Role of Snowmelt in Generating Streamflow During Spring in East Nepal

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Abstract Streamflow in most of Nepal’s rivers is at a minimum in winter and early spring as flows recede rapidly after the summer rains. This period of minimum flow is problematic for local water supply and run-of-river hydroelectric facilities. The Arun River of east Nepal provides an example of minimum flow influencing the feasibility of proposed hydropower development. Snowmelt runoff has been assumed to provide relief from the low flows of winter for one to two months before rainfall-runoff provides high flows in summer. However, there have been few studies of snowmelt runoff and its importance in augmenting streamflow anywhere in Nepal. This paper examines changes in recorded streamflow during the March through June period in seven tributaries of the Kosi. Streamflow increased by about 10 to 25% from March to April and by 45 to 65% from April to May in most of the rivers studied. Pre-monsoon rainfall appears to contribute much of this runoff, particularly in the Tamur and Arun.

INTRODUCTION

Melting snow and ice supply water to much of the Himalayan region in the dry months before the summer monsoon. Snowmelt runoff is most important in the western Himalaya where melt-water comprises about 70% of the annual discharge of the Indus and its tributaries (Tarar, 1982). The proportion of annual streamflow generated from snowmelt in the high mountains declines from west to east. In Nepal, melt-water is thought to account for about 10% of the average annual streamflow (Sharma, 1977). Knowledge of snowpack and glacier-melt regimes can improve planning and design of water projects. Forecasting of seasonal and even daily melt-water flows can improve the operational efficiency of hydroelectric and irrigation projects. With many large- and small-scale projects under consideration, more information about the role of snow in Himalayan hydrology should lead to better decisions.

Although studies of snow cover and glaciers in the Himalaya began with the building of the Tarbela Dam in Pakistan (Vohra, 1981), there has been remarkably little snow research or monitoring anywhere in the range until the past decade. Consequently, even less is known about this component of the
hydrologic cycle in the Himalaya than about other poorly understood processes. Measurements of snowpack water equivalence and glacier mass-balance are quite rare and of limited geographic extent in the few existing cases. Attempts at establishing snow survey networks have been intermittent (e.g. Priest, 1962; Gupta, 1985). Snow surveys in east Nepal and Sikkim in the late 1940s found little snow and little basis to continue monitoring seasonal snow cover (Dhar et al., 1985 and 1986). The area of snow cover determined from satellite imagery is the most easily accessible information and has shown great potential in forecasting spring streamflow in the western Himalaya (Rango et al., 1977; Ferguson, 1985).

The Glaciological Expedition to Nepal has provided the first detailed look at Himalayan glaciology (Higuchi et al., 1982). Although some streamflow measurements were made in two high-altitude catchments during this project (Higuchi et al., 1976; Nakawo et al., 1976), flow was not related to snowmelt during the spring season. Glaciological work by Japanese scientists has continued in the Langtang Himal (e.g. Higuchi, 1984; Motoyama et al., 1987). An intensive study of glaciers and seasonal snow cover in the Karakoram was conducted in the mid-1980s (e.g. Hewitt, 1986; Hewitt et al., 1989; de Scally & Gardner, 1988). The Nepal-German Snow and Glacier Hydrology Project is currently monitoring snow conditions at several sites in Nepal. Swiss glaciologists and hydrologists have also begun collaborative studies in the early 1990s (L. Braun, ETH, Zurich, personal communication). Although researchers are making progress (this proceedings), many critical unknowns concerning snow and glacier hydrology in the Himalaya have been identified (Kattelmann, 1987): snow accumulation and melt at high elevations during the monsoon; proportion of annual flow contributed by snow melt in each basin; magnitude of evaporative losses from snowpacks; snowpack energy balance at high altitude; importance of ephemeral snow cover at lower elevations; glacial fluctuations; and applicability of snow-covered area-based runoff models.

