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Low-flow Hydrology in the Nepal Himalaya: The Madi Watershed

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Abstract

Nepal Himalaya is facing the crucial problem of increasing water scarcity for irrigation and household consumption in many parts. Stream flow remains very low for 9 months a year from October to June. This paper attempts to examine the relationship between stream flow during the dry season and catchment characteristics and identify the most important variables that control flow during the dry season. The relationship between stream flow and different variables of catchment characteristics was examined using bivariate correlation coefficients and regression models. The results show that the topographically influenced climatic condition is important in the control of low flow at larger scales, whereas human induced changes in land use and land cover are important in areas with similar physical environments at smaller scales. Our study highlights the need for proper management of grazing land in the Middle Mountains of Nepal, which could lead to sustained stream flow during the dry season.

Key words: Low-flow; drainage network; Nepal Himalaya; Madi watershed; catchment characteristics

I. Introduction

The Nepal Himalaya, with high relief, is influenced by highly seasonal monsoon precipitation. As a result, this region has been facing a serious problem of excess water during the summer monsoon season and a lack of it during winter (ICIMOD, 2009). The flow of water in many of the rivers remains very low during the dry period (March-May), resulting in severe water scarcity. A study on water balance in the river basins of Nepal shows that the major basins have aurplus flow and the medium basins have deficit flow in the certain rivers (MOESTE, 2014). This has profound implications on sustainable development in the context of increasing demands for water for household consumption, irrigation, and hydropower development as a result of rapid population growth, lifestyle changes, and intensification of cultivation. A recent study in two watersheds in the Middle Mountains of Nepal shows that water resources are becoming increasingly scarce (Merz et al., 2003a). It further shows that 33–41% of households have experienced water shortages for irrigation, and 17–37% of households have experienced water shortages for domestic use (Merz et al., 2003b). Many households in the Madi watershed, particularly from the ridge and upper slopes in the Middle Mountains, have already migrated permanently to the valleys and lower slopes because of an increasing shortage of drinking water. As a result, agricultural lands in their place of origin have been abandoned and left idle, resulting in several adverse socio-economic and environmental consequences (Khanal, 2002).

The flow of a river is a complex natural process. It comprises the different components of recharge, storage, and discharge. Recharge is largely controlled by precipitation, whereas storage and discharge are complex functions of catchment physiographic characteristics (Smakhtin, 2001). The hydrological response of the catchment can be estimated from quantifiable physical catchment properties (Mwakalila, 2003). Since low-flow is the actual flow in a river during the dry season of the year, its generation mechanism is significantly affected by the catchment physiographic properties. The effects of flow are a function of arange of various bio-physical factors such as topography, geology/soils, climatc and vegetattion (Blummenfeld et al., 2009; McCartney et al., 2013). As such, an understanding of the relationship between physical catchment properties and low-flow characteristics provides a basis for not only estimating low-flow in ungauged catchments but also for developing strategies for sustainable river basin management programs.

Recently, a few efforts have been made to study low-flow characteristics for the Himalayan basins of Nepal (MacDolald and Partners, 1982; WECS/DHM, 1990; Rees et al., 2002; Chalise et al., 2003; Hannah et al.,

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2004; Sharma and Adhikari, 2004). These studies provide invaluable information regarding hydrological responses at large scale. Because the shape (temporal variability) and magnitude (size) of precipitation and river flow regimes in a country with an extreme physical environment are largely influenced by the topography and other basin characteristics (Hannan, 2004; Kansakar, 2004), an understanding of the small-scale spatial variation of different mountain areas is necessary. It is in this context that an attempt has been made here to discuss low-flow characteristics in different sub-catchment areas of the Madi watershed. The specific objectives are to examine the relationship between stream discharge during the dry season and catchment characteristics and to identify the catchment characteristics that most control low-flow so that strategies for the sustained flow of water be developed.

II. Materials and methods

The Madi River and its tributaries have been selected for the study. Both secondary and primary sources of information have been used. Quantitative information on the drainage network, catchment size and shape, geology, relief, and land use and land cover were generated from available analog maps prepared during different periods with the help of Geographic Information Systems using ARC/INFO and ArcView. Topographical maps prepared by the Survey Department, HMG/Nepal between 1998 and 2001 based on air photographs taken in 1996 were used. The Madi watershed is covered by 10 map sheets (seven sheets at the scale of 1:25,000 with reference sheet numbers of 2784 01B, 2784 02A, 2884 13A, 2884 13B, 2884 13D, 2884 14A, and 2884 14C; three sheets at the scale of 50,000 with reference sheet numbers of 2884 09, 2884 10, and 2884 05). All the rivers shown on these maps were digitized. Similarly, contours at intervals of 100 m and areas under different land use and land cover types were also digitized. Land utilization maps prepared by Land Resource Mapping Project, Survey Department, HMG/Nepal (1984/85) at the scale of 1:50,000 (sheet no. 71D/2, 71D/3, 71D/4, 71D/7, 71/D8, 72A/1, 72A/5) were used to generate information regarding areas under different types of cultivation. Geological information was compiled from geological maps published by the Department of Mines and Geology, HMG/Nepal in different periods.

