3. HYDROLOGY

3.1 GENERAL

The main purpose of hydrologic investigations is the determination of design parameters for the hydroelectric projects under consideration. These comprise basically:

- Available discharges for power generation
- Floods
- Sediments

The discharges cannot be measured directly in a continuous manner in natural streams. Therefore, the procedure is to continuously observe water levels (stages) and to carry out regularly flow (discharge) measurements. Stage-discharge rating curves are then determined on basis of the flow measurements. Their reliability depends on the characteristics of the control sections and the frequency of flow measurements. Flows are then calculated on basis of the observed water levels and the fitted rating curves.

Floods are extreme conditions presenting a risk for any infrastructural development and therefore decisive for the layout, design and construction of hydropower projects. These are calculated on basis of the fitted rating curves and observed maximum water levels. Floods are generally difficult to measure and the reliability of the estimates strongly depends on the quality of the rating curves and the available data about extreme high water levels.

Suspended sediments and bed load affect all types of water resources projects, having a direct impact on the technical and economic viability of the projects. Depending on the characteristics of the streams and the proposed developments, sediment load transported by the streams affects the design of seasonal and daily reservoirs, weirs, dams, intakes and sand traps. The useful life of important project components strongly depends on the sediment load and their handling.

The most frequent problem faced in high mountain areas is the scarcity of basic data, which often requires relying on regional studies to estimate parameters in ungauged areas. The identification and evaluation of hydropower resources require stream flow estimates at many sites for which stream flow measurements are not available.

The following paragraphs contain initially a description of collection and processing of hydrological data. The processing and estimation of design parameters are shown in the next chapter.

Before data collection is described, first the use of hydrologic data as part of hydropower implementation is illustrated in the next two paragraphs.

3.1.1 DISCHARGES

Before details are discussed concerning the data collection in the field, some more information on the type, source, processing and purpose of data shall be given. This is to illustrate the purpose of collecting data.

In this context, two types of information can be distinguished for discharges:

- Unregulated water flows
- Regulated water flows
  - Drinking water

- Irrigation
- Minimum flow requirements to protect ecosystems
- Other uses (water mills, industry, etc.)

Especially the issue of water rights is very critical in development of high head hydropower projects in rural areas. The resource water can be considered as decisive for life sustainability in mountainous areas. Permanent human settlements cannot exist without suitable sources of water for domestic consumption and irrigation water for agricultural activities. These water requirements have priority over other uses and have to be considered during development of hydropower to avoid conflicts and negative impacts on the social, political, economic and environmental setup in the areas of influence of the projects.

Unregulated and regulated discharges can be determined through flow measurements but preferably through the installation and operation of gauging stations. The prevailing water rights can be established through measurements, which can be made during different seasons to have a clear picture about the consumption patterns. However, future requirements have to be determined by carrying out surveys, consulting local, regional and national organizations, etc. The reason is that especially for drinking water and irrigation, present and expected future water needs have to be considered to quantify the requirements (water rights).

The availability of water for power generation has to consider present and future water rights as well as the requirements to protect the ecosystem in the watercourse. Seasonal as well as daily consumption patterns have to be kept in view. It must be noted that the water requirements do not necessarily occur simultaneously. For example, the irrigation requirements in winter are lees than in summer and irrigation activities take place mostly during the day. On the other hand, power requirements tend to be larger in winter and at night.

Concerning the hydrologic and sediment transport regime, the human influence plays a very important role. Therefore, in this respect two water bodies have to be distinguished:

- Canals
- Rivers

The maximum capacity of a canal is determined and can only be changed through remodeling. On the other hand, the discharge of a river is highly variable due to the influence of various natural phenomena such as melting of snow and ice, monsoon rains, tropical cyclones, etc. The following sketch gives an overview over the type and source of discharge data and its purpose.

Additionally to the parameters shown in the sketch, with some exceptions, floods affect all natural streams. These have an enormous impact on the design of diversion structures required during construction as wells as on the relief structures during the useful life of the projects. The chosen return period, which reflects the accepted level of risk, is also important for the sizing of the structures. This will be explained in detail in the following paragraphs.

