it was diverted for such as evaporation from soil and water surfaces and deep percolation in irrigated land.
- **Non-depleted water** is water that is not lost after it has been diverted for a use such as hydropower or for in-stream uses.
- **Committed flow** is the water committed for certain uses such as for fisheries or to downstream rights for irrigation.
- **Uncommitted flow** is water that is neither depleted nor committed and thus available for use within the catchment or for downstream users.

9

Table 9.7: **Water accounting in the Jhikhu Khola and Yarsha Khola catchments**					
Description		**Jhikhu**		**Yarsha**	
		Total	**Parts**	**Total**	**Parts**
1. Gross inflow:		1295		2206	
	Surface diversion		0		0
	Precipitation		1295		2206
	River inflow		0		0
	Sub-surface flow		0		0
Storage change		0		0	
	Surface storage		0		0
	Sub-surface storage		0		0
2. Net inflow		1295		2206	
3. Depletion		886		776	
Process		493		365	
	Irrigation-crop evapotranspiration		484		356
	Municipal and industrial use		9		9
Non-process, beneficial		38		63	
	Irrigation-flows to sinks		38		63
Non-process, beneficial		355		348	
	Home gardens, forest		355		348
Beneficial		848		713	
Low and non-beneficial		38		63	
4. Outflow		411		1349	
	Committed outflow for downstream water rights		0		0
	Committed outflow for environment		0		0
	Uncommitted outflow	411		1349	
	Utilisable		411		1349
	Non-utilisable		0		0
5. Available water at catchment level (net minus committed minus non-usable)		1295		2206	
6. Available water for agriculture		931		1849	
Source: Merz 2004					

In summary the results reveal that:

- there is a net inflow (all from precipitation) of about 1300 mm into the Jhikhu Khola and 2200 mm into the Yarsha Khola catchments per year;
- crop evapotranspiration accounts for about 55% or 484 mm of the total process depletion of 886 mm in the Jhikhu Khola catchment;
- in the Yarsha Khola catchment crop evapotranspiration accounts for 356 mm or 46% of the total 776 mm of depleted water;

- about 40% or 355 mm accounted for non-process evapotranspiration by forests in the Jhikhu Khola and 348mm or 45% in the Yarsha Khola catchment. (Note that evapotranspiration is a beneficial depletion as this water goes to producing biomass);
- only 38 mm or 4% are non-process depleted meaning that it is lost without benefit to the users in the Jhikhu Khola catchment, mainly through evaporation from free soil surfaces and water bodies. In the Yarsha Khola this portion accounts for 8% or 63 mm; and
- all outflows from the catchments are usable and not committed to any downstream agreements. They provide a potential source of additional water for the people residing near the catchment outlets.

Merz (2004) gives a full account of these calculations.

The difference between the two catchments in terms of uncommitted flow as well as the percentage of beneficial depletion (the water required to produce biomass and crops) is evident. In the Yarsha Khola catchment more than 60% of the gross inflow is contributing to uncommitted flow suggesting that ample water is available in the catchment for further development of agricultural or other business activities that use water. In the Jhikhu Khola uncommitted flow amounts to only about 30% of the gross inflow. It is however important to note that these are annual values and include monsoon flows. During the dry season the uncommitted flow is reduced to a minimum in the Jhikhu Khola catchment and accounts for only about 7 mm in the driest months of March and April. In the Yarsha Khola catchment the uncommitted flow in February, the driest month is 20 mm.

The results of this water accounting exercise show that in both catchments there is more water available to be used and it could be used more efficiently. However, during the dry season there is little scope to improve water use efficiency in the Jhikhu Khola as there is already a high degree of beneficial depletion mostly for biomass and crop production accounting for 85% of the available water and hardly any uncommitted outflows. There is scope to better use monsoon waters. In the Yarsha Khola catchment, even during the dry season months there is scope to increase the beneficial depletion with increased biomass and crop production as there is a high outflow and low process depletion (productive use of the available water resources). This could be achieved by increasing the irrigated area or applying more irrigation water to more demanding crops.