Low flow during winter and early spring is a critical constraint on hydroelectric production and irrigation supplies. When streamflow begins to increase in March or April, the source of runoff has been assumed to be snowmelt (e.g. Sharma, 1977; Chyurlia, 1983). Dry-season flow is most dependable in areas with some glacier cover, where glaciers may provide about 1 mm day$^{-1}$ of water to streams (Motoyama et al., 1987). Although snowmelt obviously provides substantial runoff in the western Himalaya, observations of limited snow cover in east Nepal lead to questions about the role of snowmelt in runoff generation in this region. This paper examines streamflow characteristics during late winter and early spring in east Nepal.

STUDY AREA AND DATA SOURCES

The Sapt Kosi of east Nepal was chosen for this study because of availability of streamflow data and potential hydroelectric development in this basin. The
Kosi system drains almost 60,000 km² of eastern Nepal and southern Tibet before entering Bihar. The basin includes half of the world’s 8000 m peaks. North of the India-Nepal border, the river is known as the Sapt Kosi or "Seven Rivers" in reference to its seven principal tributaries. Upstream of their confluence at Tribeni, the three main tributaries of the Sapt Kosi (Sunkosi, Arun, and Tamur) drain portions of the basin covering the full range of Himalayan geologic and life zones.

Streamflow and precipitation data were obtained from various reports (e.g. Karmacharya, 1982; Japan International Cooperation Agency, 1984; Nepal Electricity Authority, 1987) and publications of Nepal’s Department of Irrigation, Hydrology and Meteorology. Discharge data were available for the Arun at Tumlingtar, Tamba Kosi at Busti, Tamur at Mulghat, Sunkosi at Pachuwar Ghat, Bhote Kosi at Barahbise, Dudh Kosi at Rabuwa Bazar, Khimti Khola at Rasnalu, and Likhu Khola at Sangutar. Precipitation data were available from seven stations in the Tamur and Arun valleys: Chainpur East, Chepuwa, Dhankuta, Dingla, Leguwa Ghat, Mulghat, Num, and Tumlingtar. Unfortunately, streamflow and rainfall records for this limited number of stations only began in 1948 or later.

The Arun River was the primary focus of this study because of the greater availability of data in this basin and proposed large-scale development. Although many hydroelectric projects are under consideration in Nepal, development in the Arun Valley appears to be the most likely large-scale prospect for the 1990s (Dunsmore, 1988; Kattelmann, 1990). A cascade of power projects was imagined for the Arun in a broad plan for the development of the Kosi River basin (Japan International Cooperation Agency, 1984). Recent planning has concentrated on one site where the river channel bends sharply around a ridge, enabling development of high head with a short tunnel.

The Arun is the largest trans-Himalayan river passing through Nepal and also has the greatest snow- and ice-covered area of any Nepalese river basin. The Arun drains more than half the area contributing to the Sapt Kosi River system but provides only about a quarter of the total discharge because more than 80% of the Arun’s drainage area lies in the rain shadow of the Himalaya. South of the Himalayan Crest, the flow of the Arun increases rapidly downstream in the seasonally-humid environment of east Nepal.

Knowledge of the streamflow regime of the Arun is largely based on ten years of record from a single gauge at Tumlingtar, about 50 km downstream of the Arun-3 site. In addition to the record of streamflow at Tumlingtar since 1975, a gauge was operated farther downstream at Leguwaghat from 1979 to 1983, and new gauges were installed at Uwa Gaon (a few km upstream of the Arun-3 site) in 1986 and near the Nepal-China border in 1989 (Fahlbusch, F., Morrison-Knudsen Engineers, personal communication). Staff gauges have also been monitored near the Arun-3 site and on the Barun tributary (Thapa, 1987).

Planning for the Arun-3 project has necessarily proceeded with little hydrologic and climatic information. With plans for diversion of up to
150 m$^3$ s$^{-1}$, water availability during periods of minimum flow is critical to success of the project. The Arun is particularly favourable in this regard because its dry-season flow is greater in absolute terms than any other river of east Nepal with comparable elevation or channel gradient near the measurement site. Most of the flow in the Arun at Tumlingtar during the dry season has been assumed to come from Tibet (Nepal Electricity Authority, 1986 and 1987; Liu & Sharma, 1988). However, dry-season contributions from the Nepalese tributaries to the Arun may have been underestimated.

