7

Water Resource Dynamics: A Comparison of Five Watersheds in the Hindu Kush-Himalayas

Pradeep Dangol[1], Bhawani S. Dongol[1], Madhav P. Dhakal[1], Juerg Merz[2], Mohammad Jehangir[3], Suhail Zokaib[3], Padma K Verma[4], Basant K. Joshi[4], Xing Ma[5], Gao Fu[5]

[1] ICIMOD, Kathmandu, Nepal (PARDYP-Nepal)

[2] Hydrology Group, Department of Geography, University of Berne, Berne, Switzerland

[3] Pakistan Forest Institute, Peshawar, Pakistan (PARDYP-Pakistan)

[4] G.B. Pant Institute for Himalayan Environment and Development, Almora, India (PARDYP-India)

[5] Kunming Institute of Botany, Kunming, China (PARDYP-China)

Abstract

PARDYP is a regional research for development watershed and natural resources management project. Much of its work focuses on water and sediment-related issues in the heavily populated areas of five watersheds of the HKH middle mountains. This paper presents the project's findings on the water resource dynamics in these watersheds. PARDYP set up a network of measuring stations to provide long-term hydrological and meteorological data to better understand the situation of water availability in the region. This network is making an important contribution to compiling and sharing information across the region to promote the better management of water resources and address water scarcity problems. This paper presents the main findings from measuring the rainfall, runoff, soil loss, high flow, and low flow patterns in the PARDYP watersheds. Unsurprisingly it was found that much of the rainfall occurs during the monsoon period. Measurements from erosion plots show that degraded and grass lands yield more runoff than agricultural land. On degraded and grassland plots rainfall events of 3 mm generated runoff whereas on rainfed agriculture plots events of 5 mm were needed to generate runoff. In many cases high flow events at plot level were found to lead to high discharges at sub-watershed and watershed level. In all five watersheds more than 80% of soil loss occurred in the April to September period for all land use types reaching a maximum of 10 t/ha in a single event from degraded land. All five watersheds had low flow situations over more than half the year.

Introduction

The Hindu-Kush Himalayas (HKH) are a huge source of water. Resource degradation and unmanaged land use are key problems in the middle mountains of the HKH. Land use changes are influencing the area's water resources. Demand is rising due to increasing population, agricultural intensification, and changing lifestyles. Most agriculture in the area relies on seasonal rainfall. This varies with monsoon high flows and associated high rates of soil erosion, and water scarcities during the dry seasons. Dry season shortages of irrigation and drinking water are the major water related issues in the region (PARDYP 2002). A good network of stations is essential to provide long-term hydrological and meteorological data to better understand the water availability situation. This did not exist prior to PARDYP and available datasets had not been analysed scientifically. Additionally, there was little regional cooperation to exchange knowledge and experiences to help better manage water resources and solve water scarcity problems.

Study Area

The People and Resource Dynamics of Mountain Watersheds in the Hindu Kush-Himalayas (PARDYP) project is a regional research for development project that focuses on watershed and natural resources management issues including water and sediment-related issues in the heavily populated areas of the middle mountains of the Hindu-Kush Himalayas. The project has generated considerable hydro-meteorological and soil erosion data that can be analysed and compared to better understand the water resource dynamics of the region.

The project is being implemented in the five watersheds of Xizhuang in China, Bheta Gad in India, Hilkot in Pakistan, and Yarsha Khola and Jhikhu Khola in Nepal (see PARDYP Teams 2005 in this volume for watershed descriptions).

Methodology

A network of meteorological, hydrological stations and erosion plots was established in the Jhikhu Khola watershed, central Nepal in 1992. This network has been continuously upgraded since then. Other networks were established in the Xizhuang, Bheta Gad, Hilkot, and Yarsha Khola watersheds in mid-1997. The networks were set up as nested series of networks from plot to watershed level in all five watersheds as described by Hofer (1998).

Information is generated at plot, sub-watershed, watershed, and regional levels. Rainfall data is derived from 8-inch diameter tipping buckets of 0.2 mm capacity per tip, and each event of 0.2 mm has been recorded on a HOBO data logger except in Xizhuang watershed. Symphonic rain gauges are used in Xizhuang. Data is crosschecked with observations from ordinary daily storage rain gauges. At hydrometric stations, water levels are measured by pressure transducers (digital) and floaters (analogue). The people responsible for taking these readings crosscheck them each day against readings from staff gauges. Discharge measurements are taken from streams and rivers at different water levels using current meters, the salt dilution method, and tracers. Based on these measurements, rating curves are developed that give the relationship between water level and discharge. The HYMOS software is used to develop rating curves of water level against discharge and to compute the discharge at various water levels. Erosion plots of between 50 and 100m^2 in size were established on areas of degraded, agriculture, and grassland. The station readers collect the sediment washed from the erosion plots into the drums after each significant rainfall event.

Hilkot watershed, Pakistan has a complete dataset for 2000-2002, Bheta Gad for 1999-2002, Jhikhu Khola for 1993-2002, Yarsha Khola for 1998-mid 2001 and Xizhuang for 1999-2002. These datasets have been compiled by PARDYP and are available as yearbooks in hard and soft copy formats from the PARDYP partner organisations (for example see GBPIHED 2003). The number of hydrological stations, meteorological stations, and erosion plots in PARDYP's watersheds are given in Table 7.1 and the seasonal climatic conditions in Figure 7.1.

Results and Discussion

Rainfall patterns

All five watersheds have excessive rainfall during the monsoon seasons causing high flows and surface erosion. They have generally low amounts of rainfall over the rest of the year. The Yarsha Khola and Xizhuang watersheds receive the most rainfall whilst Pakistan's Hilkot watershed receives the least.

Table 7.1: **Measurement sites in the five PARDYP watersheds (as of 2002)**

Watershed	Hydrological stations	Meteorological stations	Erosion plots
Xizhuang	5	10	6
Bheta Gad	6	5	4
Jhikhu Khola	5	10	7
Yarsha Khola	6	11	4
Hilkot	5	6	4

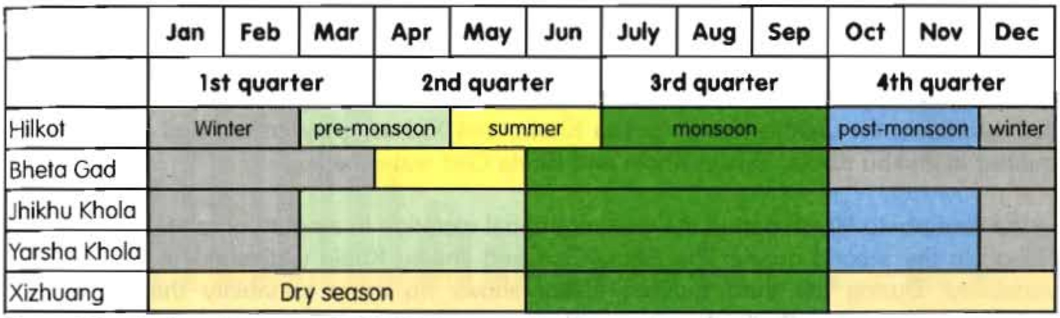

Figure 7.1: **Timing of seasons in PARDYP's watersheds**

Most rainfall occurs between May to October in all the watersheds with only small amounts the rest of the year (Figure 7.2). Yarsha Khola has the highest rainfall in any one month (July). Overall, the most rainfall occurs in July and August except for Xizhuang where it is highest in September. The most winter rainfall occurs in the Hilkot and Bheta Gad watersheds. In Hilkot much of the winter precipitation falls as snow.