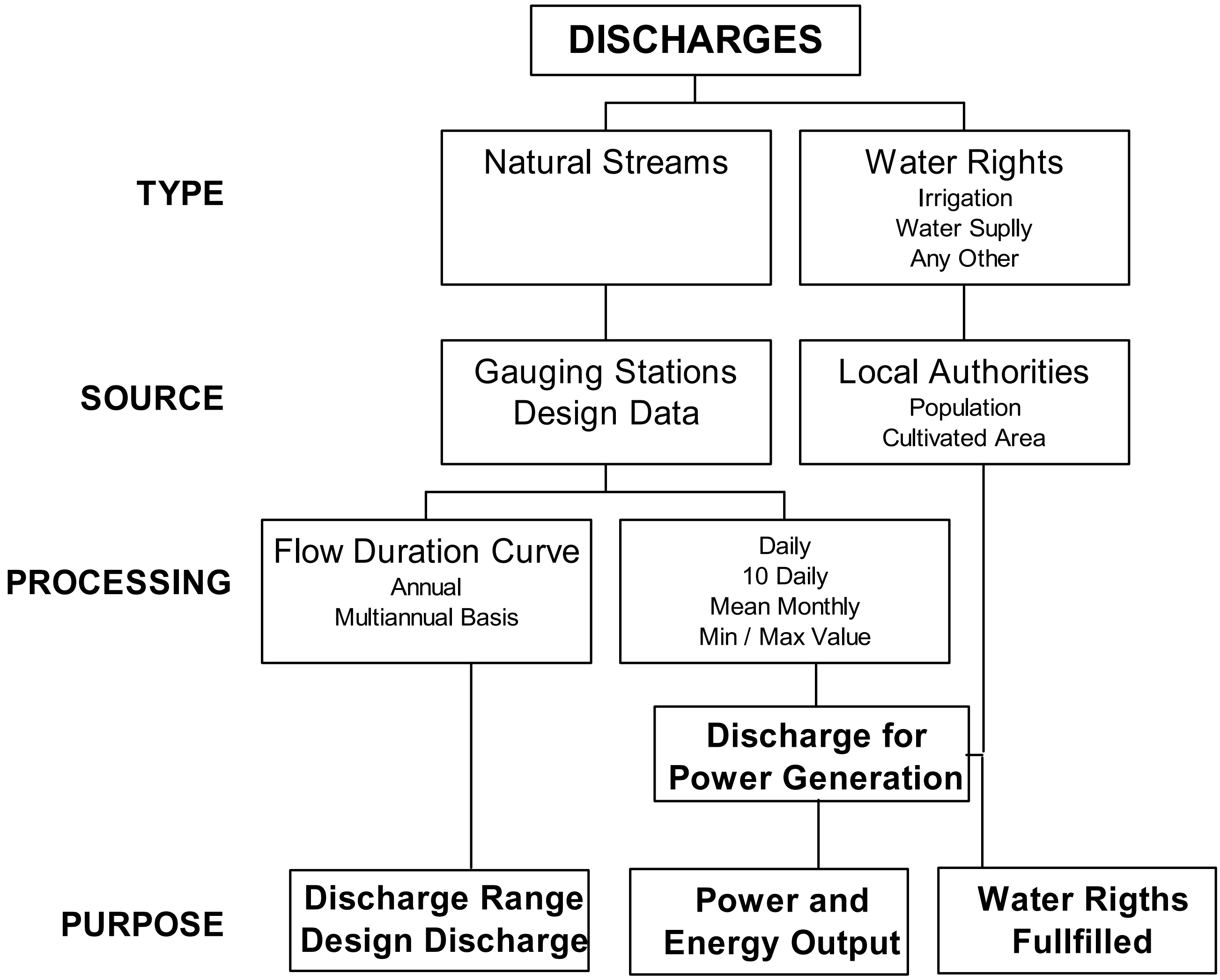


Fig. 3.1: Type, source, processing, and purpose of discharge data for canals

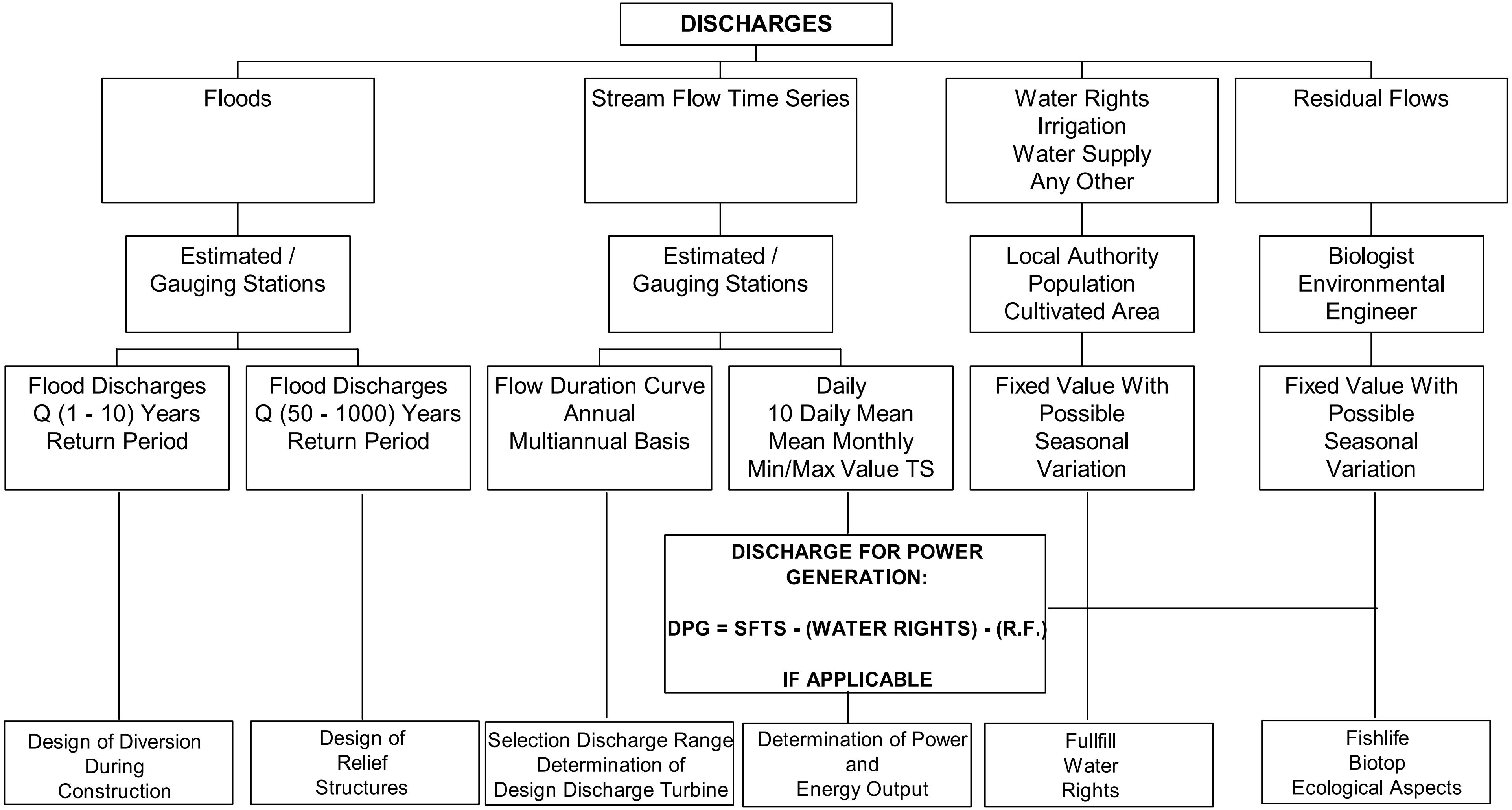


Fig. 3.2: **Type, source, processing, and purpose of river discharges**

3.1.2 WATER LEVELS

For hydropower projects water levels at following sites are of special interest:

- Headwater (weirs, dams, intakes, etc)
- Tailwater (powerhouse, tailwater, etc.)
- River crossings (bridges, siphons, etc.)

The data is obtained from gauge readings and topographic surveys. Through detailed processing of the water levels and discharges, rating curves, extreme minimum and maximum water levels and other relevant parameters can be determined. Thereby the available head for power generation can be determined for the whole range of operational conditions. This allows the determination of the expected power and energy output of the project.

Depending on the hydrologic regime and the morphology of the river course, tailwater levels can have an effect on the available head for power generation. Significant reductions in head can occur due to high flows in narrow river courses.

Minimum tailwater levels are critical to establish the setting of the turbines, especially in case of Francis turbines.

Extreme floods are critical to decide about the location of the powerhouse. In order to minimize risks, the structures have to be placed above the maximum flood level. Alternatively, sufficient protection has to be foreseen to avoid damage when a lower level is selected. The decision has technical and economic implications. A higher powerhouse causes a loss of head and reduces the output of the hydropower project. Protection structures on the other hand are costly and always have a certain risk level associated with them.

