Section 3
Explanatory Notes

1 Climatic Maps and Diagrammes

1.1 Temperature Maps

Because of the complex terrain, the existing network of temperature stations (80 stations) does not portray a realistic picture of the temperature pattern. To achieve a more realistic picture of the temperature pattern in Nepal, an objective method was developed, as described below.

Temperature correlates closely with elevation, and, at the same time, it also depends upon many other factors such as latitude, longitude, wind, orientation, slope, aspect, and the height of temperature inversion. Inclusion of all these factors in a model makes the problem more complex. Hormann (1994) presented the use of a regression equation model to chart temperatures in a region with complex terrain. Here, only elevation, latitude, and longitude are taken into consideration for the development of the model, as depicted by the following:

$$T = A \times \text{Elevation} + B \times \text{Latitude} + C \times \text{Longitude}$$

where A, B, and C are coefficients and T is the temperature. The elevation is in metres and the latitude and longitude are in degrees.

The coefficients A, B, and C for each month are calculated by using the elevation, latitude, and longitude variables and the mean monthly temperature data from the 80 available stations, using records for more than five years. The coefficients A, B, and C are calculated for mean monthly maximum temperature and mean minimum temperature separately. The elevation data at every minute grid-point coordinate were retrieved manually from the 1:50,000 map produced by the Survey Department of His Majesty's Government of Nepal. The number of grid points extracted totalled 41,800, and, at every point, the coefficients were applied to generate the temperature value. The coefficient of correlation between temperature generated and observed temperature was found to be more than 0.99, demonstrating the usefulness of the model. The mean maximum temperature and mean minimum temperature generated were then used to analyse and prepare the individual monthly maps.

The mean monthly temperatures were computed by averaging the monthly maximum and minimum temperatures generated.

1.2 Precipitation Maps

Considerable spatial variations in precipitation were observed, due to the exceptionally rugged terrain of Nepal. The minimum density of rain-gauges recommended by the WMO for pluviometric networks is 100 to 250 per sq. km., i.e., about 600 to 1,500 stations will be necessary in Nepal for good representation. But, because of the financial and topographical constraints, as well as the lack of manpower in the remote mountain areas, the recommended norms could not be followed, especially in the northwestern parts of the country. Available data from 264 stations with records going back over five years up to the year 1990 were used for the precipitation analysis. With these data, mean monthly precipitations were computed for all the stations and used in mapping.

The mean annual precipitation was computed by considering the total precipitation of the 12 mean monthly precipitation from all stations used for the analysis. The precipitation during the monsoon season (June-September) contributes about 80 per cent of the annual total, and so the understanding of its characteristics becomes important. Therefore, the total mean monthly precipitation data for the period from June through September are presented.

The frequencies of rainy days (>1.0 mm per day) are presented on a monthly basis, but, for the monsoon months of June through September, additional frequencies of other intensities such as > 10 mm, >20 mm, and >30 mm per day are also presented.

The highest 24-hour precipitations were extracted from the records available from the 264 precipitation stations till the year 1995. These data were analysed to prepare the highest 24-hour precipitation map. This will help to identify the region with a greater tendency for heavy 24-hour precipitation.

1.3 Relative Humidity Maps

In most meteorological stations, dry-bulb and wet-bulb temperature observations are taken at 0300 UTC (0845 NST) and 1200 UTC (1745 NST) and monthly mean relative humidity is computed at these times. The relative humidity average at these two times is taken as the mean relative humidity for that month. In a real sense, this value can deviate from the actual relative humidity, but these are the only data available, and so the computations are performed in this way. It is expected that this will provide some idea of the relative spatial distribution of this parameter.

For analysis and mapping, data from 106 station were used with records going back at least five years.

1.4 Sunshine Duration Maps

Sunshine duration is measured in Nepal by using the Campbell-Stokes' sunshine recorder. The number of stations with this equipment is low for the purposes of having a representative map and, therefore, 41 stations with records going back at least two years were included in the analysis.

1.5 Fog Frequency Figures

Fog is a meteorological phenomenon which is observed and recorded regularly at synoptic stations. In this Atlas, the daily frequencies in fog occurrence were calculated from the observations taken at 0000, 0300, 0600, 0900 and 1200 UTC at twelve synoptic stations, namely, Taplejung, Biratnagar, Dhankuta, Okhaldhunga, Kathmandu, Simara, Pokhara, Bhairahawa, Birendranagar, Jumla, Dipayal, and Dadeldhura. The data used were from the period from 1981 - 1990.