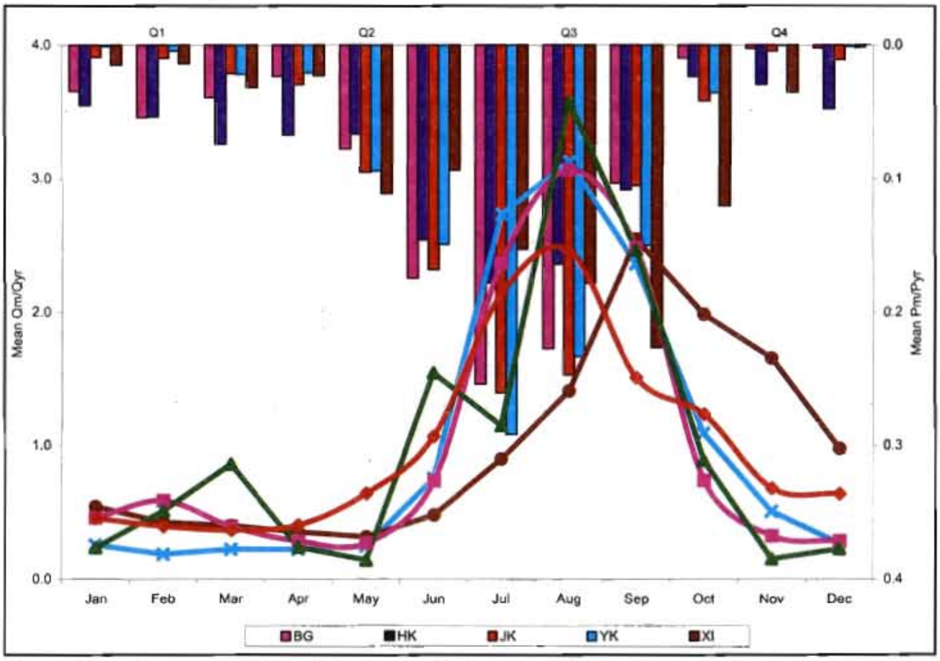

Figure 7.2: **Mean monthly rainfall and discharge at the main hydrological and meteorological stations, five PARDYP watersheds, 1997-2002**

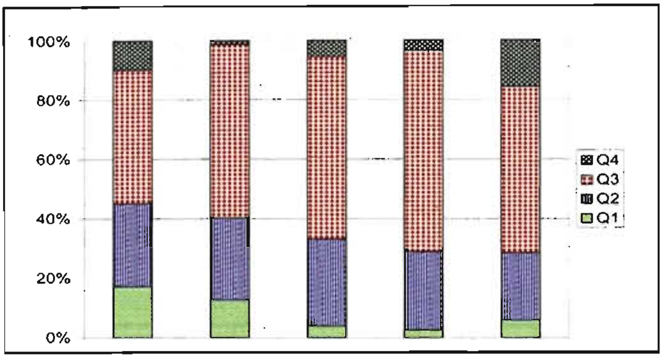

Figure 7.3: **Quarterly distribution of rainfall at the main PARDYP meteorological stations**

More than 60% of rainfall occurs in the third quarter of the year in all watersheds except for Hilkot where only about 40% occurs in this period (Figure 7.3). Very little rainfall occurs in the first quarter in the Jhikhu Khola, Yarsha Khola, and Xizhuang watershed and in the fourth quarter in Jhikhu Khola, Yarsha Khola and Bheta Gad watersheds.

In the January to March period the greatest annual variation in amount of rainfall occurred in Hilkot. In the second quarter the Bheta Gad and Jhikhu Khola watersheds have the most variability. During the third quarter, Hilkot shows no more variability than the other watersheds. In the fourth quarter, Jhikhu Khola and Bheta Gad have the most variability.

Rainfall runoff

The project recorded the number of rainfall events where significant amounts of rainfall fell in order to be able to trace the soil loss and discharge patterns. To analyse the recorded rainfall runoff events, the amount of rainfall in each runoff event was measured and then these measurements were put into 8 mm class intervals. This showed that the most events gave 8-16 mm of rainfall runoff accounting for about 30% of all events (Figure 7.4). For class intervals of rainfall below 8 mm, the frequencies for the generation of runoff was highest in the eastern-most watershed (Xizhuang) whereas for the 16 to 24 mm class the highest readings were in the western-most watershed (Hilkot) and the lowest in the eastern-most. The data shows that the higher the rainfall class then the less the number of events.

Number of runoff events

The number of runoff events were measured from the degraded, agricultural, and grassland erosion plots. The number of such events in the first quarters (January to March) amounted for only less than 10% of all runoff events for all the kinds of land use plots in all five watersheds. In the second quarter (April-June), the number of events amounted to between 20 and 30% on all plot types except for the Yarsha Khola degraded land plots. The third quarter (July-September) accounted for about 60% of runoff events except for Hilkot watershed. Less than 8% of runoff events occurred in the fourth quarter (Oct-Dec) except for Xizhuang watershed, when about 14% of runoff events were recorded (Figure 7.5).

Pattern of runoff

The five watersheds have monsoon climates with most rainfall occurring between June and September. High intensity pre-monsoon and monsoon rainfall causes most of the annual rainfall runoff across all the land use plots in all the watersheds. In Yarsha Khola and Jhikhu Khola watershed more than 92% runoff, in Bheta Gad and Xizhuang more than 85%, and in Hilkot more than 75% of total runoff occurred in the April to September period (Figure 7.6).