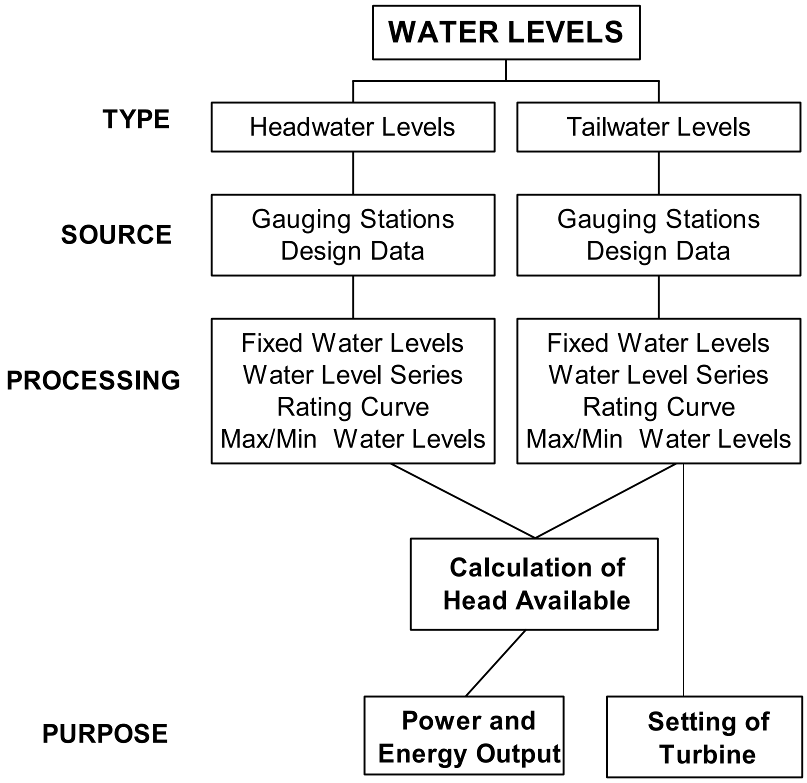


Fig. 3.3: **Type, source, processing, and purpose of data for canals**

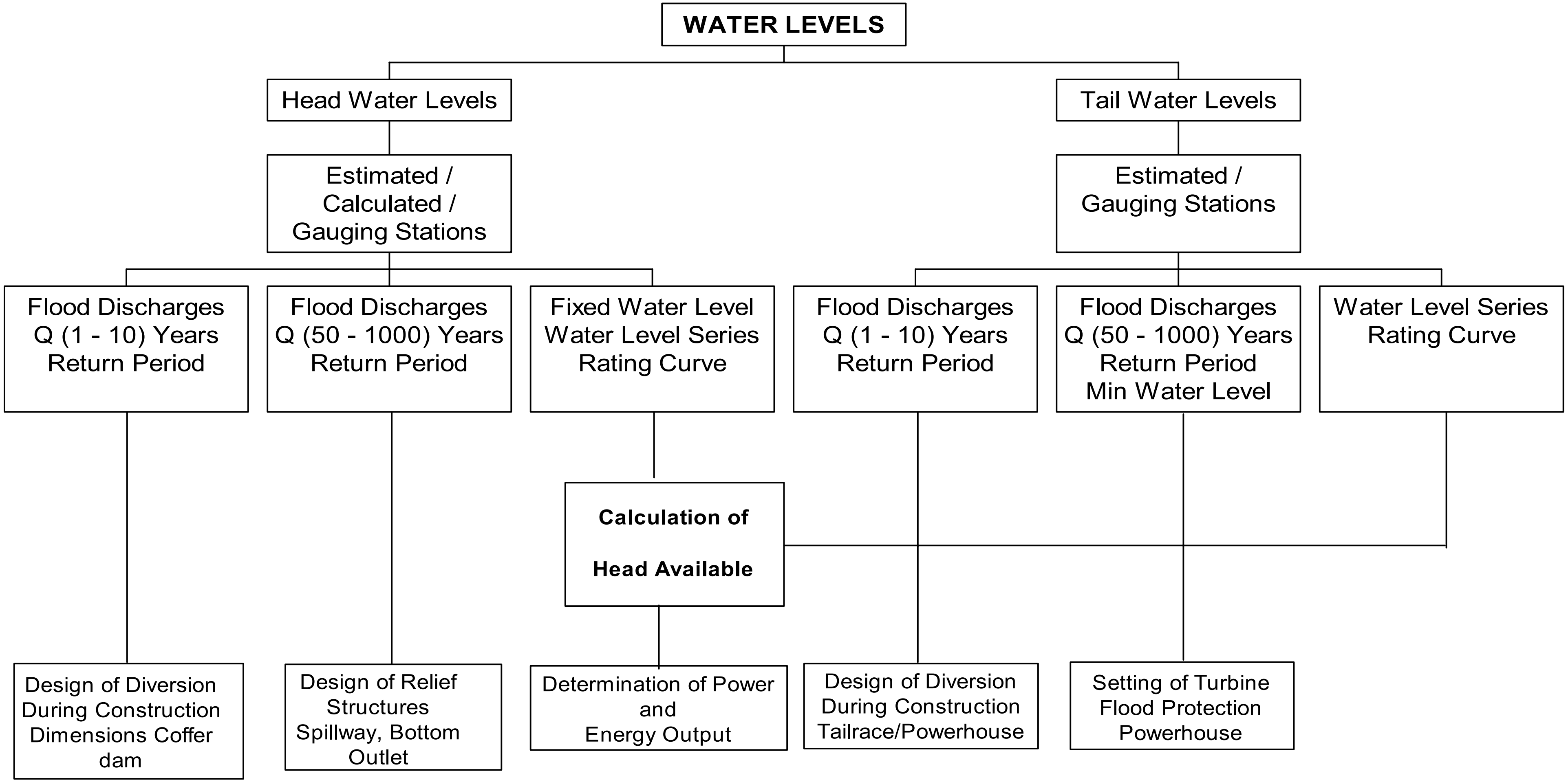


Fig. 3.4: **Type, source, processing, and purpose of water levels for rivers**

3.2 DATA COLLECTION

Collection of hydrologic data comprises the measurement of physical and chemical parameters of the water bodies (natural and man-made) in the field. These activities comprise topographic surveys, water level measurements, flow measurements, sediment sampling, chemical sampling, etc.

In natural streams and canals, discharge data is collected regularly at gauging stations or sporadically at any other points. The flows can also be estimated from discharges through hydraulic structures such as weirs, gates and spillways as well as from pumps and indirectly from the output of water turbines.

3.2.1 SPORADIC MEASUREMENTS

Sporadic measurements have been made for various purposes, but most often comprise low flow measurements. Permanent staff gauges are normally not installed and only the measured discharges with indication of site and date are reported. These measurements are frequently made to obtain preliminary information at relatively low cost. In some areas where no other data is available, these records constitute the only source of information.

For an adequate interpretation and use, sporadic discharge measurements need to be correlated in some manner with continuous records of gauging stations. This is due to the fact that sporadic measurements do not necessarily provide a comprehensive picture about the secular hydrologic regime of the stream under consideration.

For example, in many parts of the world the period of low flows extends over roughly two months. However, the severity can vary according to the type of year (dry, medium or wet), catchment size and elevation, etc.