Future Water Availability

Increasing water demands from the growing world population and higher per capita water use are putting ever greater demands on the world's limited water resources. The uncertain effect of global climate change is another important factor with potentially serious implications for the world's water resources. For example, Lal (2002) projects decreasing winter rainfall and increased monsoon rainfall during the monsoon for the Indian sub-continent (Table 9.8). Lal projects a decrease of 10 to 20% in winter rainfall by the year 2050 leading to an about 25% decrease by 2080. The same author projects an increase of 30% or more in monsoon precipitation over India. He further suggests that there will be an increased variability in the onset of the monsoon. However,

Table 9.8: **Projected climate change parameters for the Indian sub-continent, 1980- 2080**

	Temperature	Precipitation
Annual	+5.6 °C	+9.9%
Winter	+6.3 °C	-25%
Monsoon	+4.6 °C	+15%

Source: Lal (2002)

there is conflicting information on the basis of different global circulation models (GCM). Lal et al. (1995) calculated a decline in mean summer monsoon rainfall of about 0.5 mm/day over the South Asian region by 2080. Experiments referred to in IPCC (1998) also suggest that a decline in summer monsoon rainfall will happen or may have already happened.

The Precipitation-Runoff-Evapotranspiration-Hydrotope (PREVAH) computer simulation model (Gurtz et al. 1997) was applied to assess the potential impact of the climate change scenario discussed above. The scenario was assessed on the basis of the data for 1997 to 1999. Overall the simulations show that, on a seasonal basis, runoff from the Jhikhu Khola catchment could well increase for the monsoon season and decrease in the remaining seasons, particularly in the pre-monsoon season (Figure 9.8). The PREVAH model predicts that potential evapotranspiration will increase by about 40% in the Jhikhu Khola catchment from 1990 to 2080 if climate changes according to Lal's projections. The actual evapotranspiration rates would change by about 10% annually. As these figures are only preliminary due to inadequate vegetation datasets no further disaggregation into different months or seasons can be worked out although this would be of particular interest for different areas of the catchments. It is notable that water availability is projected to decrease in the seasons when water is already scarce.

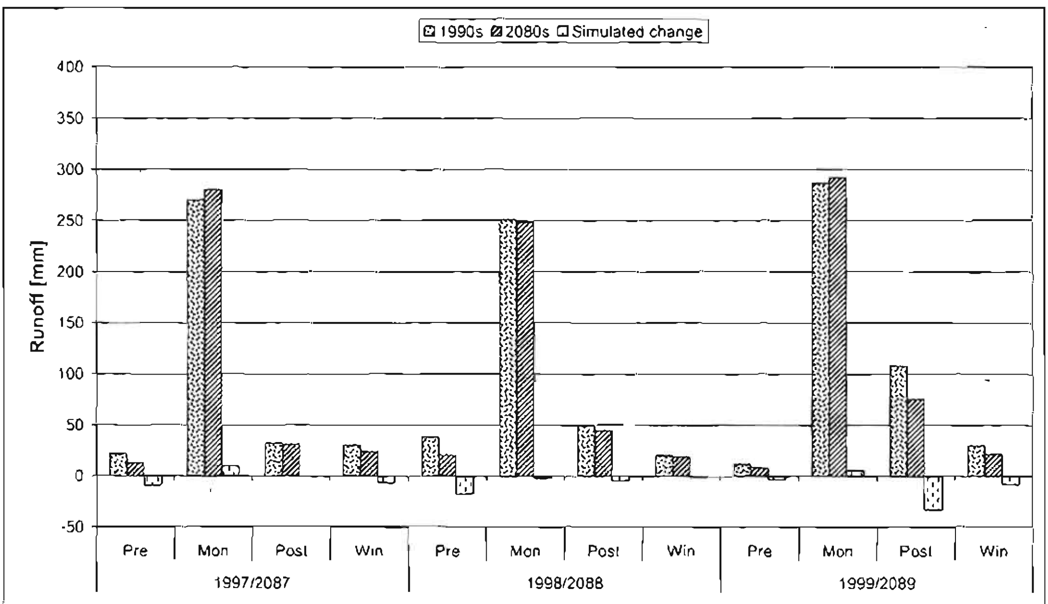

Figure 9.8: **Seasonal changes of runoff from the Jhikhu Khola catchment with global climate change determined by applying PREVAH model** (Merz 2004)

Lutz and Goujon (2002) have projected the population of Nepal according to high fertility and low fertility growth scenarios. Using these figures and an estimated daily water demand of 50 litres per person for basic domestic water needs (Gleick 1996), the forecasted water needs in the Jhikhu Khola catchment by the 2080s ranges between 14 and 25 mm (Table 9.9).

