Application of the regional flow estimation method in the Himalayan region

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Abstract The regional flow estimation method (RFEM) has been used in the UK and Europe for many water resources planning applications. The method, which is based on the fact that the temporal variability of flows at any point in a river is controlled by the physical characteristics of the upstream basin, provides an estimate of the flow-duration curve at ungauged sites. This paper describes the adaptation of the method in Nepal and the Indian state Himachal Pradesh; a region typified by high mountains and a monsoon-dominated climate and having relatively sparse hydrometric and meteorological observations. By relating the observed river flow data to pertinent basin characteristics, regional statistical models, capable of describing the flow regime at any location in the study area, were derived. Though the data available to the project was limited, the results were generally satisfactory, comparing favourably with those from similar studies in Europe.

Key words regional models; multivariate regression; flow-duration curves; ungauged basins; Himalayan region; Nepal; Himachal Pradesh

INTRODUCTION

The regional flow estimation method (RFEM) (Gustard et al., 1992) has been applied in the UK and Europe (Rees et al., 2000) for many years. The method provides an estimate of the flow-duration curve at ungauged sites and can be used for a variety of water resources planning applications, such as, determining appropriate levels of abstractions and discharges for irrigation, water supply or hydropower generation. This paper describes how the method was applied in the Himalayan and sub-Himalayan region of Nepal and Himachal Pradesh, India.
CHARACTERISTICS OF THE REGION

The Hindu Kush–Himalayan region extends in a broad arc across the northern part of the Indian sub-continent. It is a region of stark contrast in relief and climate, from the fertile sub-tropical plains of the Ganges and Indus basins to near polar conditions in the great mountains of the Himalaya and Hindu Kush ranges. Annual average rainfall varies widely throughout the region due to the combined effect of monsoon and topography. Monsoon occurs in the summer months as weather systems from the southeast, bring moist air inland from the Bay of Bengal. Typically, runoff is concentrated in the monsoon period, with discharges from July to September accounting for between 65% and 75% of total annual runoff (Alford, 1992). Flows start to recede during October and the low-flow period continues until the start of the next monsoon.

MODEL DEVELOPMENT

The regional flow estimation method

The regional flow estimation method (RFEM) is based on the fact that the temporal variability of flows in a river, as described by the flow–duration curve, is controlled by the natural storage characteristics of the upstream basin. These characteristics are closely related to the soils and geology within the basin, although, at higher altitudes, the presence of snow and ice is also an important factor. If the flow–duration curves of different basins are standardized by the basin mean flow, certain low flow statistics, such as the 95th-percentile flow \( Q_{95} \), can be used to describe the whole flow–duration curve. With the RFEM, multivariate regression is to determine \( Q_{95} \), standardized by mean flow, for different soils or geology types. These are then used to create a map of standardized \( Q_{95} \). Overlaying a basin boundary onto the map enables the \( Q_{95} \) of any basin within that area to be determined. The estimate of \( Q_{95} \) may be used to identify a typical (standardized) flow–duration curve for the basin. The curve is selected from a family of flow–duration “type” curves that characterize the range of flow regimes that are likely to be encountered. Finally, to express the selected flow–duration curve in units of \( \text{m}^3 \text{s}^{-1} \), a suitable method to estimate the basin mean flow is necessary.

Database development

The project was conducted as two separate sub-projects with a different regional model resulting from each. In Himachal Pradesh the study was confined to a relatively homogeneous rain- and snow-fed region, at an elevation of between 2000 and 5000 m. For Nepal, however, the whole country was considered as a single region; the limited availability of data precluded the ability to develop statistical models for smaller areas. In both study areas, the criteria for basin selection were as follows. First, the basins should have a long record (5 years, or more) of daily (or FAO 10-daily, in India) flow data with a minimal amount of missing values (<5%). Second, the basins should be less than 1000 km² and be free of significant artificial influences. Finally, the selected
basins should be representative of conditions throughout each respective study area. Applying these criteria pragmatically, 52 gauging stations were selected in Nepal, most being located at elevations of between 1000 and 4000 m. Sixty stations were similarly selected in Himachal Pradesh. Quality control checks (e.g. inspection of hydrographs, flow-duration curves and double-mass plots, rainfall/runoff comparisons) further reduced the sample data set to 40 in Nepal and 41 in Himachal Pradesh. The boundary for every selected basin was digitized. Various spatial data, describing the climate (e.g. rainfall, temperature) and physiography (e.g. geology, soils, land use, topography) were also obtained.