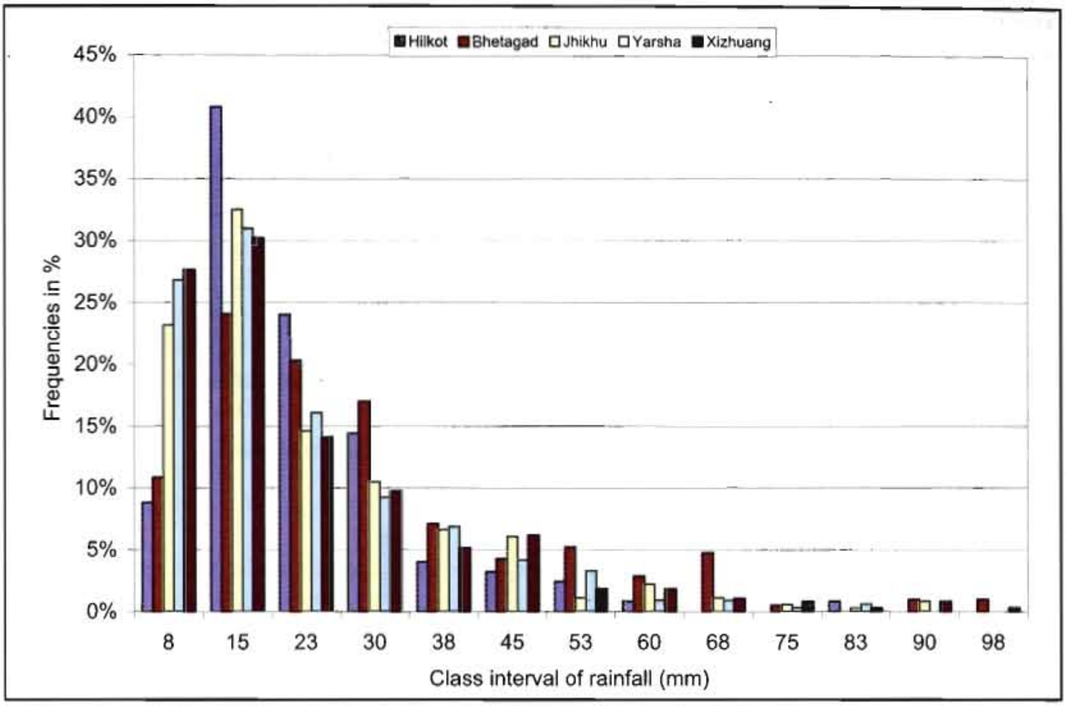

Figure 7.4: **Rainfall frequency which generates runoff on erosion plots**

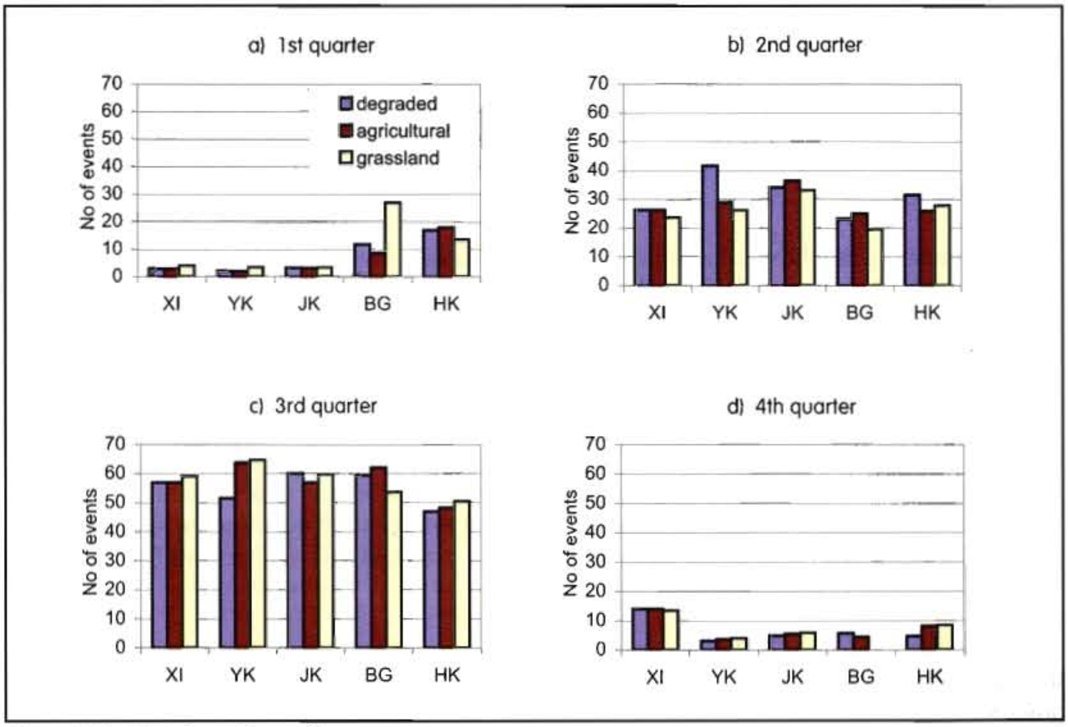

Figure 7.5: **Number of runoff events per quarter**

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The most runoff was measured in the Yarsha Khola and Jhikhu Khola watershed for all three types of erosion plots. The amount was very low in the Bheta Gad and Hilkot watersheds probably due to their lower amounts of rainfall.

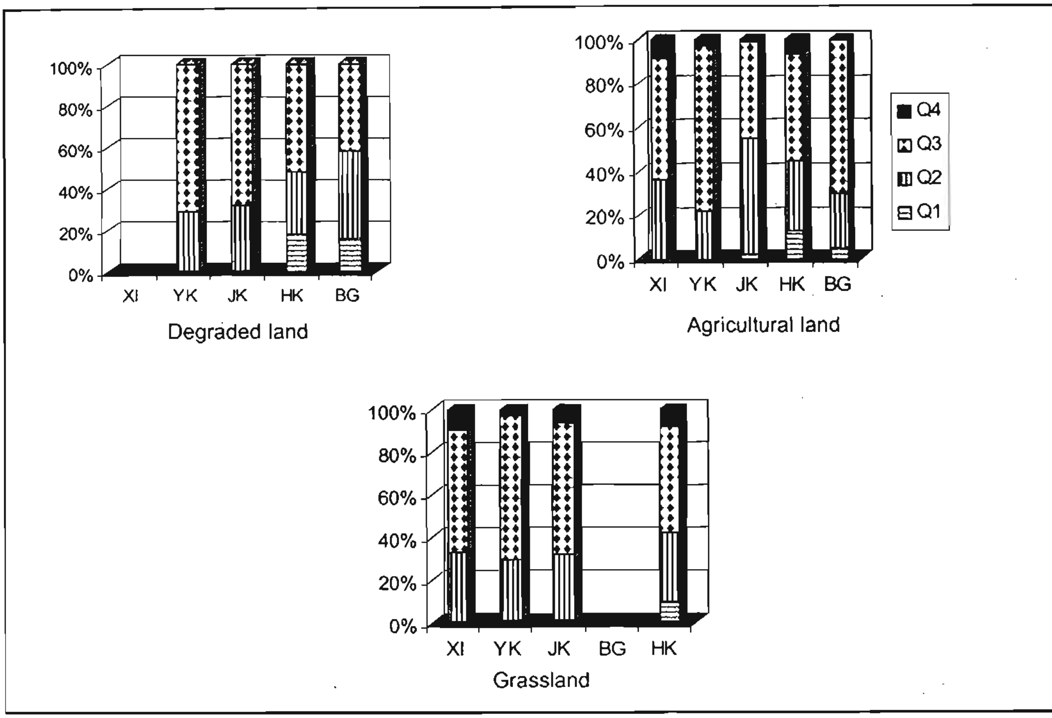

Figure 7.6: **Distribution of runoff on degraded land, agricultural land, and grassland plots**

The amounts of runoff varied between the different types of erosion plots. The highest annual rates were recorded on the degraded land plots in Jhikhu Khola watershed where it reached up to 6740 m^3/ha/yr. The runoff from the Hilkot and Bheta Gad degraded plots was only about 500 m^3/ha/yr.