**SNOW COVER AND SNOWMELT RUNOFF**

There is a virtual absence of data about snow cover throughout the Kosi basin. The only known snow surveys were conducted from 1947 to 1949 in the Tamur basin between 3000 and 5000 m (Dhar et al., 1985 and 1986). These surveys only found snow in isolated patches in shaded locations. However, anecdotal information reported in mountaineering journals (e.g. *Himalayan Journal, American Alpine Journal*) and books imply that substantial snowpacks sometimes accumulate in the approach areas to the Khumbu, Makalu, and Kanchenjunga Himals. Such reports suggest snow cover tends to be highly variable, being scoured from wind-exposed slopes and redeposited in sheltered locations. Small areas also accumulate deep snowpacks where a combination of conditions happens to be favourable. For example, the Shipton Pass area south of the Barun Valley often has deep snow cover while adjoining areas are snow-free. Cooler temperatures at the end of the monsoon may result in most of the annual accumulation of snow (Sharma, 1985). During the Glaciological Expedition to Nepal, most snowfall in the Khumbu at 4200 m occurred in October during the transition period after the monsoon (Yasunari, 1976). Occasional western disturbances penetrating farther east than usual add snow during the winter months.

Snowmelt has been assumed to be responsible for the first rise in water levels after the month of February (e.g. Sharma, 1977). In low-elevation basins with little or no contributing area in the mountains, streamflow continues to recede into May when rainfall produces direct runoff. Clear evidence of snowmelt runoff could be provided by hourly discharge data of headwater streams showing a daily rise and fall in flow corresponding to the lagged daily cycle of snowmelt. Daily snowmelt peaks were distinguishable in hydrographs from two gauges on the Karnali in west Nepal from May into early June (Chyurlia, 1983). However, hourly records are not known to have been examined in this regard in east Nepal. Applying hydrograph-separation techniques to discharge records of the Kosi at Tribeni (57 000 km$^2$), Chyurlia (1983) estimated that snowmelt accounts for about 20% of the flow in March, 50% in April, 70% in May, and 40% in June.
STREAMFLOW CHARACTERISTICS

Annual hydrographs of tributaries to the Sapt Kosi demonstrate that streamflow begins to increase during spring after a winter minimum (Fig. 1). However, the rate of increase is quite low until June when monsoon rains begin to produce substantial streamflow. Monthly proportions of annual discharge were calculated from average values over the available record for seven gauges within the Kosi drainage basin (Table 1). February or March were the months of minimum streamflow in all cases. On the average over 10 to 25 years, depending on the river, streamflow began to increase by about 10 to 25% from March to April over the previous month’s volume. From April to May,

![Average Monthly Discharge](image)

![Average Monthly Discharge](image)

**Fig. 1** Average annual hydrographs for tributaries to the Sapt Kosi.

<table>
<thead>
<tr>
<th>River</th>
<th>Jan.</th>
<th>Feb.</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likhu</td>
<td>2.2</td>
<td>1.6</td>
<td>1.6</td>
<td>1.7</td>
<td>2.5</td>
<td>7.6</td>
</tr>
<tr>
<td>Tamba</td>
<td>1.7</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
<td>3.3</td>
<td>10.0</td>
</tr>
<tr>
<td>Dudh</td>
<td>1.9</td>
<td>1.4</td>
<td>1.5</td>
<td>1.7</td>
<td>2.9</td>
<td>10.6</td>
</tr>
<tr>
<td>Bhoite</td>
<td>2.3</td>
<td>1.7</td>
<td>1.8</td>
<td>2.2</td>
<td>3.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Khimti</td>
<td>1.9</td>
<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
<td>2.7</td>
<td>11.7</td>
</tr>
<tr>
<td>Sunkosi</td>
<td>1.6</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>2.1</td>
<td>6.4</td>
</tr>
<tr>
<td>Arun</td>
<td>2.5</td>
<td>2.2</td>
<td>2.9</td>
<td>3.5</td>
<td>5.6</td>
<td>11.7</td>
</tr>
<tr>
<td>Tamur</td>
<td>1.7</td>
<td>1.2</td>
<td>1.3</td>
<td>2.0</td>
<td>4.4</td>
<td>11.8</td>
</tr>
</tbody>
</table>
streamflow increased by 45 to 65% in most of these rivers. The exception was the Tamur where streamflow increased by 50% from March to April and by 120% from April to May, on the average. For rivers other than the Tamur, these increases represent an average of 5 mm of runoff spread over the basins’ areas between March and April and 15 to 20 mm of increased flow between April and May. In the Tamur, the equivalent depths were twice as great.