Precipitation and temperature data published by the Department of Hydrology and Meteorology, HMG/Nepal were compiled. A map of precipitation zones was prepared by interpolating the mean annual precipitation recorded at nearby meteorological stations between 1956 and 1998. There is only one hydrological station located at Sisaghat in the Madi River. Monthly discharge data between 1978 and 1995 were compiled in order to study temporal variation in the discharge of the Madi River.

Discharge was measured at 35 different sites in the Madi River and its tributaries between April 25 and May 2, 2004. These cross sectional one-time measurements were used to evaluate the relationship between river discharge during the dry season and catchment characteristics. Bivariate correlation coefficients between discharge and different catchment characteristics, including annual precipitation at different scale, were calculated at the watershed and sub-watershed level. Three different regression models were constructed for a) the Madi watershed as a whole, b) the Middle Mountain region in the lower part of the watershed, and c) the High Mountain and the High Himal physiographic regions in the upper part of the watershed.

III. Study area

The Madi watershed, with an area of 1123 km^2 is located in the central part of Nepal (Figs. 1 and 2). The altitude ranges from 307 to 7937 MASL within a north-south distance of 68 km as the crow flies (Fig. 2B). It comprises almost all the ecological regions of the mountain areas in the country. This area comprises three major geological formations – the Tibetan sedimentary zone in the upper region, the Higher Himalayan Crystalline in the middle region, and the Lesser Himalayan Metasediments in the south (Fig. 2A). The lower part of the Tibetan sedimentary zone is mainly calcareous, whereas the middle part is pelagic and the upper part is rich in detrital sediments. The Higher Himalayan Crystalline formation consists of Precambrian high-grade metamorphic rocks comprising gneisses, quartzite, and marble. The Lesser Himalaya is divided into two groups – the Nuwakot and Kunchha. The Nuwakot group consists of argillaceous to finely quartic grey phyilites and dark slates with subordinate bands of limestone/dolomite and calc-phyilites, whereas the Kunchha group consists of phyilites, semi-schist, and mica-grewake phyllitic quartzite.

The watershed is highly rugged. Gently sloping lands (<5º), including alluvial plains, fans, and river terraces, compose less than 9% of the total basin area. Moderately sloping lands (5–30º) account for 21% of the total basin area. Very steep hillslopes and rock headwalls comprise more than 70% of the total catchment area.

The Madi watershed lies in the monsoon climate regime. However, several microclimates are created due to differences in the altitude, gradient, and orientation of slopes. The Madi watershed can be classified into five major temperature zones that more or less follow the contour lines. These include the i) sub-tropical zone below 1,000 m in altitude, with a mean annual temperature between 20 and 35ºC; ii) warm temperate zone between 1,000 and 2,000 m in altitude, with a mean annual temperature between 15 and 20ºC; iii) cool temperate zone between 2,000 and 3,000 m, with a mean annual temperature between 10 and 15ºC;