Village development committees (VDC) are the village level administrative units in Nepal. The disaggregated water demand information according to VDCs in the Jhikhu Khola catchment predicts the highest increases in water demand at VDCs along the main Araniko and

Table 9.9: **Projected population and water demand in the Jhikhu Khola catchment by 2080**

	1996	2080 Low fertility	2080 High fertility
Population	48,728	85,646	150,238
Population density [people/km²]	437	769	1349
Annual water demand [mm]	3.7	14.0	24.6

Dhulikhel–Bardibas highways as the population grows and development happens there (Figure 9.9). In 1996 the water demand in all Jhikhu Khola VDCs was between 0-15 mm per year. The water demand to cover basic requirements under the low fertility scenario would shoot up to 15-30 mm in the VDCs that lie along the two highways and up to 15 mm in the other VDCs. In the high fertility scenario Rabi Opi, Paanchkhal, Patlekhet, Dhulikhel and Phoolbari VDCs would demand 30-45 mm per annum. Comparing these values with the annual precipitation values, or even the monthly precipitation values, would mean there would still be adequate water available for domestic purposes in 2080. However, so far in this area the local population do not generally use rainwater for domestic purposes and rely on surface water or shallow groundwater. In this respect the increasing pollution, as observed in the Jhikhu Khola catchment (Merz et al. 2004), would put further pressure on available water resources and local people would come to depend even more on the few clean and non-polluted water sources. In addition as mentioned above, the agricultural water demand is far more significant.

With the current high level of agricultural intensity in the catchment, agricultural expansion is only possible by bringing marginal lands under production.

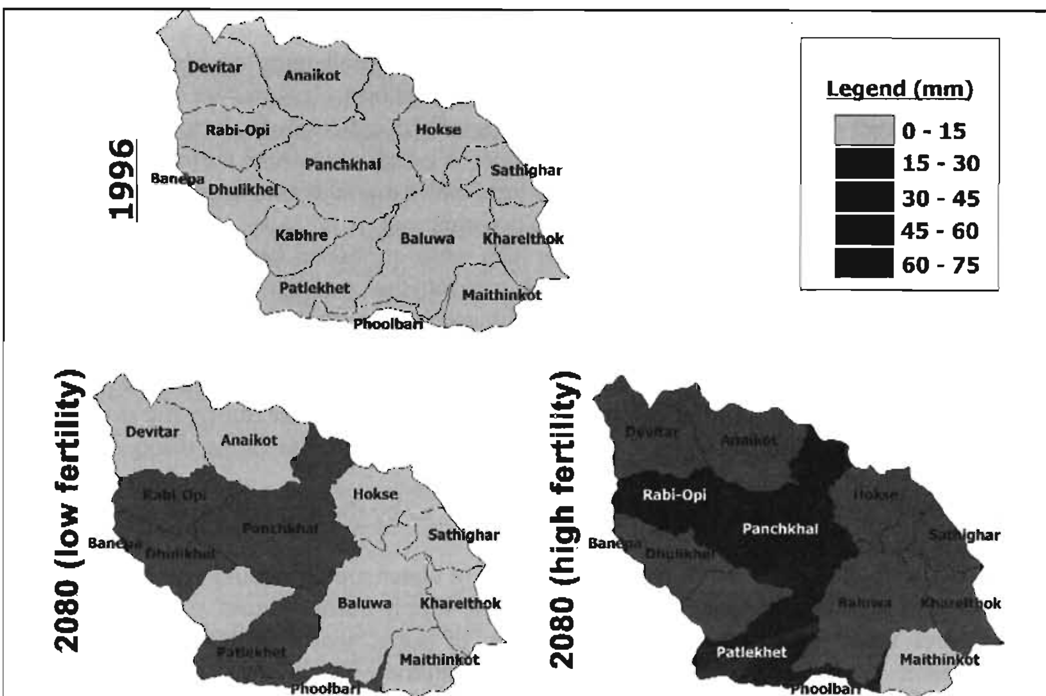

Figure 9.9: **Projected water demand 1996-2080 in Jhikhu Khola VDCs**

In summary:

- water demand for domestic purposes will increase with population growth;
- the main water demand increase is not expected from population growth, but will come about to meet Gleick's (1996) estimated basic water supply need of 50 litres per person per day; and
- the main water demand increase in the Jhikhu Khola catchment is most likely to come in the areas along the two highways that cross the catchment. The VDCs in the upper part along the catchment divide will have an important function as recharge areas and water supply for the valley bottoms and areas near the catchment outlet. This stresses the importance of local level planning and management of the water resources at the catchment level.