In the grassland plots the most annual runoff was recorded from the Jhikhu Khola and Yarsha Khola watersheds with over 7000 m^3/ha. The lowest amounts occurred at Hilkot with 226-436 m^3/ha/yr. Annual runoff from the agriculture land plots was the highest in the Yarsha Khola watersheds (4587 m^3/ha/yr). The runoff in the Jhikhu Khola and Bheta Gad watersheds was low, with only 50 and 61 m^3/ha/yr of annual runoff recorded.

Biggest runoff events

Big rainfall runoff events were associated with a major portion of total annual runoff in all three land use type plots in all watersheds. The largest single runoff events were recorded from the Jhikhu Khola with 588 m^3/ha from the grassland plot and 561 m^3/ha from the degraded plot.

About six events of over 300 m^3/ha were recorded on the degraded and grassland plots from the two Nepal watersheds. The largest event in the Yarsha Khola was 320 m^3/ha on the grassland plot. The largest event recorded from Hilkot was only 80 m^3/ha on its grassland plot and the largest from Bheta Gad was from its degraded land plot at around 300 m^3/ha with very little runoff from the agricultural plot. The largest runoff events on the Xizhuang watershed were much less than those recorded from the Yarsha Khola, Jhikhu Khola and Bheta Gad watersheds.

Runoff from different land uses

Rainfed agriculture, grazing and degraded lands are likely to have larger levels of rainfall runoff than irrigated land which generally has inward-sloping terraces that accumulate water (Agarwal and Narain 1991). Likewise, well-managed forests reduce peak flows at the micro- and lower meso-scale (Bruijnzeel and Bremmer 1989). In general, records from the five watersheds show a good correlation between rainfall and runoff on degraded land but a poor one on agriculture land (Figure 7.7). The rates of runoff on the degraded and grassland plots are generally higher than from agricultural land plots with the highest events leading to the runoff of more than 10 mm of rainfall. The amount of rainfall that produces runoff was lower on the degraded and grassland plots than on the rainfed agricultural plots. The threshold amount of rainfall is estimated at 3 mm on the degraded and grassland plots and 5 mm on rainfed agriculture plots (Dangol et al. 2002).

On all the erosion plots seasonality only affected runoff on some of the rainfed agriculture plots where second quarter rainfall events yielded higher runoff rates than in the rest of the year. This is probably due to rainfall occurring when the plots were unvegetated and cultivated. Fields are typically prepared after the first pre-monsoon rains occur between the end of April and early May.

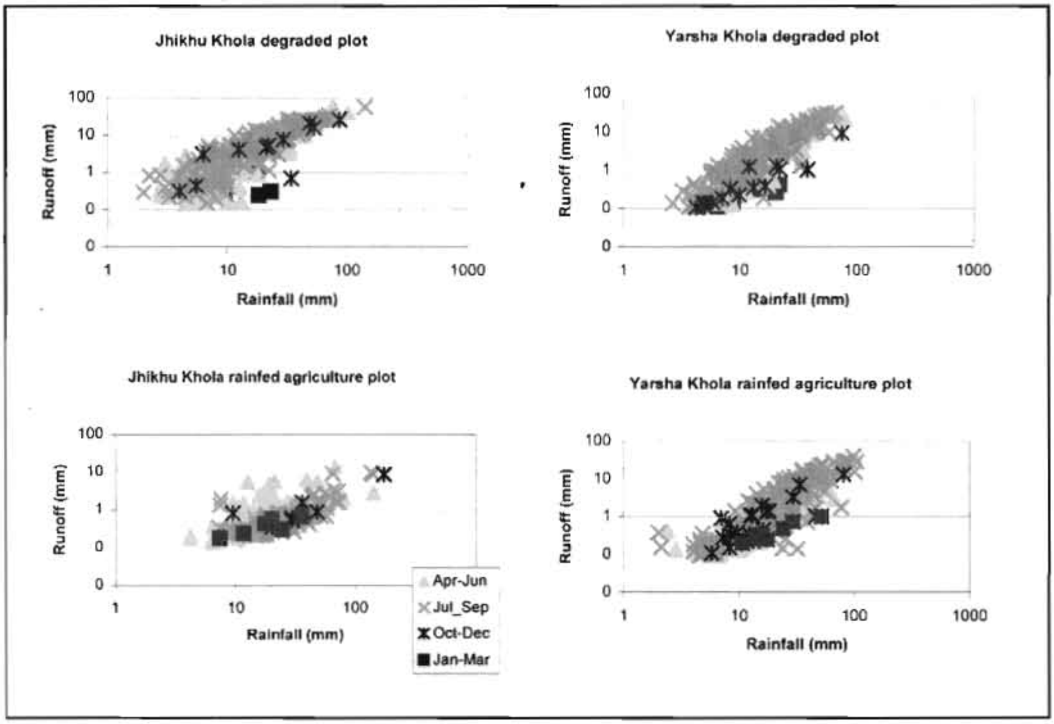

Figure 7.7: **Daily rainfall verses daily runoff on degraded plots and rainfed agriculture plots**

Correlation of plot and watershed scale runoff

The five largest plot runoff events were selected to investigate the relation between plot-scale and watershed-level runoff. Graphs of total runoff against discharge at each watershed's outlet are given at Figure 7.8. This analysis shows that in Hilkot four of the five largest runoff events on the erosion plots occurred at the same time as large events recorded at the main station at the main outlet point. On the Jhikhu Khola and Yarsha Khola watersheds between two and four of the five largest events (depending on land use type) matched the largest events at the main hydro station. But in Bheta Gad and Xizhuang watersheds events on erosion plots and main hydro station events did not match.

Summary of runoff measurements

- Rainfall amounts of between 8 and 16 mm generate the most runoff events.
- The number of runoff events from erosion plots was greatest in the eastern-most watershed's plots (Xizhuang) in the first quarter and least in the fourth quarter.
- More than 75% of annual total runoff in all land uses occurred in the second and third quarters in all watersheds.
- Most runoff was generated in the Yarsha Khola and Jhikhu Khola watersheds in all land uses while it was very low in Bheta Gad and Hilkot watersheds.
- Degraded and grassland plots yielded more runoff than agricultural land plots.
- Runoff events were the largest in the Jhikhu Khola watershed, especially from degraded and grassland plots.
- Degraded and grassland plots did not show seasonal effects, while the agriculture land plots (especially in the Jhikhu watershed) showed clear seasonal effects.
- On the degraded and grassland plots about 3 mm of rainfall generated runoff whilst on the rainfed agriculture plots the threshold was 5mm.
- The data showed much less runoff of rainfall from the agricultural plots than from the degraded and grassland plots.
- In most cases plot level runoff events occurred at the same time as high level flows at sub-watershed and watershed level.