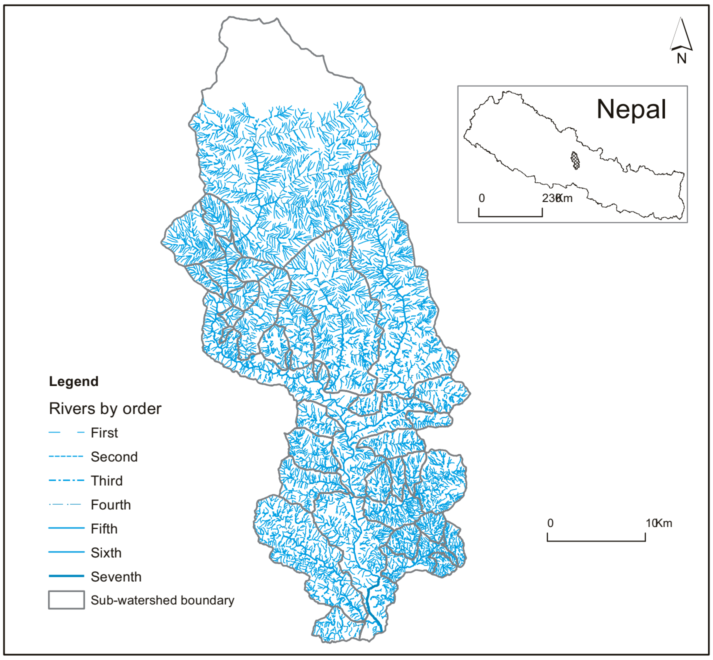

Fig. 1. Location and drainage network of the Madi watershed

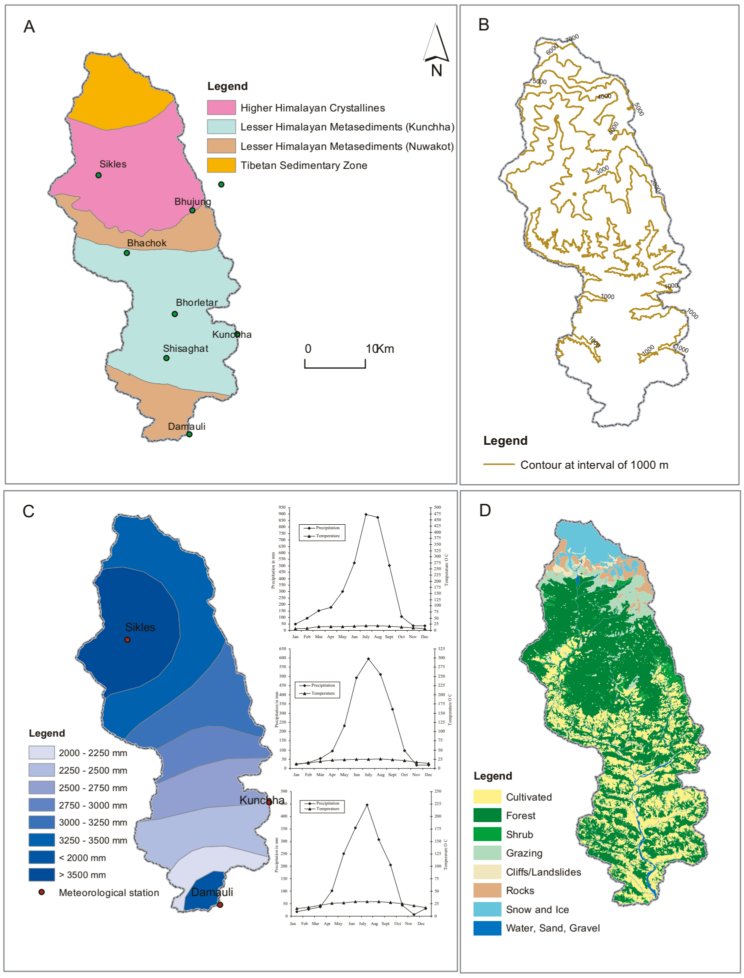

Fig. 2. Physical environmental conditions including: A) geology, B) relief, C) an ombrothermic diagram showing mean monthly precipitation and temperature recorded at three different sites – Damauli in the south, Kunchha in the middle region, and Sikles in the upper region – and the distribution of annual precipitation (mm) in the Madi watershed, and D) land use and land cover

iv) sub-alpine and alpine zone between 3,000 and 4,500 m, with a mean annual temperature below 3 and 10ºC; and v) arctic line zone above 4,500 m, with a mean annual temperature below 3ºC.

The recorded mean annual precipitation in the watershed ranges from 1,795 mm at Damauli in the south to 3,743 mm at Sikles in the north (Fig. 2C). The average number of rainy days ranges from 103 day/year in the south to 187 day/year in the north. Nearly 70–80% of the total precipitation occurs during the four summer months (June–September). The winter months are drier, and this trend is more pronounced in the middle and the lower parts of the watershed (Fig. 2C). Some years experience continuous drought for up to four months during the winter, particularly in the middle and lower parts of the watershed. Daily precipitation events with more than 100 mm occur frequently in the watershed in summer.

Nearly 25% of the total catchment area is under cultivation. The lower and middle regions of the watershed have been extensively utilized for agricultural purposes (more than 40%). Forest makes up about 55% of the total catchment area (Fig. 2D). Nearly 5% of the uppermost part of the watershed is covered by snow and ice. Another major land cover type in the upper part of the watershed is highland pasture (8%). According to the 2001 Population Census, this watershed is inhabited by about 0.2 million people. The gross density of population decreases from the lower and middle parts (about 200 people/km^2) to the upper part (63 people/km^2) of the Madi watershed (Khanal, 2002).

According to the Strahler system of stream ordering, the Madi River is a seventh-order river. There are two sixth-order streams, followed by 11 fifth-order, 258 third-order, 1,163 second-order, and 4,776 first-order streams in the watershed. The bifurcation ratio, the regression coefficient derived from a semilogarithic plot of the order versus the number of streams, is 4.37 for the Madi watershed as a whole. There is a slight variation in the bifurcation ratio at the sub-watershed level, which ranges from 3.33 to 4.66 depending upon the geology and catchment shape (higher in the Higher Himalayan Crystalline than in the Lesser Himalayan Metasediments group and catchments with more elongated shape). However, these ratios are within the range (3–5) of values commonly found elsewhere (Strahler, 1964).

The average length of a stream segment ranges from 0.53 km for first-order streams to 0.61 km for second, 1.18 km for third, 2.71 km for fourth, 8.47 km for fifth, and 30.94 km for sixth-order streams, with a length ratio of 1.88 in the Madi watershed as a whole.