**Derivation of regional \( Q_{95} \) models**

In Nepal, the \( Q_{95} \) analysis was based on the 1:1 000 000 scale Geological Map of Nepal, which describes 20 major rock types. In Himachal Pradesh, the 1:500 000 scale Soil Survey Map of India, which describes 96 soil types, was the basis of the analysis. By arranging the 96 soil types according to the description of their drainage properties (e.g. drained, well drained, and excessively drained) and depth, a more manageable set of 17 soil groups was defined for Himachal Pradesh. In both study areas, the presence of permanent snow and ice was inferred from the US Geological Survey GTOPO30 digital elevation model (US Geological Survey, 1996). On the recommendation of local hydrologists, permanent snow and ice was considered to be present at all altitudes above 5000 m in Nepal and 4500 m in Himachal Pradesh. The resulting maps were overlaid onto the respective soils or geology maps to give an additional “snow/ice group” in each case. The snow/ice group, rather than the underlying soil or geology, was assumed to dominate the hydrological response wherever it occurred.

The digitized basin boundaries were used to determine the proportional extent of each soils or geology group in the basins. Stepwise multivariate regression was then applied in both study areas, iteratively grouping soils or geology types according to their physical and hydrological properties until sensible parameter estimates of \( Q_{95} \) were obtained for each group. Nine groups of soils were defined in the final regression model for Himachal Pradesh. In Nepal the same procedure resulted in eight groups being defined, though an inability to obtain a stable parameter estimate for the predominant geology of the Terai resulted in this part of the country being excluded. The \( Q_{95} \) parameter estimates for Nepal and Himachal Pradesh are shown in Tables 1 and 2. An inevitable feature of this type of analysis is that as the number of variables reduces during successive regressions, so does the coefficient of multiple determination \( (R^2) \). Coefficient of multiple determination values of 53% for the regression equation for \( Q_{95} \) in Himachal Pradesh and 45% for that in Nepal, compare very favourably with results obtained in Europe, where \( R^2 \) values ranged from 30% in Spain to 50% in the UK (Rees et al., 2000). The relatively high standard errors for the parameter estimates of some groups compared to others reflect that these particular groups were poorly represented in the sample data set (i.e. the groups concerned occurred in small proportions in a few basins only). However, the overall standard error of the estimate for \( Q_{95} \), being 4.6% of mean flow and 5.3% of mean flow in Nepal and Himachal Pradesh respectively, was deemed acceptable in both cases.
Table 1 \( Q_{95} \) parameter estimates for final grouping of geology types in Nepal.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Description</th>
<th>Parameter estimate (% mean flow)</th>
<th>Standard error of parameter (% mean flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROUP 1</td>
<td>Fluvio sediments</td>
<td>9.5</td>
<td>5.4</td>
</tr>
<tr>
<td>GROUP 2</td>
<td>Sedimentary rocks</td>
<td>24.3</td>
<td>3.4</td>
</tr>
<tr>
<td>GROUP 3</td>
<td>Impermeable crystalline rocks</td>
<td>16.3</td>
<td>1.9</td>
</tr>
<tr>
<td>GROUP 4</td>
<td>Impermeable granitic rocks</td>
<td>11.4</td>
<td>4.0</td>
</tr>
<tr>
<td>GROUP 5</td>
<td>Schistose metamorphics</td>
<td>23.6</td>
<td>6.6</td>
</tr>
<tr>
<td>GROUP 6</td>
<td>Clastic metasediments</td>
<td>5.4</td>
<td>3.3</td>
</tr>
<tr>
<td>GROUP 7</td>
<td>Glacio-fluvial metasediments</td>
<td>23.9</td>
<td>43.6</td>
</tr>
<tr>
<td>GROUP 8</td>
<td>Permanent ice and snow</td>
<td>26.3</td>
<td>15.3</td>
</tr>
</tbody>
</table>

\( R^2 = 0.45 \); standard error of the estimate of \( Q_{95} = 4.6 \% \) mean flow.