Conclusion

This study has found that the two middle mountain catchments have enough annual rainfall, as indicated by the high rainfall amounts and the considerable runoff that leaves the catchments. The accounting exercise showed that the current agricultural, domestic and livestock water requirements can be easily met. During the dry season water is sometimes scarce in parts of the catchments and sometimes even over the whole catchment areas. But, on average, even during this time, there is adequate water from groundwater sources to produce surpluses that leave the catchment as uncommitted flow. There are, however, pocket areas in the catchment that face considerable water shortages. These are the areas along the catchment divide and on spurs and river terraces. In addition, due to seasonal differences in water availability, there is not much scope to expand agricultural activities during the dry season months as long as approaches and technologies remain the same. This study has also shown that water demands are very likely to increase. Projected climate changes will reduce the amount of water available during the dry season.

The findings of this and other studies suggest that the main challenges in water management in rural catchments of Nepal's middle mountains are as follows.

- The improved management of water resources will be critical in the future. Although at present the overall availability of natural water is adequate, water shortages are being observed. This suggests that in some places local water management is not coping with the supply and demand situation and needs to be improved.
- Initiatives need to be taken to balance the high water monsoon surpluses with low water availability in the dry season. This would prolong the growing season and allow for increased food production. This could be achieved by monsoon water storage in the soil profile in cisterns or ponds. The artificial recharge of areas that do not get saturated during the monsoon is another option by artificially charging unsaturated soil profiles or other potential aquifers with monsoon runoff that can be extracted later during the dry season. Water stored into the dry season can be applied to high value crops using alternative irrigation methods such as drip or sprinkler irrigation.
- Alternative water sources should be explored, such as by digging wells and exploiting the shallow groundwater.
- The decentralised and community management of water supplies could improve access to water resources and improve maintenance of the supply infrastructure.
- Measures need taking to improve the quality of public water supplies. These include catchment protection, source protection, and alternative methods for making water suitable for consumption. PARDYP is testing the SODIS system of purifying drinking water by exposure to the sun (Wegelin and Meierhofer 2002).

- Overall, water resources should be managed catchment-wise rather than by administrative units that often cut catchments into different sections. This would promote the sustainable use of existing and seasonally replenishing water resources to satisfy the needs of upstream and downstream users.

Acknowledgements

The authors would like to acknowledge the support of their colleagues in the PARDYP Nepal team. The comments of Roger White, Suresh Chalise, and Richard Heggen were greatly appreciated and helped to improve the manuscript.

References

Adhikari, T.R.; Upadhayay, B.P.; Dhakal, M.P.; Dangol, P.M.; Shrestha, S.; Nakarmi, G.; Prajapati-Merz, B.; Jha, P.C. (2003) 'Sustainable Water Management in the Jhikhu Khola Catchment.' In Domroes, M. (ed.) *Translating Development – The case of Nepal*, pp. 47–78. New Delhi: Social Science Press

Agarwal, A.; Narain, S. (eds.) (1991) *Floods, Flood Plains and Environmental Myths. State of India's Environment Report 3*. New Delhi: Centre for Science and Environment

Alford, D. (1992) *Hydrological Aspects of the Himalayan Region*. Occasional Paper No. 18. Kathmandu: ICIMOD

Chalise, S.R. (2000) 'Water Resources Management in the HKH: An Overview.' In Banskota, M.; Chalise, S.R. (Eds.) *Waters of Life. Perspectives of Water Harvesting in the Hindu Kush-Himalayas*. Kathmandu: ICIMOD

Chalise, S.R.; Bhatta, B.R.; Shengji, P.; Shah, P.B.; Gurung, J.D. (1993) *Natural Resources Management in a Mountain Environment. ICIMOD 10th Anniversary Symposium on Mountain Environment and Development – Constraints and Opportunities*. Kathmandu: ICIMOD

Chalise, S.R.; Khanal, N.R. (2002) 'Recent Extreme Weather Events in the Nepal Himalayas.' In Snorrason, A.; Finnsdottir, H.P.; Moss, M.E. (eds.) *The Extremes of the Extremes: Extraordinary Floods. Proceedings of a Symposium held in Reykjavik*, July 2000, pp. 141-146. Publication no. 271. Wallingford: IAHS

Chalise, S.R.; Shrestha, M.L.; Thapa, K.B.; Shrestha, B.R.; Bajracharya, B. (1996) *Climatic and Hydrological Atlas of Nepal*. Kathmandu: ICIMOD