Soil loss

Over 80% of soil loss from all the erosion plots occurred in the second and third quarters of the year (Figure 7.9). In the Jhikhu Khola and Yarsha Khola watersheds 95 to 99% of soil loss occurred in these two quarters and in Bheta Gad 83 to 96% occurred. In the first and fourth quarters only a little soil loss occurred due to the low level and intensity of rainfall.

Soil loss response

In most years across all five watersheds the highest rates of soil loss occurred in the Jhikhu Khola plots with between 23 and 38 t/ha from its grassland plot compared to only 0.1 to 0.4 t/ha from the Yarsha Khola grassland plot and 0.3 to 5 t/ha from the Hilkot grassland plot. Soil loss in the Hilkot watershed was low due to well-established vegetative cover and well-compacted soil. Soil loss in the Bheta Gad watershed was very low because of its rocky soil. Total annual soil loss from the agricultural land plots was comparatively higher in Hilkot and Xizhuang ranging from 3-5.5 t/ha in the former and 4.1-5.2 t/ha in the latter. Soil loss from the agriculture land plot was negligible at Bheta Gad.

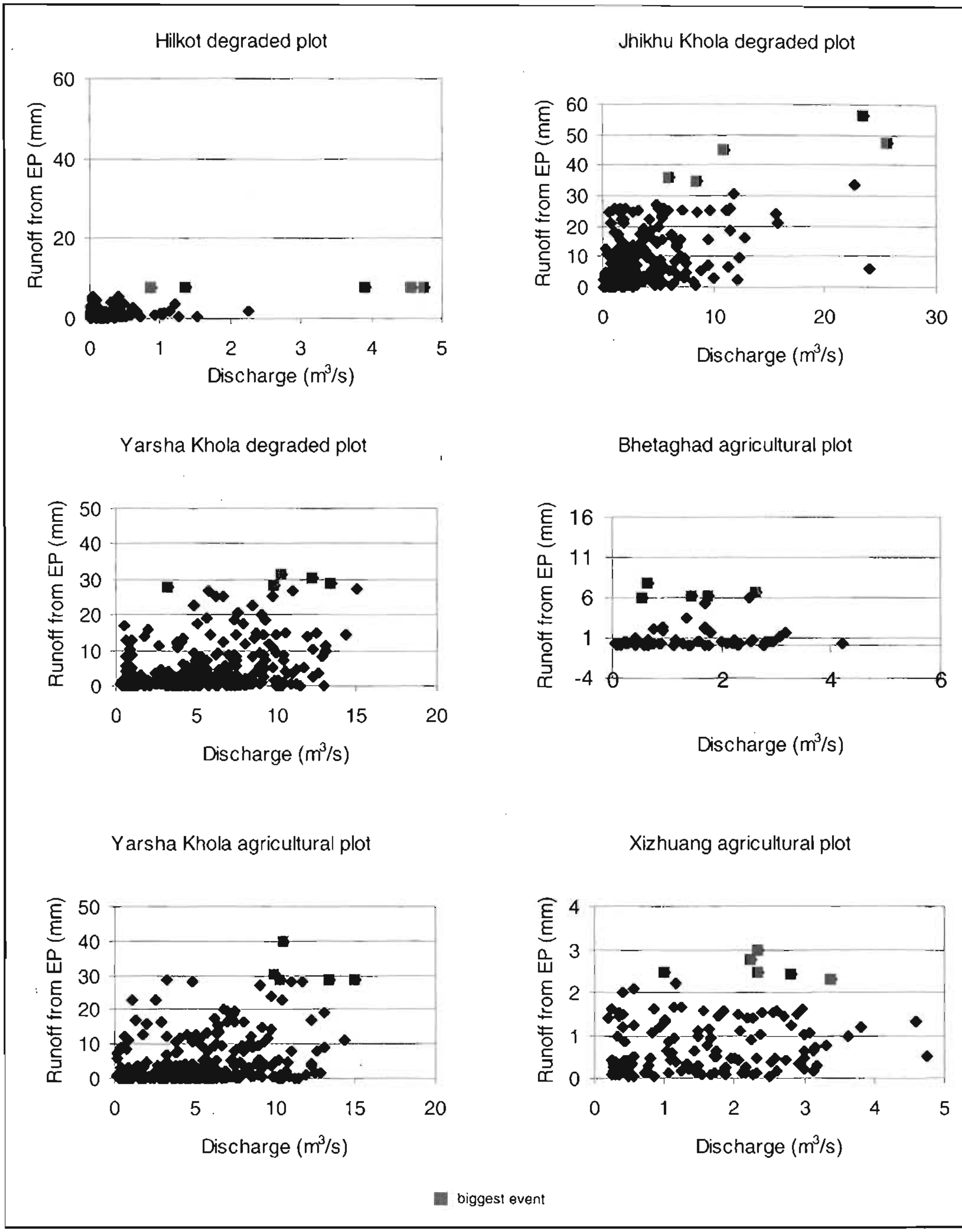

Figure 7.8: **Five biggest runoff events and runoff from erosion plot versus discharge at watershed outlets**

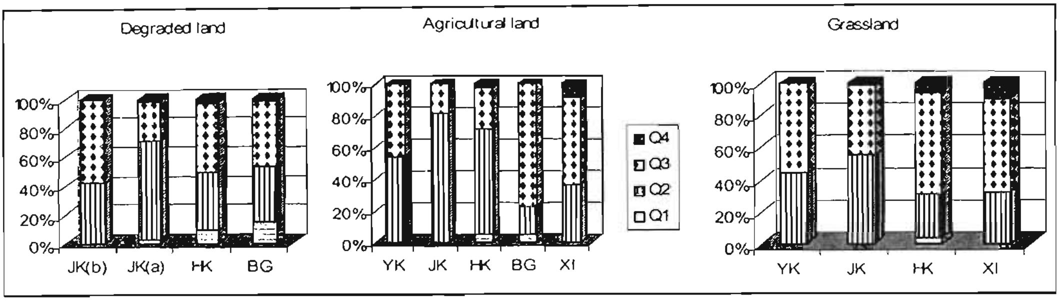

Figure 7.9: **Quarterly distribution of soil loss from three types of erosion plots**

Biggest soil loss events

Several events were recorded that led to large amounts of soil erosion in a short time. These occurred in pre-monsoon and monsoon seasons when the land surface was desiccated and bare or only partially covered with vegetation and therefore vulnerable to erosion. The most such events occurred in the Jhikhu Khola plots with losses from degraded land of 10 t/ha and 7.5 t/ha from the grassland plot in a single rainfall events. At Hilkot only one big soil-loss event was recorded with a loss of 3 t/ha when soil was bare and soft just after sowing. Such intense rainfall caused losses of less than 1 t/ha when there was more vegetative cover.