Table 2 \( Q_{95} \) parameter estimates for final groupings of soils in Himachal Pradesh.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Description</th>
<th>Parameter estimate (% mean flow)</th>
<th>Standard error of parameter (% mean flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROUP 1</td>
<td>Deep, excessively drained Medium deep, excessively drained</td>
<td>49.5</td>
<td>9.6</td>
</tr>
<tr>
<td>GROUP 2</td>
<td>Deep, moderately well drained Deep, well drained</td>
<td>35.8</td>
<td>4.0</td>
</tr>
<tr>
<td>GROUP 3</td>
<td>Medium deep, excessively drained Deep, excessively drained</td>
<td>24.7</td>
<td>4.4</td>
</tr>
<tr>
<td>GROUP 4</td>
<td>Medium deep, well drained</td>
<td>39.4</td>
<td>5.8</td>
</tr>
<tr>
<td>GROUP 5</td>
<td>Mountain and valley glaciers and rock outcrops</td>
<td>30.8</td>
<td>10.9</td>
</tr>
<tr>
<td>GROUP 6</td>
<td>Rock outcrops Shallow, excessively drained</td>
<td>22.8</td>
<td>2.3</td>
</tr>
<tr>
<td>GROUP 7</td>
<td>Shallow, somewhat excessively drained</td>
<td>42.3</td>
<td>5.0</td>
</tr>
<tr>
<td>GROUP 8</td>
<td>Shallow, well drained</td>
<td>21.0</td>
<td>3.4</td>
</tr>
<tr>
<td>GROUP 9</td>
<td>Permanent snow and ice</td>
<td>20.8</td>
<td>3.3</td>
</tr>
</tbody>
</table>

\( R^2 = 0.53 \); standard error of the estimate of \( Q_{95} = 5.3 \% \) mean flow.

The models were also assessed in terms of the bias, where the predicted \( Q_{95} \) minus the observed is expressed as a percentage of the observed. The minimum bias observed in Nepal was \(-40\%\), whilst the largest bias was over \(+300\%\). The absolute bias is greatest for basins where observed \( Q_{95} \) is less than \( 10\% \) of the mean flow. This is a numerical feature of the comparison, where small absolute differences between observed and predicted give rise to large values of bias. Consequently, the distribution of bias is skewed with the average bias being \( 51\% \). Non-parametrically, \( 68\% \) of stations were found to have bias values of between \(-23\%\) and \(+127\%\). For Himachal Pradesh, the minimum bias was \(-30\%\), whilst the largest bias was \( 54\% \). The mean bias was \( 3\% \), with \( 68\% \) of stations having bias values between \(-15\%\) and \(+18\%\). As in Nepal, the bias increases as observed \( Q_{95} \) lessens. Using the parameter estimates for each soils or geology group, grids of standardized \( Q_{95} \) were mapped at a 1 km by 1 km grid resolution for both study areas. The \( Q_{95} \) map for Himachal Pradesh is shown in Fig. 1.
Regional flow–duration type curves

The next activity in either study area was to derive flow–duration “type” curves typifying the full range of basin responses, from those having a significant amount of natural storage and corresponding low variability in flows to those having very little natural storage and a high variability in flows. A similar approach was used in both, where the standardized flow–duration curves for the selected basins were “pooled” into classes based on the $Q_{95}$. For each class, the average curve (or type curve) was determined, resulting in the definition of a “family” of flow–duration type curves.