A brief explanation of the type of fog observed is presented here. Fog, in any place, usually occurs when ambient temperature tends to be equal to dew-point temperature. In valleys, radiation fog dominates in the winter season, with less or no occurrence of fog during other times of the year. The stations over the ridges and slopes show a greater frequency of fog during the summer (rainy) season. In fact, these stations are within the cloud deck, which is mostly formed due to the mechanical and thermal lifting processes of air masses.

1.6 Monthly Variation of Temperature and Precipitation for Selected Stations

In the previous maps of temperature and precipitation, spatial features for each month were depicted. In this case, the temporal features are presented on a monthly basis of maximum temperature, minimum temperature, and precipitation for a period of one year at 12 stations. The average, maximum temperature, minimum temperature, and precipitation values used here were derived from the long-term data available from those stations and can be taken as the representative values for those stations.

2 Hydrologic Maps/Figures

2.1 Drainage System of Nepal

The scale of the map (Map 1) is 1:2,000,000. The map depicts the drainage network and the delineation of major sub-catchments. Forty regularly operating stations, along with seven stations that had been operating regularly for at least for ten years, are indicated in the map with reference numbers. Details incorporating the location, elevation, drainage area, instrumentation, and date of establishment for each station are presented in Section 2.1. The map is useful for general hydrological studies. The main constraints to the establishment of a minimum/optimum hydrological network are remoteness, poor accessibility, and lack of resources. Frequently, stations are destroyed by floods, landslides, and intense sediment/debris flows. Insufficient and unskilled manpower hamper routine hydrometric work and hydrological data analysis.

The map has been prepared with information gathered from the various sources (Dept of Hydrology and Meterology 1983; Survey Dept, HMG Nepal 1985; Water Induced Disaster Prevention Technical Centre, HMG/N 1994)

2.2 Hydrographic Scheme for the Karnali, Sapta Gandaki, and Sapta Koshi with Tributaries Equal to or Greater than 10 kilometres (Figures 1.1 to 1.3)

Sometimes it is essential to measure the length of tributaries and the main stream for various planning purposes. Therefore, tributaries longer than 10 kilometres for the three major river systems, namely, the Karnali, Sapta Gandaki, and Sapta Koshi, have been straightened out linearly and are depicted in Figures 1.1 to 1.3.

The length of various rivers can be measured efficiently and accurately, and such a scheme is very useful in morphometric and hydrologic studies. A base topographical map on a scale of 1:506,880, published by the Department of Survey, Ministry of Defence, United Kingdom (1967), has been used for the preparation of the hydrographic scheme. Preparation of a more elaborate hydrographic scheme using a larger scale map to incorporate tributaries less than 10 kilometres in length would be useful for a more detailed understanding of hydrographic and morphological characteristics.

2.3 Water Availability Histograms for Major Rivers in Nepal (Figure 2)

Water is the most important natural resource in Nepal. The annual mean streamflow in Nepal is estimated to be about $200 \times 10^9 m^3$. The major glacier-fed rivers, namely, the Sapta Koshi, Karnali, and Narayani, contribute about 72 per cent of this amount. About 75 to 80 per cent of the total surface water flows out of Nepal in the monsoon season only. Water availability histograms for major rivers, namely, the Narayani, Sapta Koshi, Karnali, Mahakali, Bagmati, West Rapti, Kankai, and Babai, have been prepared with long-term mean monthly discharges acquired from the Department of Hydrology and Meteorology (DHM), HMG/N. For each hydrometric station, the volume of discharge during the monsoon season (June 15 to September 15), non-monsoon season, and during the entire year have been calculated and depicted in the form of histograms in Figure 2. These statistics are useful for water resource planning and management. Discharge data have been made available by the DHM/N. At least twelve years of data for each station have been used for this purpose.

2.4 Probable Maximum Floods and Unusual Flood Discharge in the Nepalese Context with Respect to Floods in Some Regions of the World (Figure 3)

Floods resulting from high intensity rainfall occurring in mountainous regions occasionally overflows the river banks and inundates the surrounding low-lying regions after reaching the plains, destroying property and lives. Floodplains are densely inhabited, because rivers satisfy man's domestic, municipal, irrigation, and other demands. Therefore, it is important to safeguard such areas from floods. Reservoirs and river training works are among the flood control measures used. Floods have to be estimated with reasonable accuracy to design such infrastructure.