Summary of soil loss

- Eighty percent of soil loss occurred in the second and third quarters of the year on all plot types.
- Total soil loss was highest from the Jhikhu Khola's degraded and grass plots.
- Total annual soil loss from the agricultural land plots was highest at Hilkot and Xizhuang.
- The largest soil loss events were in the Jhikhu Khola degraded and grassland plots.

Discharge Patterns

Most water discharge occurs during the monsoon months causing flooding and soil erosion. The rest of the year there are limited or low flows leading to a lack of irrigation and drinking water. The discharge peaks in August in all watersheds except Xizhuang where it peaks in September (Figure 7.2). The only source of streamflow in four of the watersheds is rainfall. Hilkot's streamflow is contributed to by large amounts of winter snow. The Yarsha Khola watershed has the higher and Bheta Gad and Hilkot watersheds the lowest levels of discharge. Figure 7.10 shows the low flow conditions over more than half the year in all the watersheds. As measured at the watersheds' outlets, more than 55% of discharge occurs in the third quarter and about 10% in each of the remaining three quarters except for Xizhuang, which has about 40% of its discharge in the fourth quarter because of high winter rainfall (Figure 7.10).

Flow pattern

The annual flow duration curves (three year averages) for the five watersheds are presented in Figure 7.11. The flow is the most variable in Hilkot and Jhikhu Khola. The other three watersheds have a more stable flow. However, the flow magnitudes are very low in Hilkot with a few big events accounting for the variability. All five watersheds have low flows during more than half of the year in the fourth and first quarters of the year.

Frequency distributions

The frequency distributions of the flow, as measured at the main stations of the five watersheds, are presented in Figure 7.12. For all five watersheds flow values were divided into twenty equal class intervals were plotted with their frequencies at the same scale to allow for comparison. In the Hilkot, Bheta Gad, and Jhikhu Khola watersheds about 90% of the time had low flow discharges with class upper limits of 25 l/s/km², while in the Yarsha Khola and Xizhuang watersheds this happened for about 60% of the time. These results show that low flows dominate for longer in Bheta Gad, Hilkot and Jhikhu Khola than in the Yarsha Khola and Xizhuang watersheds.

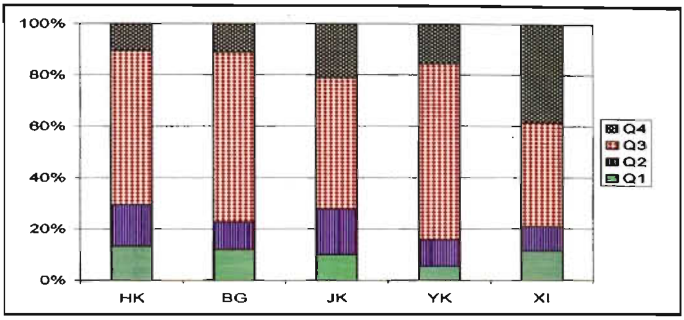

Figure 7.10: **Quarterly distribution of discharge at watershed outlets**

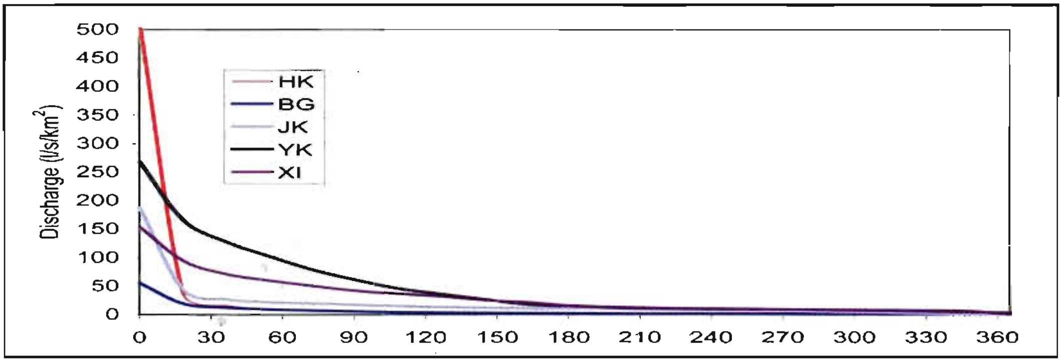

Figure 7.11: **Flow duration curve in the PARDYP watersheds (3 year averages)**

Low flow frequencies

The ten lowest flow values for each of the three years were identified for all five watersheds. Then these 30 lowest low flow values were divided into twenty equal class intervals and their frequency was analysed. Figure 7.13 shows that the frequency of lowest low flow (here classed up to 0.5 litres/s/km²) was the highest in Hilkot (100%) and the Jhikhu Khola watersheds (60%). Yarsha Khola and Xizhuang watershed had more other classes of low flow, comparatively more widely distributed over time. The results suggest that Hilkot, Jhikhu Khola, and Bheta Gad are more susceptible to prolonged low flows whilst the situation in Yarsha Khola and Xizhuang is more variable.

Base flow patterns

Base flow index analysis was carried out according to the method in Institute of Hydrology (1992). The results are presented in Figure 7.14. The base flow index is calculated as the volume of water beneath the base flow line divided by the volume beneath the recorded hydrograph line. Note that the base flow index and base flow line should not be confused as they are different things. Xizhuang watershed had the highest base flow index of 0.842 and