IV. Results

River discharge

Water flow data recorded at Sisaghat in the Madi River between 1978 and 1995 show that the mean flow ranged from 16.8 m^3/s in February to 225.7 m^3/s in August. The minimum mean monthly flow in February was nearly 14 times less than the highest mean monthly flow recorded in August. As in other rivers in Nepal Himalaya, the flow remains quite high during the summer monsoon period (Fig. 3a). The annual variation in mean monthly flow is higher in summer (Fig. 3b). Minimum instantaneous flow records range from 2.73 to 20.8 m^3/s, with an average of 11.0 m^3/s (Fig. 3c). The minimum instantaneous flow during this period was recorded between the last week of December and the second week of May.

Low-flow volume and rate

Figure 4-left shows flow volume measured at 35 different sites in the Madi watershed between April 24 and May 2, 2004. Flow at these sites ranged from 0 l/s in some of the streams in the Middle Mountains to more than 25,000 l/s in the Madi River near Damauli. The Handi (third-order), Khahare, and Golandi Khola (fourth-order) streams located in the middle part of the Madi watershed did not have flow during the dry season. Similarly, flow during the dry season remained less than 100 l/s in 12 streams, ranging from second- to fifth-order. There are 10 streams with flows between 100 and 500 l/s during the dry season. These include the Kalesti, Risti, Khalte, Birdi, Ramche, Makai, Thak, Gyamrang, and Seti Khola. There are three streams with flows between 500 and 1,000 l/s during the dry season in the watershed. Those include the Sange in the lower part and the Patku and Chipli in the upper part. Only two rivers, the Madi and Midim, have flows greater than 5,000 l/s during the dry season. Both originate from the High Himal. The uppermost part of the Madi River is covered by snow and ice. The melting of snow and ice contributes a considerable volume of water during the dry season.

The discharge rate (l/s/km^2) during dry season exhibits three distinct hydrological response regimes in the Madi watershed (Fig. 4). In general, the Middle Mountains in the lower part of the watershed have low runoff (<10 l/s/km^2) compared to the High Mountain in the middle part (10-30 l/s/km^2) and the High Himal in the upper part (> 30 l/s/km^2).

Low-flow volume and catchment characteristics

Bivariate correlation coefficients between instantaneous discharge during the dry season and each catchment characteristic parameter were calculated, and the results are presented in Table 1. These relationships were evaluated after the square root transformation of all datasets. For further analysis, the Madi watershed was divided into two distinct hydrological regimes – the Middle Mountains in the lower part of the watershed and the High Mountain and the High Himal in the upper part. River discharge measured at 19 different sites in the lower part and 14 sites in the upper

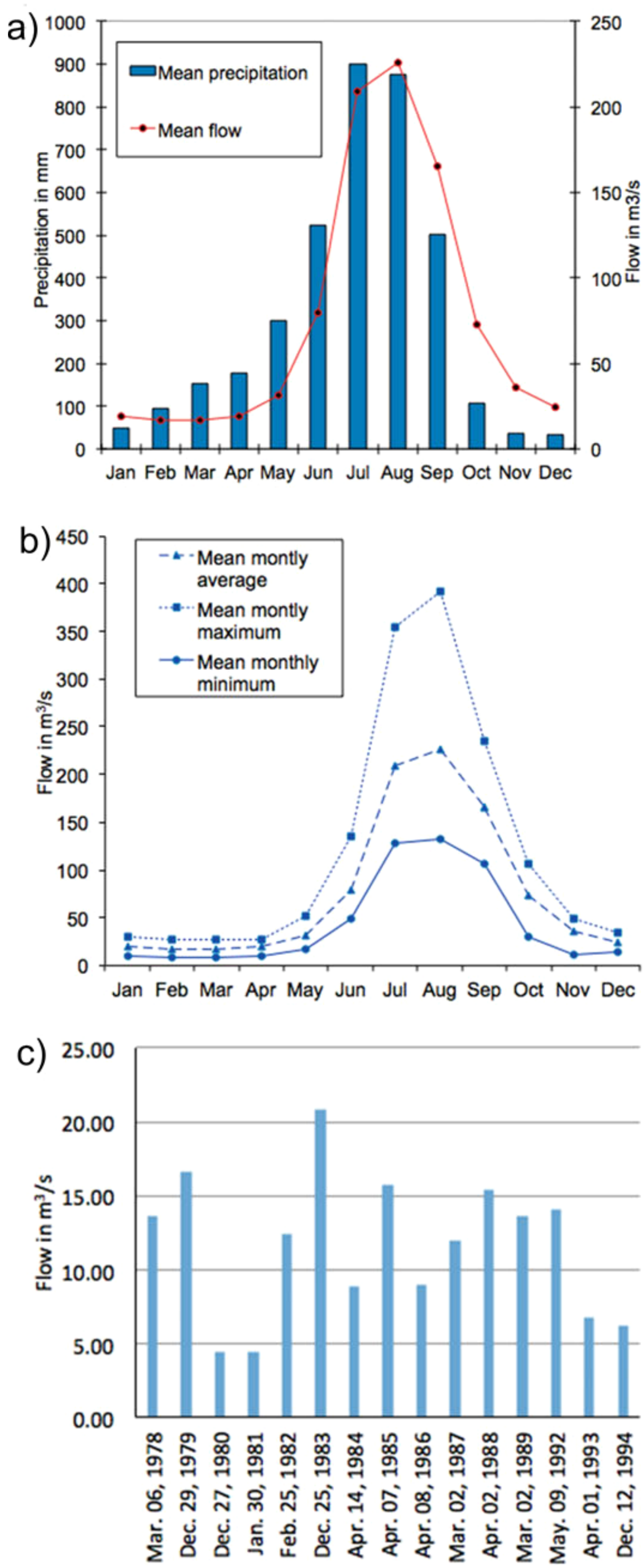

Fig. 3. Precipitation and river discharge
a) mean monthly precipitation at Sikles and discharge in the Madi River, b) mean monthly minimum and maximum discharge, and c) minimum instantaneous discharge in the Madi River.