The purpose of Figure 3 is to compare the estimated and unusual floods measured in Nepal (WIDPTC 1994 and Ministry of Water Resources 1985, 1989, and 1990) with those from other regions of the world. These floods have been plotted on a curve (Raudhivi 1977 and Mutreja 1986) from Creager's equation given by:

$$Q = 46CA^{(0.894A^{-0.048}-1)}$$

where Q is the extreme specific flood discharge in ft^3/s per sq. mile, A is the catchment area in sq. miles, and C is the coefficient dependent on flood characteristics. The curves presented in Figure 3 are in SI units. These envelope curves are used extensively to gain an indicative idea of extreme floods for planning water resources' projects.

2.5 Flow Duration Curve for a Typical Himalayan River, Karnali at Chisapani (Figure 4)

In hydrology, one important aspect is the study of runoff variability. One way of doing this is by plotting flow duration curves. A flow duration curve is plotted with the rate of runoff on the ordinate against the percentage of time such flow is equalled or exceeded on the abscissa. Such curves can be drawn using daily, weekly, and monthly values. Flows are arranged in descending order of magnitude with each flow value being assigned a rank. The percentage of probability, P, for each flow which is equalled or exceeded, is calculated as

$$P = \frac{m}{n} \times 100$$

where m is the rank assigned to the flow and n is the total number of data in array. An example of the flow duration curves for a typical Himalayan river, the Karnali at Chisapani (Ministry of Water Resources 1989), is shown in Figure 4. Discharge of about $3.5 \times 10^2 m^3/s$ with 0.80 probability excedence occurs during the lowest flow months, December to March. On the other hand, discharge of about $34 \times 10^2 m^3/s$ in the highest flow month of August occurs with 0.80 probability of excedence. The flow duration curves allow evaluation of flows occurring at different levels of probability. This is very useful for determining the potentials for firm and/or average power generation. Such curves can also be used in design of drainage systems and other structures. These curves have been developed with 25 years of data from 1962 to 1986.

2.6 Drainage Density Map of Nepal (Map 2)

Drainage density can be interpreted as a measure of the closeness of the spacing of stream channels. Low drainage density reflects poor drainage conditions in a basin. Such basins are generally resistant to erosion or are very permeable with fewer slopes and scanty vegetation cover. Drainage density, D, is the ratio of the total length of streams of all orders in the basin, ΣL, to the basin area, A, and is given by

$$D = \frac{\Sigma L}{A}$$

The drainage density shown as Map 2 includes only the wet course of rivers/rivulets with lengths greater than two kilometres up to the outlet gorges in the Siwalik Range for major rivers (Dept of Survey, UK 1967). Kankai river basin has the highest value of 0.37 km/sq.km. The other drainage basins have values ranging from 0.35 to 0.29 km/sq.km. The average drainage density of Nepal is about 0.31 km/sq.km. Drainage density is important in hydrology as it affects the speed of runoff following a period of precipitation. Water generally moves faster through a well-developed system of river channels. In other words, with greater drainage density the lag time for runoff decreases, resulting in higher peak.

2.7 Monthly Average Flow of Major Rivers (Figure 5)

Streamflow records constitute the most important data for engineers and hydrologists, because these data are used in the design of water resources' projects. The discharge data can be graphically presented in many ways. One convenient way to present them is with a bar diagramme on a monthly basis. Long-term monthly average histograms and the average annual flow of major rivers, namely, the Mahakali, Karnali, Babai, West Rapti, Narayani, Bagmati, Sapta Koshi, and Kankai, are depicted as insets in the map. Amongst the main glacier-fed rivers, the Narayani River has more mean monthly discharge during the monsoon and post-monsoon seasons than the other rivers. On the other hand, the Karnali has more mean monthly flow during the pre-monsoon season than the others. All rivers obviously show high flows during the monsoon and low flows during the pre-monsoon months.

The histograms shown in the map include only major and medium rivers. The data period used for this purpose differs from station to station, depending upon the availability of records. Discharge data have been obtained from the DHM/N. At least ten years' data have been used for each station. The monthly flow variations give a quick comparison of flow for different major rivers across the country. Dry and wet months can be delineated for studies relating to water resources' planning and management.