3.2.2 GAUGING STATIONS

3.2.2.1 STAFF GAUGES

Gauging stations, independently of the technique adopted, require the installation of staff gauges to monitor the water levels. Readings of the staff gauges constitute the reference level for any measurement or additional equipment installed at the station.

Staff gauges have to be properly fixed in order to avoid their destruction during floods. An additional reference point beyond the reach of the floods has to be provided. This reference point is necessary in order to continue the water level record from the same reference level when the staff gauges have to be replaced, which normally occurs when severe floods damage or even wash them away.

When recording instruments are not installed, records of water levels are *discrete* and require the appointment of personnel for this specific job. Readings are made with different frequency according to the time of the year, distance of the gauging station from nearest population center, etc. An example of staff gauging readings can be seen in Table 3.1.

Table 3.1: **Daily Staff Gauge Readings**

Daily Gauge Heights

Gauging Station:	Jildat	Elevation above sea level:	1951 m
River:	Ushu	Latitude:	35° 29 15
Month:	June	Longitude:	72° 35 45
Year:	1999	Code Number:	35724503
Unit:	cm		

Date	*Morning*		*Noon*		*Evening*		*Remarks*
1	*Time*	*Height*	*Time*	*Height*	*Time*	*Height*	
2	8:00	128	12:00	129	16:00	130	
3	8:00	134	12:00	136	16:00	138	
4	8:00	152	12:00	152	16:00	151	
5	8:00	150	12:00	150	16:00	153	
6	8:00	157	12:00	157	16:00	150	
7	8:00	155	12:00	158	16:00	160	
8	8:00	167	12:00	168	16:00	170	
9	8:00	171	12:00	171	16:00	172	Flow Meas.12:00
10	8:00	168	12:00	165	16:00	160	
11	8:00	148	12:00	145	16:00	142	
12	8:00	140	12:00	138	16:00	135	
13	8:00	134	12:00	136	16:00	138	
14	8:00	152	12:00	151	16:00	154	
15	8:00	157	12:00	159	16:00	156	
etc.							