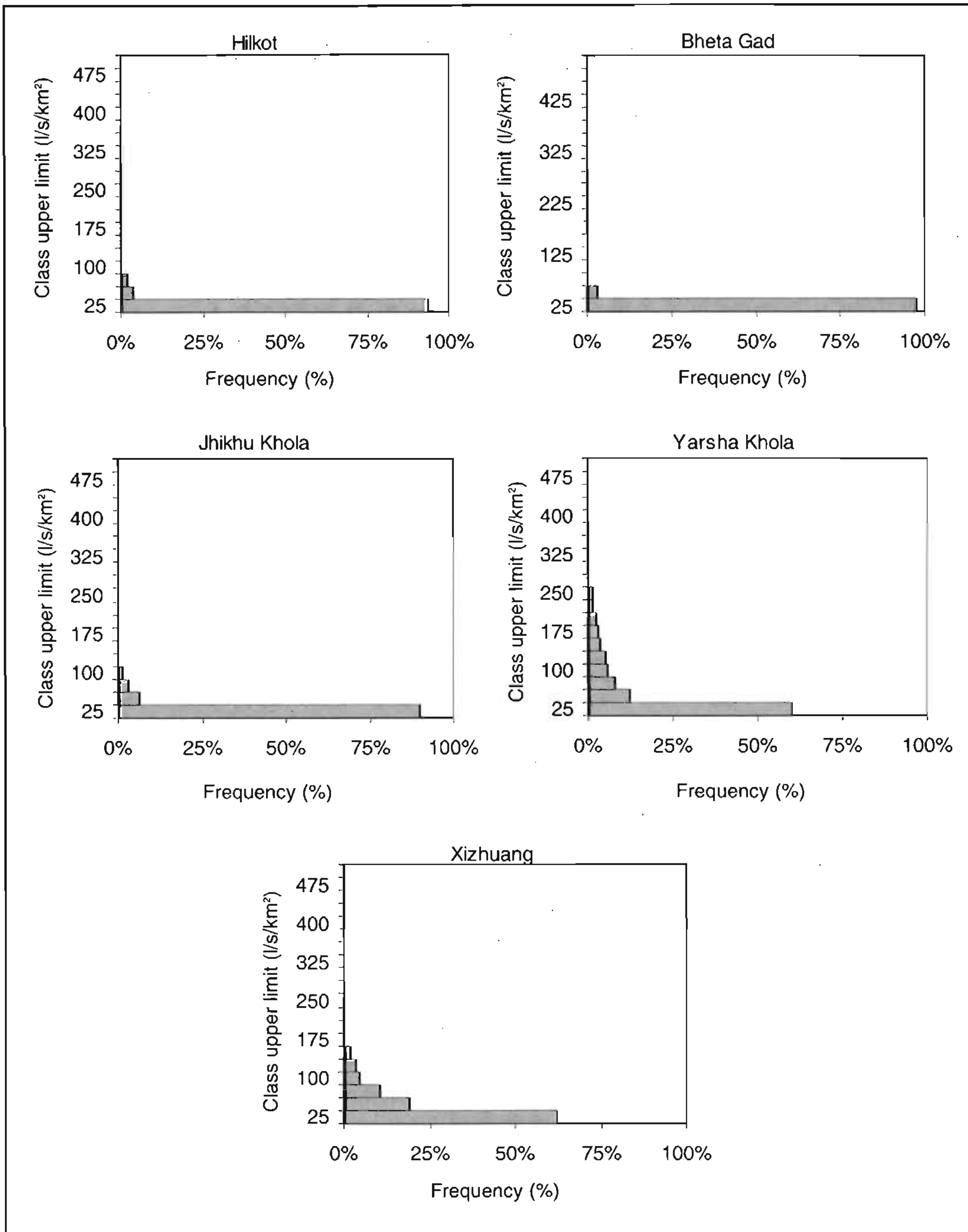

Figure 7.12: **Frequency distributions at the main stations (at outlets)**

Hilkot the lowest at 0.109. It is difficult to see the base flow line of Hilkot watershed in Figure 7.14 because of its very low discharge. Yarsha Khola had the second higher index but the magnitude of base flow was higher in Yarsha Khola than in Xizhuang. The higher the base flow index then the higher is a watershed's storage capacity. The base flow magnitudes were

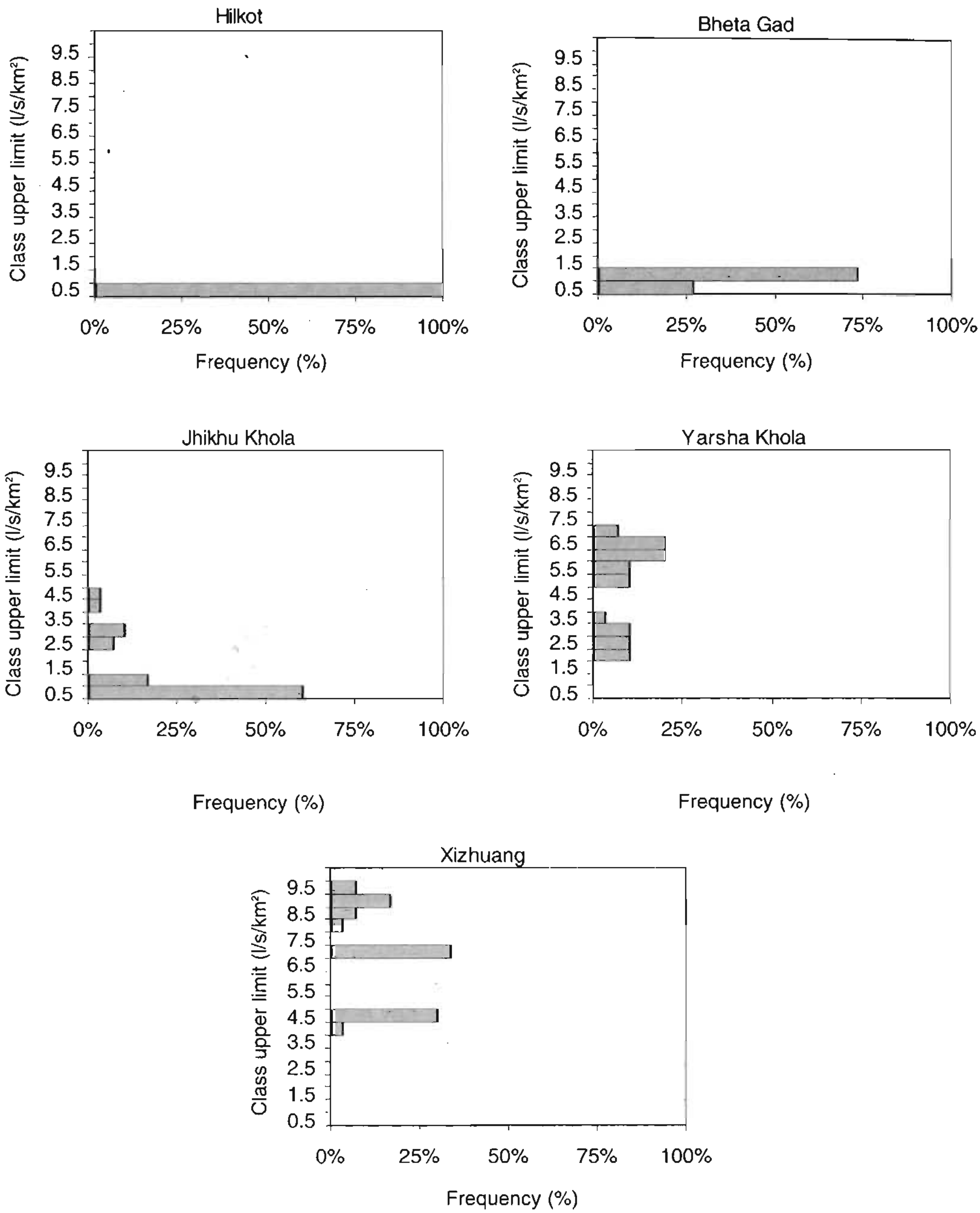

Figure 7.13: **Low flow frequency distributions**

higher in Yarsha Khola and Xizhuang watershed, though the discharge magnitudes were higher in the Jhikhu Khola watershed. Jhikhu Khola watershed had more fluctuations and peaks in the recorded hydrograph. Therefore it seems that Xizhuang and Yarsha Khola watershed have more stable base flows than the other watersheds.