2.8 Flood Frequency Curves for Major Rivers (Figures 6.1 to 6.10)

Design of culverts, roads, drainage works, irrigation diversion works, etc requires reliable estimates of floods for the site concerned during a specific period of time in future. Runoff, being essentially a random process, can be estimated only with specific probability. A design flood with certain probability is adopted for the design of structures after useful consideration of economic and hydrologic factors. As the magnitude of the design flood increases, the capital cost of the structure increases, but the probability of risk will decrease. The most economical design flood can be found after studying various alternatives

The prediction of future floods based on historical records is an important aspect in hydrology. The frequency analysis makes use of the observed data to predict the future flood magnitudes along with their probability of return periods. By definition, the return period or recurrence interval, T, is calculated as

$$T = \frac{1}{p}$$

where P represents the probability of flood occurrence. Log normal distribution, which reasonably fits most Nepalese flood discharges, has been used to draw the frequency curves for various rivers. The 100-year floods for major rivers, such as the Narayani, Sapta Koshi, Karnali, and Bagmati, are estimated to be about 25.5 x 10^3 m^3/s, 22.5 x 10^3 m^3/s, 19.5 x 10^3 m^3/s, and 12.5 x 10^3 m^3/s respectively. For the Bagmati River, discharge data from Karmaiya station from 1965 to 1979 have been incorporated with those from Pandherodobhan station from 1980 to 1990, since these stations are within a distance of 1.5 km of each other,and the former station has been abandoned. It is to be noted that prediction of floods is probabilistic rather than deterministic. Data for maximum floods have been obtained from the DHM/N. At least eleven years' data have been used. Most stations have data going back 19 to 28 years.

2.9 Monthly Distribution of Flow for Different Types of Rivers (Figure 7)

Most of the rivers originating from the Himalayan and the Mahabharat ranges are perennial in nature, whereas those originating in the Siwaliks generally dry up in the summer season. Three categories of river are found in Nepal, considering their sources.

These are:

a). rain-fed rivers
b) rain-fed and snow-fed rivers, and
c) rain-fed, snow-fed, and glacier-fed rivers.

The Bagmati is typically categorised as a rain-fed river, whereas the Khimti is a rain-fed and snow-fed river. The Arun is a rain-fed, snow-fed, and glacier-fed river, considering the main sources. Base flow contribution persists for all of these rivers throughout the year. Monthly flows, obtained from the DMH/N and the Ministry of Water Resources (1993), have been used to represent the flow distribution histograms. These flows have been converted into percentages of maximum monthly flows for better comparison. The Arun has about 14 per cent of the maximum average monthly flow in its driest month. The Khimti and Bagmati have about 6 per cent and 4 per cent of the maximum average monthly flow in the driest months. This bar diagramme is very useful for comparison of rivers originating from different zones. Glacier-fed rivers have substantial flows in the dry season. The other two classes of river originating below the permanent snowline are fed significantly by groundwater, including springs, in the dry season. Rivers originating in the Siwalik Range generally dry up in the summer and have not been included in the figure due to inconsistent data.

2.10 Water Balance for Some Typical Stations (Figures 8[a] to 8[c])

The distribution of water balance elements in time and space can reflect the water potential for agriculture. Using monthly average temperature and precipitation data up to 1990, Thornthwaite's water balance technique has been used for three typical stations. Thornthwaite's method has been used to calculate the potential evapotranspiration (Thornthwaite and Mather 1955). If rainfall and soil moisture together do not equal potential evapotranspiration, then water deficiency occurs. Subsequent rainfall may check the water deficiency. On the other hand, when rainfall exceeds the water need, soil moisture gradually increases and saturates the soil to give surface runoff. Soil plays a unique role in the water balance of a region, since it can store water during the rainy season and release it later on through evapotranspiration. For the computational procedure, field capacity was assumed according to the soil type conditions in Nepal in order to establish the depth of stored water in the root zone.

In the water balance accounting procedure, the precipitation, P, is compared with potential evapotranspiration, PE, and, if PE is greater than P, then the difference indicates the amount by which the precipitation has failed to meet water needs. On the other hand, if P is greater than PE, then the difference is the amount of water in excess of water needs.