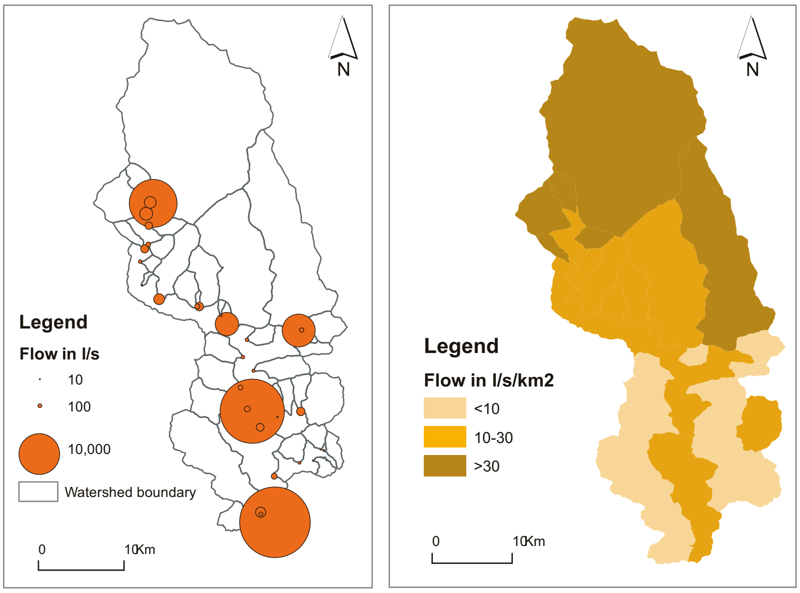

Fig. 4. Dry season flow volume and rate measured at different sites in the Madi watershed: left) flow volume and right) flow rate

Table 1. Correlation coefficients between low-flow (l/s) and basin parameters

Parameters	Madi watershed (N=35)	Middle Mountain (lower part) (N=19)	High Mountain and High Himal (upper part) (N=14)
1. Area, Perimeter and Length			
Area (km^2)	.973(**)	.894(**)	.987(**)
Perimeter (km)	.955(**)	.882(**)	.954(**)
Length (km)	.953(**)	.827(**)	.948(**)
2. Shape (Dimensionless)			
Elongation ratio ($A^{1/2}/L$)	-0.185	0.134	0.066
Relative perimeter ($P^{1/2}/A$)	.492(**)	-0.036	0.248
3. Relief			
Relief (Altitude: max-min)	.952(**)	0.327	.944(**)
% area < 1000 m	-.334(*)	0.19	-0.28
% area 1000-2000 m	0.029	-0.2	-.679(**)
% area 2000-3000 m	.554(**)	.(a)	0.482
% area 3000-4000 m	.869(**)	.(a)	.930(**)
% area 4000-5000 m	.873(**)	.(a)	.897(**)
% area > 5000 m	.823(**)	.(a)	.758(**)
% area < 2000 m	-.654(**)	.(a)	-.785(**)
% area > 2000 m	.712(**)	.(a)	.720(**)
4. Slope			
Relative relief ratio (H/L)	-0.235	-.711(**)	-.614(*)
% area with slope < 10^0	-0.315	0.405	-0.366
% area with slope $10\text{-}20^0$	0.175	-0.174	0.292
% area with slope $20\text{-}30^0$	-0.035	-0.154	0.108
% area with slope > 30^0	0.244	0.09	0.081
% area with slope > 20^0	0.197	-0.156	0.11
4. Precipitation			
Annual precipitation (mm)	0.329	-0.116	-0.077
5. Drainage density			
Drainage density (km/km^2)	-.411(*)	-0.13	-.534(*)
6. Land use and land cover			
% of cultivated land	-.430(**)	-0.02	-0.496
% of forest land	0.095	0.141	-0.027
% of shrub land	0.307	0.001	0.214
% of grazing land	.451(**)	-0.413	0.385
% of ice and snow area	.823(**)	.(a)	.758(**)
% of other land use/cover	.705(**)	0.372	.640(*)
% of both forest and shrub	0.12	0.133	-0.01
% of valley cultivation	-0.114	0.217	0.033
% of level terraces	0.134	0.245	-0.041
% of sloping terraces	0.079	-0.147	0.485
% of hillslope cultivation	0.182	-0.222	0.111

*: Significant at the 0.05 level, **: Significant at the 0.01 level, a: Cannot be computed

part were used to examine differences between regions.