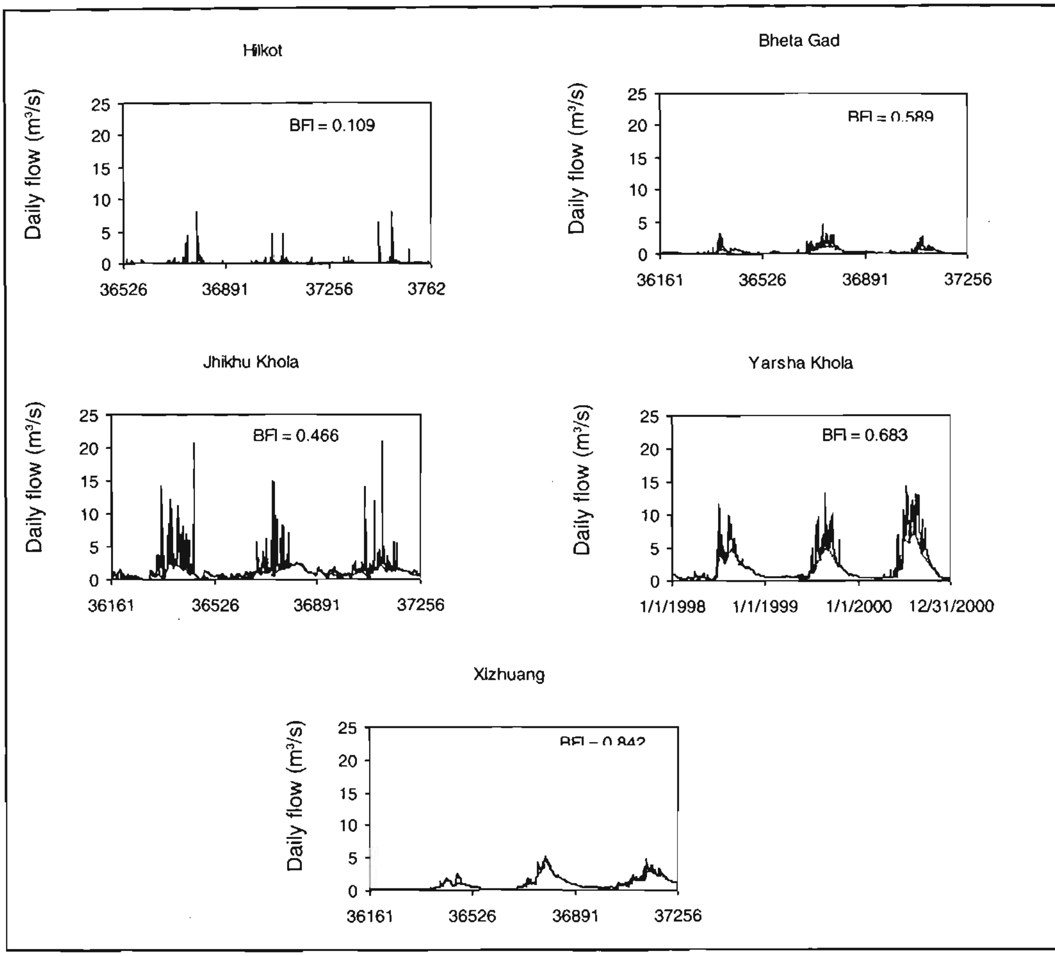

Figure 7.14: **Base flow indexes (BFI) of five PARDYP watersheds**

Low flow patterns

The low flow index (LFI) was calculated using the technique given in Institute of Hydrology (1980). The results are presented in Figure 7.15. The low flow index was higher in the Yarsha Khola then the Xizhuang watershed. Hilkot watershed had the lowest low flow index. It has already been mentioned above that the base flow magnitudes are higher in Yarsha Khola than in the Xizhuang watershed. However the base flow index (BFI) was higher in Xizhuang. This analysis suggests that the low flow index can be used to compare base flows in the watersheds.

Summary of flow at watershed outlets

- Discharge magnitude is highest in August, except in Xizhuang where it is highest in September.
- The discharge magnitude is lowest around April and May in all watersheds.
- About 55% of outlet discharge occurred in the third quarter of the year.
- All five watersheds have low flows for more than half of the year.
- Hilkot, Bheta Gad, and Jhikhu Khola watershed have prolonged low flow regimes.
- Base flow index is highest in Xizhuang watershed and lowest in Hilkot watershed.
- Low flow index is highest in Yarsha Khola watershed and lowest in Hilkot.

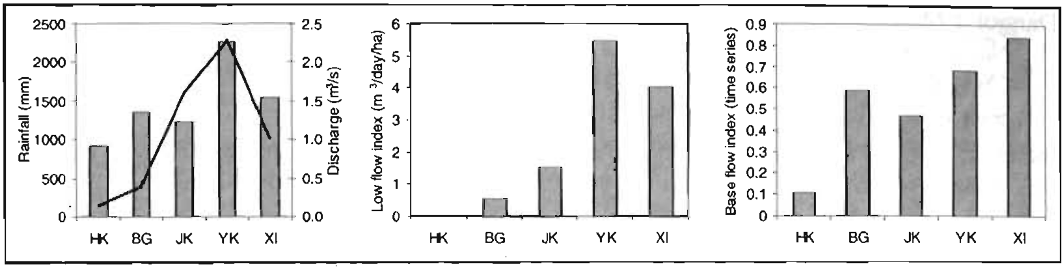

Figure 7.15: **Low flow indexes for five PARDYP watersheds**

Conclusions

All five watersheds are influenced by skewed rainfall, with much during the monsoon and little in the rest of the year. The most frequent runoff events occur when between 8 and 16 mm of rain falls. More than 75% of total annual runoff from all the land use plots occurred in the second and third quarters of the year in all watersheds with degraded and grassland plots yielding higher runoff rates than the agriculture land plots. On degraded and grassland plots rainfall events of 3 mm generated runoff whereas on rainfed agriculture plots events of 5 mm were needed to generate runoff. The degraded and grassland plots did not show seasonal effects, whilst the agriculture land plots did for runoff generation. In many cases high flow events at plot level are reflected in high discharges at sub-watershed and watershed level. All the plots lost most soil in the second and third quarters of the year. In all watersheds, more than 80% of soil loss occurred in these two quarters on all land use types. The degraded plots lost far more soil than the other plots. Over more than 50% of the year all five watersheds had low flows.

The excess surface runoff in the wet seasons can be mitigated and managed by recharging groundwater, by building eyebrow terraces, contour trenches, and water harvesting tanks, and by other soil and water conservation measures. The conserved water can then be used for dry period irrigation. Surface water can be harvested from degraded lands due to their high runoff and low infiltration rates. Soil conservation measures such as contour hedgerow, terrace improvement, gully stabilisation, rehabilitation of degraded lands reduce soil loss and runoff.

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