Accumulated potential water loss, APWL, is obtained by progressively adding all the values of (P-PE). If the soil has never reached field capacity, the first value of APWL is obtained by a successive approximation method using the field capacity table. The amount of soil moisture held in the soil is derived from the APWL and field capacity table (Thornthwaite and Mather 1955). When measured values of field capacity are not available, they can be assessed by considering the soil type and vegetation cover. When P is equal to or greater than PE, the actual evapotranspiration, AE, will be equal to PE. However, if P is less than PE, AE is obtained by adding P to the change in soil storage ΔS. The water deficiency, W_D, is given by (PE - AE). Water surplus, W_S, occurs only after the soil has been recharged to its field capacity.

Water balance has been estimated for three typical stations, namely, Pokhara, Dhankuta, and Jomsom, which are located in relatively wet, moderately wet, and dry regions respectively. The monthly water balance and the different climatic elements of these stations are given in Figures 8(a) to 8(c). Pokhara's precipitation significantly exceeds the water needs for most of the year (Figure 8[a]). Climatically, an annual amount of 2,653 mm of water surplus is accumulated from April to October. For Dhankuta (Figure 8[b]), precipitation is greater than the potential evapotranspiration from June to September. Precipitation above the water need is stored in the soil and brings the upper layer to field capacity in July. After the soil moisture reaches field capacity, any further precipitation, which is not required for potential evapotranspiration, is considered as surplus ultimately lost as runoff. Dhankuta has an annual water surplus of 215mm accumulated from July to September. In October, precipitation fails to supply the water needs by 14mm, and 12mm are supplied by the water stored in the upper layer of the soil. There is only a 2mm water deficit during October. However, in November, water needs of 46mm are not supplied by precipitation. As the soil dries up, water is not readily available from the upper soil layer and only 31mm can be obtained from the soil. Deficit persists until May, when potential evapotranspiration falls below precipitation.

Jomsom (Figure 8[c]) does not experience water surplus as precipitation does not exceed potential evapotranspiration throughout the year. The June to October period is comparatively wet.

SECTION 3: Data Processing

3.1 Software Used

The software programmes used for the analysis and preparation of climatic maps were.

a. Surfer for Windows version 5 and
b. ARC/INFO version 6.1 on an IBM RS/6000 platform.

3.2 Preparing Precipitation, Relative Humidity, Sunshine Duration, and Rainfall Frequency Maps

Generation of Contours (Isolines)

Surfer for Windows was used to generate the isolines of Precipitation, Relative Humidity, Sunshine Duration and Rainfall Frequency.

Step 1. *Creating a Grid from the Data File*

A grid file was created from the given data for a given month. After a number of trials with various grid sizes, an optimum grid size of 60 rows by 100 columns, each cell being 0.08333 x 0.0847 degrees, was adopted. The extent of the grid was from 25.5 degrees latitude and 80 degrees longitude to 30.5 degrees latitude and 88.25 degrees longitude, so that it covered the whole country.

Step 2. *Generating Contours from the Grid File*

There are various options available for generating contours from SURFER software. The method adopted was that of KRIGGING with medium smoothing of lines. A copy of this contour with gray shading and contour labels was printed out so that the different regions could be clearly identified.

Converting the Contour Maps to ARC/INFO Coverage

Step 3. *Exporting the Contour File to DXF Format*

The surfer file was exported to the AutoCAD DXF format. Default parameters were adopted during conversion.

Step 4. *Importing the DXF File to Arc/Info*

The DXF files were then converted to Arc/Info coverages. After creating the labels, a polygon coverage of a corresponding file was built.

Step 5. *Assigning User Ids to Different Polygons*

The coverage was then clipped with the country boundary of Nepal in Arc/Info software. User ids were assigned to the different polygons with the help of the contour map with shade and contour labels. This method, though more mechanical, proved to be simple and less time consuming than various other alternatives such as using CAD and TIN.

3.3 Preparing the Temperature Maps

A different procedure was followed in preparing the temperature maps. First, a point coverage was generated from the source data. The monthly temperatures were assigned as the attribute data for those points.

A *Triangular Irregular Network (TIN)* was generated from the point coverage with the temperature of a certain month as its spot item. This *TIN* was then converted into a grid. A polygon coverage was created from the grid using **gridpoly**. The polygon coverage was then clipped with the country boundary of Nepal and final maps were prepared.

3.4 Map Preparation and Printing

Once the Arc/Info coverages were ready, the map-making process was automated with the use of simple AML (Advanced Arc Macro Language) programmes of Arc/Info. Those maps were then printed in A3 sizes on a Tektronix Phaser III colour printer for high quality reproduction.