Catchment area, perimeter, and length are positively correlated with discharge at all levels - the watershed as a whole, as well as the lower and upper parts of the watershed individually. All correlation coefficients were significant. However, catchment shape factors (elongation ratio, $A^{1/2}$/L, and relative perimeter, $P^{1/2}$/A) are not consistent or significant at all levels.

There is significant positive correlation between discharge and relief (the differences between maximum and minimum altitude) at the watershed level and in the High Mountain and High Himal regions (upper part), but this correlation is poor in the Middle Mountains (lower part of the watershed). The percentage of land area below 2,000 m in altitude is negatively correlated with discharge, whereas the percentage of land area above 2,000 m is positively correlated with discharge.

The relative relief ratio (differences in height/length) is negatively correlated with discharge. It is consistently and significantly high in the lower part of the watershed. The percentage of land area under different slope categories does not show consistent or significant correlation with low-flow at all levels.

The annual volume of precipitation shows a positive correlation with discharge at the watershed level, but this correlation is not consistent or significant at sub-regional scale. Drainage density shows a consistently negative correlation with low-flow, but it is not significant at all levels.

The relationship between discharge and land use and land cover is variable. The percentage of cultivated land with respect to the total area is consistently negative. It is significant only at the watershed level. The percentage of shrub land within the total basin area shows a consistently positive relationship to discharge at all levels. The percentage of grazing land shows a significantly positive correlation to discharge at the watershed level, but the correlation is negative in the lower part at the sub-regional scale. Similarly, the percentage of land area under snow and ice cover is positively correlated with discharge. The correlation is significant at the watershed level only.

Stepwise regression analysis was carried out to identify catchment characteristics that most influence low-flow.

Because the linear regression model using data after a square root transformation explained a higher proportion of the variation in the observed low-flow with statistically significant constants and coefficients, this model was chosen for further analysis. Moreover, this model was applied earlier to evaluate the relationship between low-flow and catchment characteristics and is recommended for the computation of low-flows at ungauged sites (Sharma and Adhikari, 2004). Though many catchment characteristic variables are highly correlated with low-flow, only two variables, catchment area and relief, appear as statistically important explanatory variables at the watershed level. Some of the variables are highly correlated, resulting in the undesirable property of multicollinearity. As precipitation increases with increasing altitude, these two variables are highly correlated, and one variable is sufficient to explain the variation in low-flow at the watershed level. The results of the best multiple regression models at three different spatial scales - the Madi watershed as a whole, the Middle Mountains, and the combination of the High Mountains and High Himal physiographic regions - are presented in Table 2. Two important variables for explaining the variation in observed low-flow in the Madi watershed as a whole are catchment area and relief (the differences between maximum and minimum altitude of the catchment). In combination, these two variables explain 98.4% of the variation in observed low-flow. Catchment area has a high degree of influence on low-flow, as indicated by a higher value of the standardized Beta coefficient. An earlier study at the national level also identified catchment area below 5,000 m as the only variable explaining 91.2 to 92.5% of the variation in the observed one-day low-flow for different return periods of 2, 10, and 20 years (Sharma and Adhikari, 2004).

In the Middle Mountains (lower part of the watershed), two variables – catchment area and percentage of grazing land – together explain 84.9% of the variation in the observed low-flow (Table 2). The coefficient of catchment area is positively significant, whereas the percentage of grazing land is negatively significant at the <0.05 alpha level.

In the High Mountain and High Himal region (upper part of the watershed), catchment area explains 97.4% variation in the observed flow during the dry season (Table 2).

Discharge rate and catchment characteristics

An attempt has also been made to examine the relationship between discharge rate ($l/s/km^2$) and different catchment characteristic variables. The bivariate correlation coefficients between discharge rate and catchment characteristics using data following a square root transformation are presented in Table 3.

The volume of mean annual precipitation, relief, altitudinal zone, steepness of slope, drainage density, land use and land cover (i.e., the percentage of cultivated land), percentage of valley cultivation, percentage of level terraces, percentage of sloping terraces, and percentage of forest and shrub are significantly correlated with the discharge rate in the Madi watershed as a whole. Discharge rate is significantly positively correlated with the volume of mean annual precipitation, relief, percentage of area above 2,000 m in altitude, slope greater than 20º, percentage of forest and shrub, and the percentage of level terraces.

However, the percentage of area below 2,000 m in altitude, percentage of slope less than 10º, drainage density, percentage of cultivated land, and percentage of sloping terraces are all negatively correlated with discharge rate.

In the Middle Mountains, there is a significant negative correlation between discharge rate and the percentage of grazing land within the total catchment area. Though the percentage of forest and shrub land is positively correlated and the percentage of cultivated land is negatively correlated with discharge rate, they are not significant.

In the High Mountain and High Himal region (upper part), discharge rate is highly correlated with the percentage of land area under different altitudinal zones and the percentage of land area under different slope categories. They are significant at or below the 0.05 level.