Dangol P. M.; Dongol, B.S.; Dhakal, M.P; Merz J.; Jehangir, M.; Zokaib S.; Verma, P.K.; Joshi, B.K.; Ma, X.; Fu, G. (2005) 'Water Resources Dynamics: A Comparison of Five Watersheds in the Hindu Kush-Himalayas'. In White, R.: Bhuchar, S.; Keeling, S.J. (eds) *Resource Constraints and Management Options in Mountain Watersheds of the Himalayas*. Kathmandu: ICIMOD

Doorenbos, J.; Kassam, A.H.; Bentvelsen, C.L.M.; Branscheid, V.; Plusje, J.M.G.A., Smith, M.; Uittenbogaard, G.O.; Van der Wal, H.K. (1979) *Yield Response to Water. FAO Irrigation and Drainage Paper No. 33*. Rome: FAO

FAO (1977) *Crop Water Requirements. FAO Irrigation and Drainage Paper No. 24*. Rome: FAO

FAO (1998) *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. Irrigation and Drainage paper 56*. Rome: FAO

Galay, V.; Schreier, H.; Bestbier, R. (2001) *Himalayan Sediments. Issues and Guidelines. CD-ROM*. Vancouver: Canadian International Development Agency and Canadian International Water and Energy Consultants

Gardner, R.; Mawdesley, K.; Tripathi, B.; Gaskin, S.; Adams, S. (2000) *Soil Erosion and Nutrient Loss in the Middle Hills of Nepal (1996–1998)*. Kathmandu and London: NARC and Queen Mary and Westfield College, University of London

Gleick, P.H. (1996) 'Basic Water Requirements for Human Activities: Meeting Basic Needs.' *Water International*, 21(1): pp. 83-92

Gleick, P.H. (2000) *The World's Water 2000–2001*. Washington: Island Press

Gurtz, J.; Baltensweiler, A.; Lang, H.; Menzel, L.; Schulla, J. (1997) *Auswirkungen von Klimatischen Variationen auf Wasserhaushalt und Abfluss im Flussgebiet des Rheins*. Zuerich: vdf Hochschulverlag, ETH Zuerich

Gustard, A.; Bullock, A.; Dixon, J.M. (1992) *Low Flow Estimation in the United Kingdom. Report No. 108*. Wallingford: Institute of Hydrology

Hofer, T. (1998) 'Floods in Bangladesh – A Highland-Lowland Interaction?' *Geographica Bernensia G48*. Berne: Institute of Geography, University of Berne

ILACO (1981) *Agricultural Compendium for Rural Development in the Tropics and Subtropics*. Amsterdam: Elsevier Scientific Publishing Company

IPCC (1998) *The Regional Impacts of Climate Change – An Assessment of Vulnerability*. Cambridge: Cambridge University Press

Jehangir, M.; Zokaib Z.; Merz J.; Dangol, P.M.; Dhakal, M.P.; Dongol, B.S.; Nakarmi, G.; Joshi, B.K.; Verma, P.K.; Gao, Fu; Xing, Ma (2005) 'Assessment of Runoff and Soil Loss in the Hindu Kush-Himalayan Region' In White, R.; Bhuchar, S.; Keeling, S.J. (eds) *Resource Constraints and Management Options in Mountain Watersheds of the Himalayas*. Kathmandu: ICIMOD

Kansakar, D.R. (2001) 'Groundwater Resources in the Hills and Mountain Regions of Nepal.' Paper presented at the Workshop on Groundwater Resource Management, Kathmandu 20 December 2001 (mimeo)

Lal, M.; Cubasch, U.; Voss, R.; Waszkewitz, J. (1995) *Effect of Transient Increase in Greenhouse Gases and Sulphate Aerosols on Monsoon Climate. Current Science* 69(9): pp. 752–763

Lal, M. (2002) *Possible Impacts of Global Climate Change on Water Availability in India. Report to Global Environment and Energy in the 21st Century*. New Delhi: Indian Institute of Technology

Lambert, L.; Chitrakar, B.D. (1989) 'Variation of Potential Evapotranspiration with Elevation in Nepal.' *Mountain Research and Development* 9(2): 129-144

Liniger, H.P.; Weingartner, R.; Grosjean, M. (1998) *Mountains of the World: Water Towers for the 21st Century*. Bern: Mountain Agenda

Lutz, W.; Goujon, A. (2002) *Unpublished Downscaling of Regional Population Projections to Country-level for the SRES A1, B1 and A2 Scenarios Corresponding to IPCC SRES Report, 1990-2100*. Laxenburg: International Institute for Applied Systems Analysis (IIASA). (Available at http://sres.ciesin.columbia.edu/tgcia/ and www.iiasa.ac.at/Research/POP/IPCC/index.html).