Mean flow estimation

The mean flow of a basin is conventionally expressed in units of $m^3\cdot s^{-1}$, however, to enable the comparison between basins of different sizes it is better expressed as an average annual runoff depth (AARD, in mm). Several different methods for estimating runoff have been described previously by FRIEND (Flow Regimes from International Experimental and Network Data) researchers, including a multiple-regression approach (Menzel & Lang, 1998), kriging methods (Leblois & Sauquet, 1997), physically-based models (Gustard et al., 1992) and empirical methods (Rees et al., 1997). Most relate the observed runoff to the climatic and physical characteristics of basins. In Himachal Pradesh basin estimates of annual precipitation derived from a 1:2 000 000 scale map were so inconsistent with the observed runoff that they had to be discarded. In the absence of other adequate climatic data for Himachal Pradesh, the runoff was calculated from the following simple regression relationship, where the mean basin elevation
(ELEV, in m) was calculated from the US Geological Survey GTOPO30 Data Set (US Geological Survey, 1996):

$$\text{AARD} = (0.5997 \cdot \text{ELEV}) - 319.692$$  \hspace{1cm} (1)

Here, the sample coefficient of determination ($R^2$) was 0.73 and standard error 306 mm.

In Nepal, the project benefited considerably from having access to the original digital maps that are shown in the Climatic and Hydrological Atlas of Nepal (ICIMOD, 1996). However, due to the lack of evapotranspiration data and the apparent unreliability of temperature-based methods for estimating evapotranspiration in mountainous areas (e.g. Thornthwaite, 1948), a multivariate regression approach was also adopted in Nepal. Using bivariate analysis and Spearman rank correlation to consider the relative importance of a variety of basin characteristics, it was found that runoff was most strongly correlated with average annual precipitation (PRECIP, in mm) and the mean basin elevation. The following regression relationship resulted, in which the sample coefficient of determination ($R^2$) was 0.73 and standard error 390 mm:

$$\text{AARD} = \text{PRECIP} + (0.187 - \text{ELEV}) - 764.712$$  \hspace{1cm} (2)

The bias in the estimated average annual runoff depth in both study areas typically ranges between −40% and +50% with a mean bias of +6% in Nepal and −5% in Himachal Pradesh. Although both models seem to conform to the general rule that evaporation losses decrease with altitude (Alford, 1992), they tend to overestimate runoff at low elevations while underestimating runoff at higher elevations. This may mean that the models are failing to account for higher losses (evaporation or seepage) at low elevations while at high elevations it may be that the models are overestimating losses or not accounting for the contribution from snow or ice. The above equations were applied to provide 1-km grids of average annual runoff depth in both study areas. The runoff grid for Nepal is shown in Fig. 2.
A PRACTICAL APPLICATION OF THE METHOD

The models described were developed to provide a means of estimating the water availability for small-scale hydropower schemes in Himachal Pradesh and Nepal. A software package incorporating the models has been developed such that, if the user simply enters the basin boundary for any prospective site, the flow-duration curve will be derived. The curve is then used to calculate the hydropower potential of the site. Thus, the software will be a useful tool for the evaluation of small-scale hydropower potential, development of which will lead to improved prosperity and quality of life for the rural poor.

CONCLUSIONS

The paper has shown that it is possible to develop RFEM-based models in the Himalayan region. As with any model, the reliability and accuracy of the results depends on the quality of the data from which it was derived. In Himachal Pradesh, focusing on a relatively hydrologically homogeneous region helped but even here some of the soil types that occur were poorly represented within the 41 selected basins. In Nepal, with most of the 40 selected gauging stations located at elevations of between 1000 and 4000 m, it is not surprising that there were difficulties representing the hydrology of basins at higher or lower altitudes. To improve the models and, thus, enable a more accurate assessment of the water resources generally, the spatial and temporal representativeness of the hydrometeorological networks of the region needs to be improved. Nevertheless, despite the limited data, the models that were developed in both study areas were considered to give generally satisfactory results, comparing favourably with the results from earlier studies in Europe.

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