3.2.2.2 WATER LEVEL RECORDERS

Recording at gauging stations may be *continuous*, which is achieved through the installation of instruments to record the water levels.

Water level recorder has been in operation for decades and consist basically of a drum, a pen holding device and the sensor. The graph chart is placed on the drum that moves at a velocity determined by the scale of the graph chart. Normally, adjustment of the velocity of the drum is possible for longer or shorter recording periods. The sensor transmits mechanically or electronically the water level to the pen holding device, which writes the water levels on the paper chart. An example of the gauging station in Kund, Allai river in Pakistan, is given in the appendix in Figure 3-2.

Three types of sensors are the most popular in use today: float, pressure, sonic and bubble. Table 3.3 shows some of the most important merits and demerits of the different types of sensors.

The characteristics of the rivers in mountainous areas may include heavy sediment load, and freezing water during winter. Under these conditions the pressure sensor offers the best performance capabilities. Therefore, pressure sensors are becoming very popular, especially due to their easy interfacing with electronic equipment.

Table 3.2: **Sensors for water level recorders**

ITEM	TYPE OF SENSOR		
	FLOAT	PRESSURE	SONIC
Stilling Well	Required	Not required	Required
Power Supply	Not required	Required	Required
Maintenance	Laborious	Simple	Laborious
Repair	Simple	By Manufacturer	By Manufacturer
Heavy sediment Load	Frequent Maintenance	No special Maintenance	Frequent Maintenance
Freezing Water	Not Suitable	Suitable	Not Suitable

3.2.2.3 DATA LOGGERS

Data loggers have a large range of applications, providing the facility of storing the data on magnetic media. The data loggers can be attached to the water level recorder or can also be directly connected to the sensor. The data is stored either in the logger's memory or on memory cards. The selected form of storage of data is important, especially when the equipment is installed and operated in a rough environment. The stored data has to be downloaded in the field when it is stored in the logger's memory. The operation of retrieving data may last from some minutes to hours, depending on the amount of data to be retrieved.

Memory cards are becoming very popular because they offer the advantage that they can be replaced in the field. The formats of the memory cards and drivers have been standardized (PCMCIA) allowing safe and easy downloading of the data in the field and/or office. Modern portable computers normally have such components built in.

Data loggers provide a convenient way to acquire and retrieve data in the field. Processing hydrological records is simplified when the information is available on magnetic media. However, to ensure reliability of the information, the stored records and the gauge readings need to be compared to ensure matching.

3.2.3 FLOW MEASUREMENTS

Besides recorded water levels, stream flow measurements are regularly taken at gauging stations to allow development of rating curves. The protocol of one measurement can be seen in Table 3.4.

Although desirable, rating curves derived strictly on basis of available stream flow measurements do not always cover the whole range of recorded water levels. In this case, extrapolation of the rating curves is required. The most common method in use is the "Slope-Conveyance" method, for which at least one cross-section of the river at the gauging site is required.

Other problems arise with the estimation of discharge values when the riverbed varies throughout the year at the gauging site. In some counties the technique of shifting the rating curve has been regularly. The method was developed by the US Geological Survey to estimate river discharges when the stage-discharge relationship does not remain constant.

Table 3.3: Discharge Measurement Protocol at Duber, Kohistan

River Name and Place: *Duber*
Date: *11.05.1999* **Measuring Unit:** *British*
Gauge Height at Start: *88 cm* **Gauge Height at End:** *88 cm*

Vert. No	Distance from initial point	Angle	Depth in Water	Depth in Air	Measuring Depth	Revolution	Time	Velocity	Area	Discharge
1	0	0	0		LWE Start	at 11:10				
2	3	0	1.4		P	20	60			
3	6	0	1.4		P	35	60			
4	9	0	2.2		P	100	60			
5	12	0	2.5		P	85	60			
6	15	0	2.5		P	60	60			
7	18	0	3		0.6	160	60			
8	21	0	3.5		0.6	225	60			
9	24	0	4.5		0.6	250	60			
10	27	0	4.9		0.8	170	60			
		0				310	60			
11	30	0	4.8		0.6	200	60			
12	33	0	5.2		0.8	190	60			
		0			0.2	500	60			
13	36	0	5.1		0.8	150	60			
		0			0.2	570	60			
14	39	0	6.1		0.8	80	60			
		0			0.2	550	60			
15	42	0	6.1		0.8	110	60			
		0			0.2	380	60			
16	45	0	4.6		0.6	340	60			
17	48	0	5.7		0.8	150	60			
					0.2	380	60			
18	51	0	5.6		0.8	200	60			
					0.2	290	60			
19	54	0	4		0.6	180	60			
20	57	0	4.5		0.6	170	60			
21	60	0	3.4		0.6	140	60			
22	87	0	0		RWE End	at 12:35				

For estimation of flows, of mean daily flows the method of shifting the rating curves is available as an option in the software of the hydrological data bank. The principle of shift is explained in the next two figures, it means:

- Shift is the correction applied to the stage of a discharge measurement to bring the measurement to the standard curve.
- Shifts vary with time and fluctuations of stream flow