The percentage of land area below 1,000 m in altitude and the percentage of land area with a slope less than 10º are negatively correlated with discharge. However, the percentage of land area above 2,000 m in altitude, particularly between 2,000 and 3,000 m, and the percentage of land area with a slope between 10 and 20º are positively correlated with discharge. Other variables are not significant at or below the 0.05 level.

Stepwise regression analysis further shows the significant influence of the annual volume of precipitation and percentage of land area between 2,000 and 3,000 m in altitude. These two variables explain 71.9% of the variation in observed discharge rate at the watershed level (Table 4). All constants and coefficients are significant at the <0.01 level. Precipitation has a higher degree of influence than the land area between 2,000 and 3,000 m in altitude, as indicated by a higher value of the standardized Beta coefficient.

In the Middle Mountains, two variables, the percentage of grazing land and percentage of shrub land, explain 49.5% of the variation in the observed discharge rate (Table 4). The percentage of grazing land has negative correlation, whereas percentage of shrub land has positive correlation. Other variables do not appear to be significant at or below the 0.05 level.

In the High Mountain and High Himal region, only one variable, the percentage of land area between 2,000 and 3,000 m, is significant; it explains 37.1% of the variation in discharge rate (Table 4).

V. Discussion and concluding remarks

There is strong seasonality in the flow of water in these rivers. The flow remains quite high during the summer monsoon period (July–September) and low during the dry season (Oct–June). The mean monthly flow during summer is 10 to 14 times higher than that in the dry season. The ratio between the maximum and minimum monthly flow (1978–1995) is greater than 48. Similarly, recorded maximum instantaneous flow is 800 times higher than the minimum recorded instantaneous flow. Some of the third and fourth-order rivers, particularly in the Middle Mountains, remain completely dry between November and May.

Many catchment characteristics variables are highly correlated with dry season river flow. Because of the multicollinearity problem caused by strong correlation between basin area and other catchment characteristics, not

Table 2. Results of the best stepwise multiple regression models (Dependent variables: discharge in l/s)

	Madi watershed	Middle Mountain	High Mountain and High Himal
R Square	0.992	0.849	0.974
Adjusted R Square	0.983	0.831	0.972
F value	986.237	45.11	457.825
df	2,32	2,16	1,12
Prob > F	0	0	0
Coefficients			
Constant	-32.432	-1.968	-1.586
Std. Error	3.262	1.774	1.956
t	-9.942	-1.109	-0.811
P>(t)	0	0.284	0.433
Basin Area	3.201(0.603)	3.071(0.844)	6.023(0.987)
Std. Error	0.256	0.362	0.282
t	12.517	8.489	21.397
P>(t)	0	0	0
Relief	0.961(0.418)		
Std. Error	0.111		
t	8.678		
P>(t)	0		
% Grazing		-1.973 (-0.230)	
Std. Error		0.852	
t		-2.317	
P>(t)		0.034	

Note: Figures in parentheses are standardized Beta coefficients

Table 3. Correlation coefficients between discharge rate and basin characteristics

Parameters	Madi watershed (N=35)	Middle Mountain (N=19)	High Mountain and High Himal (N=14)
1. Shape (Dimensionless)			
Elongation ratio ($A^{1/2}/L$)	-0.226	0.376	-0.253
Relative perimeter ($P^{1/2}/A$)	0.117	-0.274	0.074
2. Relief			
Relief (Altitude: max-min)	.524(**)	0.151	0.245
% area < 1000 m	-.790(**)	0.193	-.552(*)
% area 1000-2000 m	.476(**)	-0.25	-0.24
% area 2000-3000 m	.770(**)	.(a)	.609(*)
% area 3000-4000 m	.502(**)	.(a)	0.413
% area 4000-5000 m	0.325	.(a)	0.166
% area > 5000 m	0.257	.(a)	0.097
% area < 2000 m	-.606(**)	.(a)	-0.474
% area > 2000 m	.738(**)	.(a)	.577(*)
3. Slope			
Relief ratio (H/L)	.366(*)	-0.342	-0.206
% area with slope < 10^0	-.616(**)	0.307	-.577(*)
% area with slope 10-20^0	0.195	-0.353	.566(*)
% area with slope 20-30^0	-0.08	-0.313	0.222
% of area with slope > 30^0	.413(*)	0.276	-0.253
% area with slope > 20^0	.358(*)	0.017	-0.046
4. Precipitation			
Annual precipitation (mm)	.799(**)	0.005	0.494
5. Drainage density			
Drainage density (km km^{-1})	-.351(*)	-0.218	0.278
6. Land use and land cover			
% of cultivated land	-.642(**)	-0.295	-0.376
% of forest land	.486(**)	0.369	0.396
% of shrub land	.492(**)	0.107	0.247
% of grazing land	0.264	-.579(**)	0.043
% of ice and snow area	0.257	.(a)	0.097
% of other land use/cover	0.271	0.325	-0.16
% of both forest and shrub	.535(**)	0.386	0.411
% of valley cultivation	-.438(**)	0.065	-0.147
% of level terraces	.400(*)	-0.083	0.062
% of sloping terraces	-.362(*)	0.187	0.166
% of hillslopes cultivation	0.252	-0.139	0.129