If 10% of each basin contributed an average of 1 mm per day of snowmelt runoff, a basin-wide average of 3 mm would be produced in a month. If 10% of each basin contributed an average of 5 mm per day of snowmelt runoff, 15 mm of runoff (spread over the basin area) would be generated in a month.

Fig. 2 Hydrographs from the Arun River at Tumlingtar show the importance of storm runoff in increasing average discharge during spring.
Substituting other reasonable proportions of snow-covered area and average melt intensities demonstrates that these incremental increases in monthly discharge could be generated by snowmelt in a small fraction of each basin.

Daily discharges were only available from the Arun River at Tumlingtar. Hydrographs from five of the spring seasons show several sharp spikes in the trace, which are characteristic of storm flows (Fig. 2). It is difficult to imagine such dramatic fluctuations as a result of snowmelt events. Unfortunately, daily precipitation records were not available for comparison. Nevertheless, the form of the hydrographs suggests that rainfall-runoff may provide a large fraction of the flow above base level during spring in the Arun.

A simple look at monthly precipitation totals from several gauges in the Arun and Tamur valleys (Table 2) reveals that rainfall during March, April, and May could also produce much of the observed increases in streamflow during these months. Although the lower-elevation sites have averages less than 100 mm during March and April, the higher sites (Num and Chepuwa) received substantial rainfall throughout spring. Depending on one's assumptions regarding representativeness of the gauges and distribution of precipitation, a case could be made that spring rainfall could produce most of the increase in streamflow before the monsoon begins in earnest.

Although hardly conclusive, the available data suggest that rainfall during spring months is capable of generating most of the initial rise in streamflow observed in rivers of the Sapt Kosi basin. Snowmelt undoubtedly contributes to streamflow at this time of year, but it appears to be far less important in east Nepal than in the western Himalaya. Analyses of precipitation and streamflow data at shorter time scales would resolve this question. Hourly discharge data from headwater streams would allow observation of daily snowmelt cycles. Daily precipitation amounts would allow comparison with streamflow fluctuations. The brief study reported here indicates that a combination of snowmelt and rainfall provide the initial relief from minimum streamflow in the rivers of east Nepal.

<table>
<thead>
<tr>
<th>Station</th>
<th>Feb.</th>
<th>March</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulghat</td>
<td>6</td>
<td>24</td>
<td>30</td>
<td>89</td>
</tr>
<tr>
<td>Dhankuta</td>
<td>11</td>
<td>30</td>
<td>48</td>
<td>69</td>
</tr>
<tr>
<td>Chainpur</td>
<td>11</td>
<td>22</td>
<td>73</td>
<td>151</td>
</tr>
<tr>
<td>Leguwa Ghat</td>
<td>8</td>
<td>23</td>
<td>84</td>
<td>212</td>
</tr>
<tr>
<td>Dingla</td>
<td>10</td>
<td>33</td>
<td>103</td>
<td>214</td>
</tr>
<tr>
<td>Tumlingtar</td>
<td>33</td>
<td>64</td>
<td>110</td>
<td>201</td>
</tr>
<tr>
<td>Chepuwa</td>
<td>71</td>
<td>126</td>
<td>168</td>
<td>259</td>
</tr>
<tr>
<td>Num</td>
<td>56</td>
<td>69</td>
<td>326</td>
<td>588</td>
</tr>
</tbody>
</table>
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REFERENCES


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