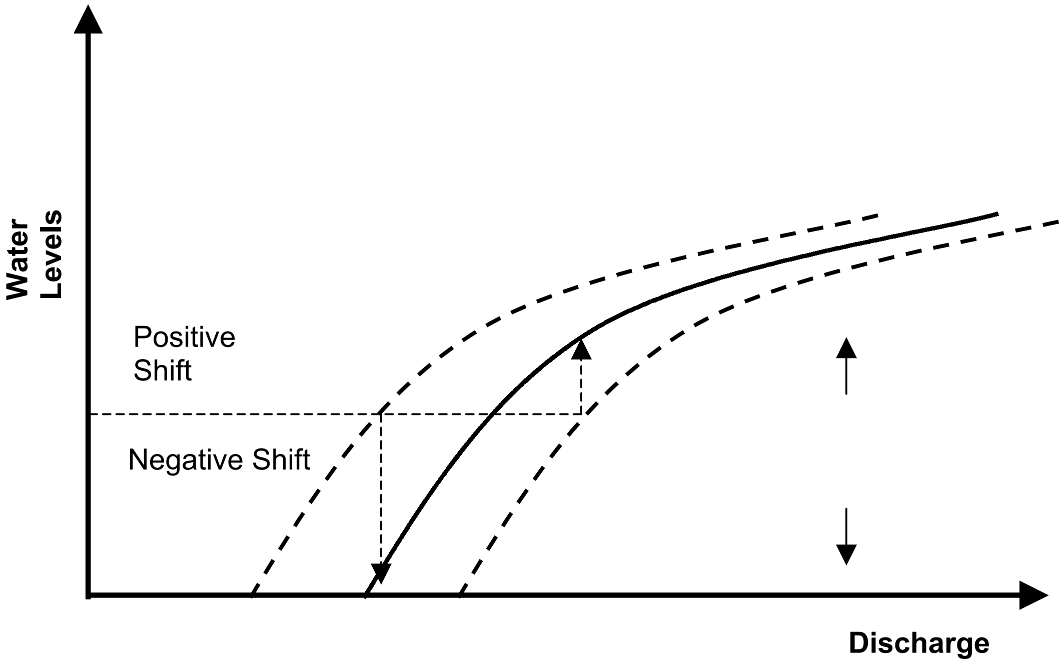


Fig. 3.5: **Shifting of stage-discharge rating curve**

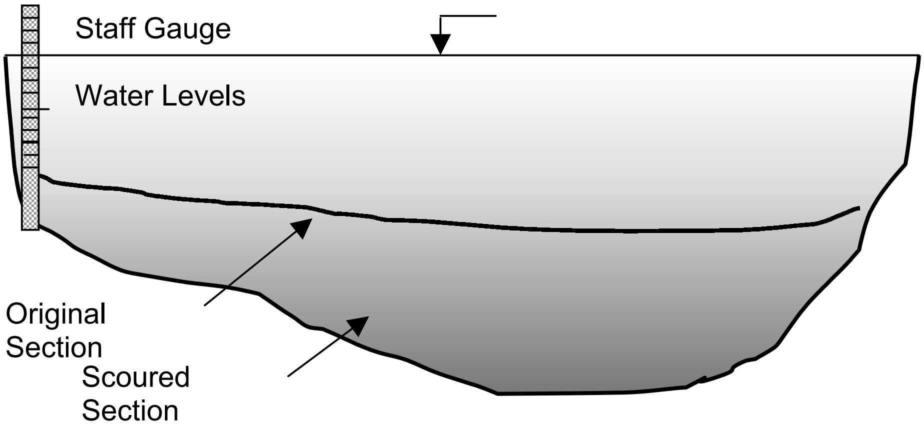


Fig. 3.6: **Application of Shifting at scoured cross sections**

3.2.4 FIELD INVESTIGATIONS

Some basic considerations concerning field measurements of discharge in mountain areas are given here. Steep gradients and thereby high flow velocities characterize mountainous rivers and torrents. Due to this, discharge measurements are sometimes difficult to carry out. For this reason in most cases concrete bridges and suspended bridges are used for the establishment of gauging stations and the location of discharge measurements. The staff should be installed at a location where flow conditions are calm. The recording equipment should be placed on stable terrain, out of the reach of floods. Areas covered with loose deposits should be avoided. Preferably the equipment should be installed at sites which cannot be eroded by the watercourse, such as rock outcrops or large boulders.

Very heavy equipment is needed to measure discharges in streams with high water velocities. In case of floods, flow velocities can easily exceed 5 m/s. Under these conditions the measurements are very difficult, sometimes dangerous and frequently unfeasible. Consequently, discharge measurements are seldom available for floods. This condition limits the available information to fit the (stage-discharge) rating curve.

A discharge measurement protocol of a typical mountain river of Himalayas is enclosed as Table 3.4 in this chapter as practical examples from the field. The river has a bed slope between 4% and 6% with a mean yearly discharge of 50m m^3/s.

3.2.5 SEDIMENT SAMPLING

This topic is treated in detail in the next chapter.

3.2.6 WATER QUALITY

The purpose is to determine the physical, chemical and biological characteristics of the water bodies.

Some parameters (i.e. temperature and turbidity) can be easily determined in the field while others require sophisticated laboratory facilities (i.e. biological analyses).

3.3 DATA PROCESSING

Processing of hydrological data from data entry to the final yearbook is performed by a series of programs that have been integrated into the hydrological data bank. Following paragraphs actually describe the performance of the series of programs contained in the data bank.

3.3.1 WATER LEVELS

3.3.1.1 STAFF GAUGES

Processing of water levels from staff gauges comprises the storage on magnetic media and review of the water levels reported by the gauge readers. The records are typed with the help of a screen especially designed for this purpose. The data is automatically scrutinized to avoid typing mistakes that may be committed frequently while typing.

The stored information can be graphically displayed for further quality control.