MacDonald & Partners (1990) *Design Manuals for Irrigation Projects in Nepal. Planning and Design Strengthening Project*. Kathmandu: His Majesties Government of Nepal, Ministry of Water Resources

Merz, J. (2004) *Water Balances, Floods and Sediment Transport in the Hindu Kush-Himalayan region. Geographica Bernensia G72*. Bern, Switzerland: Institute of Geography, University of Berne

Merz, J.; Nakarmi, G.; Shrestha, S.; Shrestha, B.; Shah, P.B.; Weingartner, R. (2002) *Water and Erosion Studies of PARDYP Nepal: Water Demand and Supply Survey. Brochure with CD-ROM*. Kathmandu: ICIMOD

Merz, J.; Nakarmi, G.; Shrestha, S.K.; Dahal, B.M.; Dangol, P.M.; Dhakal, M.P.; Dongol, B.S.; Sharma, S.; Shah, P.B.; Weingartner, R. (2003) 'Water: a Scarce Resource in Rural Catchments of Nepal's Middle Mountains.' In *Mountain Research and Development*, 23(1): 41-49

Merz, J.; Nakarmi, G.; Shrestha, S.K.; Dahal, B.M.; Dongol, B.S.; Schaffner, M.; Shakya, S; Sharma, S.; Weingartner, R. (2004) 'Public Water Sources in Rural Catchments of Nepal's Middle Mountains – Issues and Constraints.' In *Environmental Management*, 34(1): 26 - 37

Miah, M.M. (1988) *Flood in Bangladesh: A Hydromorphological Study of the 1987 Flood*. Dhaka: Academic Publishers

Mosley, M.P.; Pearson, C. (1997) 'Introduction: Hydrological Extremes and Climate in New Zealand'. In, Mosley, M.P.; Pearson, C. (eds) *Floods and Droughts: the New Zealand Experience*, pp 1-14. Wellington: New Zealand Hydrological Society

Pujara, D.S.; Khanal, N.R. (2002) 'Use of Pesticides in Jaishidihi Sub-catchment, Jhikhu Khola Catchment, Middle Mountain in Nepal.' In Herrmann, A.; Schumann, S. (eds.) *International Workshop on Environmental Risk Assessment of Pesticides and Integrated Pesticide Management in Developing Countries*. Heft 38. Braunschweig: Institut fuer Geooekologie, Technsiche Universitaet Braunschweig

RWSSSP (1994) *Palpa District – Water Supply and Sanitation Development Plan* (Draft). Kathmandu: Department of Water Supply and Sewerage, HMG/Ministry of Housing and Physical Planning

Schaffner, M. (2003) *Drinking Water Quality Assessment and Improvement in the Jhikhu Khola Watershed, Nepal*. Publikation Gewaesserkunde Nr. 281. Berne: University of Berne

Scherr, S.J.; Yadav, S. (1996) *Land Degradation in the Developing World: Implications for Food, Agriculture, and the Environment to 2020. Food, Agriculture and the Environment Discussion Paper 14*. Washington: International Food Policy Research Institute

Subba, B. (2001) *Himalayan Waters*. Kathmandu: Panos Institute

Tahal Consulting Engineers (2002) *Technical Report No. 4 Meteorological Study. Nepal Irrigation Sector Project*. Kathmandu: Department of Hydrology and Meteorology, Ministry of Science and Technology

The PARDYP Teams (2005) 'The PARDYP Project's Five Watersheds and Six Components'. In In: White, R.: Bhuchar, S.; Keeling, S.J. (eds) *Resource Constraints and Management Options in Mountain Watersheds of the Himalayas*. Kathmandu: ICIMOD

Wegelin, M.; Meierhofer, R. (2002) 'SODIS – A New Method Gradually Used Worldwide to Improve the Drinking Water Quality.' *SANDEC News 5*, June 2002. Duebendorf: EAWAG/SANDEC

WHO (1993) *Guidelines for Drinking Water Quality. Volume 1: Recommendations, 2nd Edition*. Geneva: World Health Organisation