*: Significant at the 0.05 level, **: Significant at the 0.01 level, a: Cannot be computed

Table 4. Results of the best stepwise multiple regression models (Dependent variable: discharge in $l/s/km^2$)

	Madi watershed	Middle Mountain	High Mountain and High Himal
R Square	0.719	0.495	0.371
Adjusted R Square	0.702	0.432	0.318
F value	40.962	7.848	7.067
df	2,32	2,16	1,12
Prob > F	0	0.004	0.021
Coefficients			
Constant	-8.296	2.368	4.417
Std. Error	2.849	0.271	0.515
t	-2.912	8.742	8.57
P>(t)	0.006	0	0
Precipitation	0.21 (0.508)		
Std. Error	0.055		
t	3.796		
P>(t)	0.001		
% area between 2,000-3,000 m altitud	0.354 (0.407)		0.321 (0.609)
Std. Error	0.116		0.121
t	3.044		2.658
P>(t)	0.005		0.021
% area of grazing land		-1.064 (-0.773)	
Std. Error		0.272	
t		-3.916	
P>(t)		0.001	
% area of shrub land		0.599 (0.445)	
Std. Error		0.266	
t		2.254	
P>(t)		0.039	

Note: Figures in parentheses are standardized Beta coefficients all of the variables could be used in assessing the control of low-flow. Such a problem has also been reported while assessing bankfull discharge in other parts of the country (Marston et al., 1996). The results of this study show that low-flow is largely influenced by topographically induced differences in climatic condition at larger spatial scales and by land use and land cover in areas with smaller spatial scales. Natural factors such as catchment area, precipitation, altitude, and steepness of the slope are important in the control of low-flow in the Madi watershed as a whole and in the High Mountain and High Himal physiographic regions (upper part of the watershed). Among these, catchment area, relief, and annual volume of precipitation appear as statistically significant explanatory variables at the watershed level, whereas catchment area and percentage of land area between 2,000 and 4,000 m are significant in the upper part of the watershed. In addition to catchment area, land use and land cover appear to be the most important variables in the Middle Mountains region (lower part of the watershed), which is densely populated. The percentage of grazing land has statistically significant negative correlation with river flow during the dry season, whereas the percentage of shrub land has a significant positive correlation.

These findings regarding the control of natural factors are consistent with generally accepted concepts of low-flow hydrology (Smakhtin, 2001). The valleys and mountain slopes in the Middle Mountains (lower part) are hot and dry compared to those in the High Mountain and High Himal (upper part). As such, the lower part is characterized by low recharge and high evaporation, resulting in a lower discharge rate during the dry season compared to the upper part of the catchment. However, the effect of land use, particularly grazing land, is not consistent at all levels. In the Middle Mountains, grazing land has a significant negative correlation with discharge volume and rate, whereas in the High Mountain and High Himal (upper part) and in the Madi watershed as a whole, there is positive correlation, though it is not significant. This finding is in agreement with the findings that the hydrological response to human activities, mainly land use changes, is highly associated with spatial scale and the natural condition (Ives and Messerli, 1989; Hofer, 1993). In small areas with more or less homogenous natural conditions, human activities associated with land use are major sources of the variation in stream flow, particularly during the dry season.

The percentage of shrub and forest land is positively correlated with rate of discharge, though it is not significant at all levels. Both increases and decreases in low-flow due to deforestation are theoretically possible (Smakhtin, 2001). A review of 94 catchment experiments worldwide shows that deforestation leads to higher annual stream flow, including seasonal low-flows, and reforestation of open lands generally leads to a decline in overall stream flow (Bosch and Hewlett, 1982). However, deforestation alone does not lead to an increase in stream flow long term; the type and intensity of usage of the deforested area also play important role. It has a profound effect on infiltration. If a change in infiltration associated with a land use change overrides the effect of reduced evaporation, this leads to increased flow peaks during the rainy season and decreased flows during the dry season (Brunjinzeel, 1990). Thus, the soil-litter-vegetation interface is important in the control of low-flow (Hamilton, 1987). In the highly populated Middle Mountains region, open mountain slopes are overgrazed, and soils are heavily compacted, resulting in quick runoff and less infiltration. Another important aspect is that the regolith thickness has been reduced to a high degree in many grazing lands as a result of increased soil erosion, leading to decreased flow in streams during the dry season. As such, the grazing lands in the Middle Mountains should be managed in a way such that the stream flow during the dry season is sustained.

Hydrological stations in Nepal are very sparse, and the available long-term discharge data are insufficient to evaluate the relationship between low-flow and catchment properties at different scales for different physiographic regions. It is in this context that the present analysis was performed using available maps and single flow measurement data at different sites during the dry season in the Madi watershed. However, there is scope for further examination using more long-term datasets in the future to better estimate low-flow in these mountain watersheds.

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