3.3.1.2 WATER LEVEL RECORDERS

Processing the graphs of water level recorders comprises the digitization of the graph, which implies discretizing the records and storing them in pairs of points of time vs. gauge heights. As many data pairs as possible should be stored to avoid loss of information and ensure reliable results. This is especially important during the flood season, when water levels tend to fluctuate considerably, especially in case of small streams.

Digitization by reading gauge height and time from the graph is possible, but it takes long time and consequently it is inefficient. Therefore, provision is made in the data bank to digitize the graph with a digitizer. A series of data pairs values of time vs. gauge height are obtained from the digitization procedure. The data pairs have to be adjusted according to the gauge reading and interpolated to obtain 24 hours readings at the exact hour.

Water levels obtained from the digitization process have to be compared with the gauge heights taken by the gauge reader to guarantee that the data have been correctly retrieved. Differences between the digitized values and the gauge readings can be mainly due to:

- Improper installation of recording paper in the water level recorder
- Loss of calibration of the recording instruments
- Freezing of the stream
- Improper initialization of the digitizer
- Inconsistent/incorrect gauge readings

Loss of calibration of the pressure sensors is due to temperature changes as well as long-term drift. These changes are very small and can be easily corrected. Frequent visits to the stations are the best way to avoid these and other problems.

3.3.1.3 DATA LOGGERS

Water levels stored on PCMCIA cards are read with help of external devices or built-in drivers. The data comprises time, water levels and battery charge. The file obtained from the memory card has to be converted into the format used for calculation of flows. Later on, the file undergoes the same comparison with the gauge readings as explained for the digitized data.

A sample of gauge readings and water levels as recorded by a water level recorder at Summar Gah at Gosak, Pakistan is shown in Figure 3.7. The continuous recording allowed keeping track of the daily fluctuations of the water levels, which could not be reported by simple reading of the staff gauge. Especially relatively small floods with a short duration can be recognized with the help of such measurement equipment. The reliability is highly increased thereby.

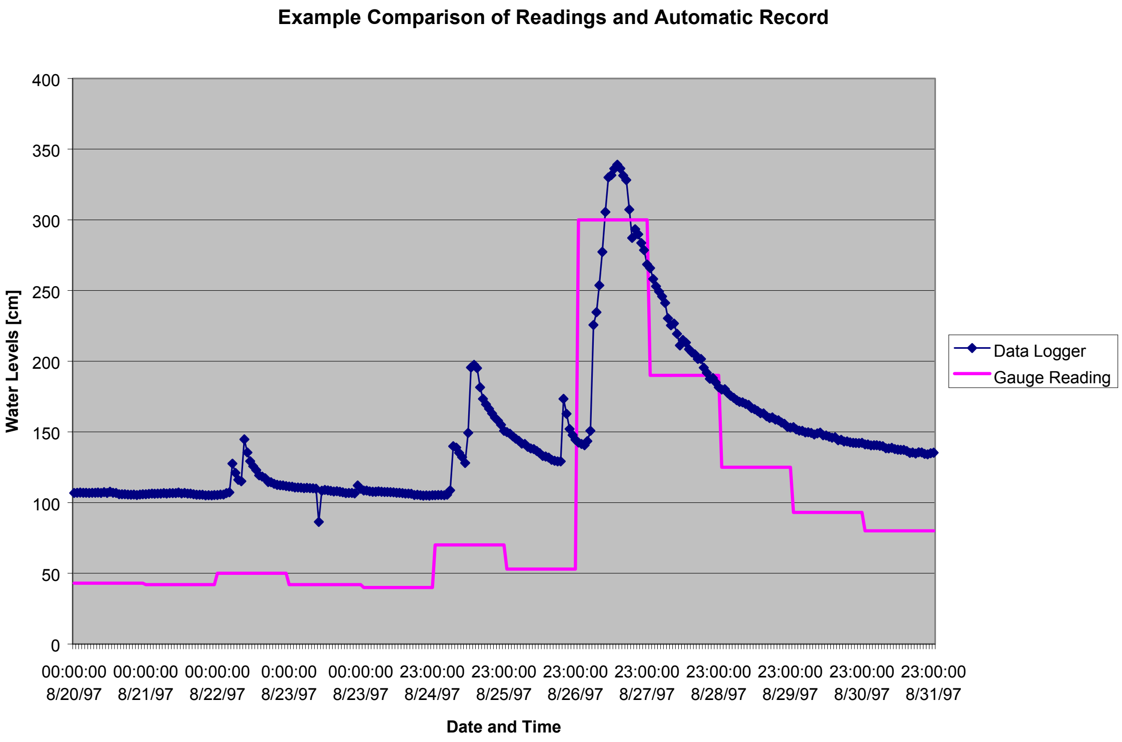


Fig. 3.7: **Comparison of Gauge Reading and Automatic Record at Summar Gah, Himalayas**

3.3.2 DERIVATION OF RATING CURVES

Rating curves relating the water levels to the discharge are derived from the flow measurements. The determination of the rating curve of a gauging station implies the fitting of a mathematical function the measured gauge height and discharges. There are various procedures to fit the rating curve:

- Manually using linear or log-log paper
- Numerically using the method of least-squares

The manual procedures were used in the past. They are time consuming, requiring plotting of each point by hand. Curve fitting is also done manually, which is not always a straightforward procedure when the data is highly dispersed. The results are to some extent subjective and subject to controversy.

Advances in the field of computer hardware and software have facilitated the development of efficient tools, which allow considerable time saving in the analysis of hydrologic data. Nowadays, numerical methods are normally used to fit the rating curves. Independently of the type of equation adopted, due to its simplicity the method of least squares is frequently applied.

The flow measurements have to be critically analyzed before fitting the rating curve. Outliers may have to be removed to avoid distortions in the analysis. This is especially important when the method of least squares is applied.

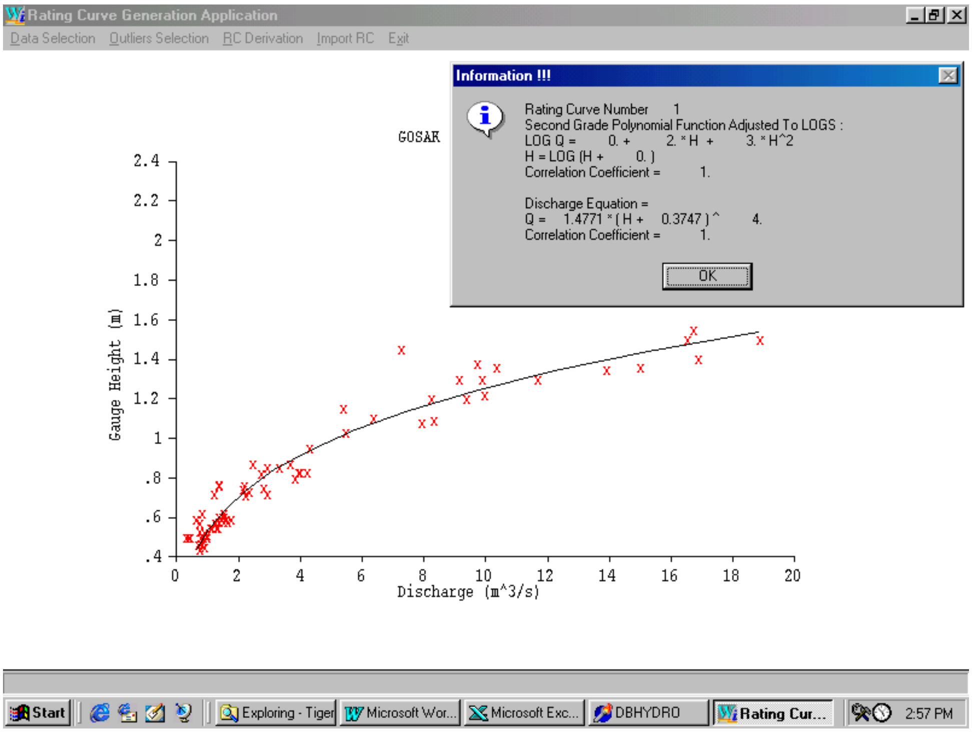
When the flow measurements do not adequately cover the range of gauge readings, extrapolation of the rating curve is required for which various methods are available. The so-called slope-conveyance method is used in most practical applications. To apply the method a series of flow measurements and a cross section at gauging point are necessary. Other information like description of the riverbed and pictures of the site are useful.

The method is based on application of the Manning-Strickler formula for steady state flow in open channels. The geometric characteristics of the section (area and wetted perimeter) used in the formula are obtained from the available cross section. Hydraulic parameters (hydraulic gradient and roughness) are estimated and extrapolated from the values obtained from available flow measurements. Estimation of flows for the higher water levels is then possible applying the Manning-Strickler formula.

A mathematical function describing the rating curve is adjusted to the flow measurements and to the estimated flows at higher stages The rating curve is then adjusted to the flow measurements and to the estimated flows at higher stages.

It has to be stressed that a reliable estimation of floods highly depends on the extrapolation of the rating curves. This is especially important in rivers draining small catchment areas where floods last for a short period of time. In this case flow measurements at the time of the floods are very unlikely. For a reliable estimation of floods frequent flow measurements during the flood season are required. Furthermore, a comprehensive method for extrapolation of the rating curves is required to ensure an accurate estimation of floods.

An example of fitting and extrapolation of a rating curve is given in Figure 3.8 for Summar Gah at Gosak in Pakistan.



```
Rating Curve Number      1
Second Grade Polynomial Function Adjusted To LOGS :
LOG Q =        0. +        2. * H  +       3. * H^2
H = LOG (H +       0. )
Correlation Coefficient =        1.

Discharge Equation =
Q =    1.4771 * ( H +    0.3747 ) ^        4.
Correlation Coefficient =        1.
```

Fig. 3.8: **Extrapolation of Rating Curve for Summar Gah at Gosak, Himalayas**

3.3.3 ESTIMATION OF FLOWS

Estimation of flows can be undertaken after water levels are known and rating curves have been fitted. Obviously, the work can be done more easily with help of computers, especially when specific software for the task is available.

Mean daily flows are basically weighted averages of the flow estimates of each day, which are estimated according to the available information of water levels.

In some cases gauge reading from a fixed point is not possible because changes in the river cross-section may occur due to scouring and sedimentation. To estimate the discharge of such rivers, shifting of the rating curve may be applied. However, to ensure an accurate estimation of flows frequent flow measurements are required. The method of shifting the rating curve was developed by the US Geological Survey and is included as an option in the hydrologic data bank.

Maximum instantaneous discharges are also estimated. Without shifting the maximum instantaneous discharge coincides with the maximum gauge height. When shifting of the rating curve is applied, the maximum instantaneous discharge has to be traced from the various daily maximum instantaneous discharges.

The procedure to estimate maximum instantaneous discharges is extremely laborious and time consuming if no computerized procedure is applied. Calculation of maximum instantaneous discharge when the curve is shifted is automatically performed with the available computer software. As an example Figure 3.9 shows the mean daily discharges estimated for a gauge in the Black Forest in Germany, for the year 1996.

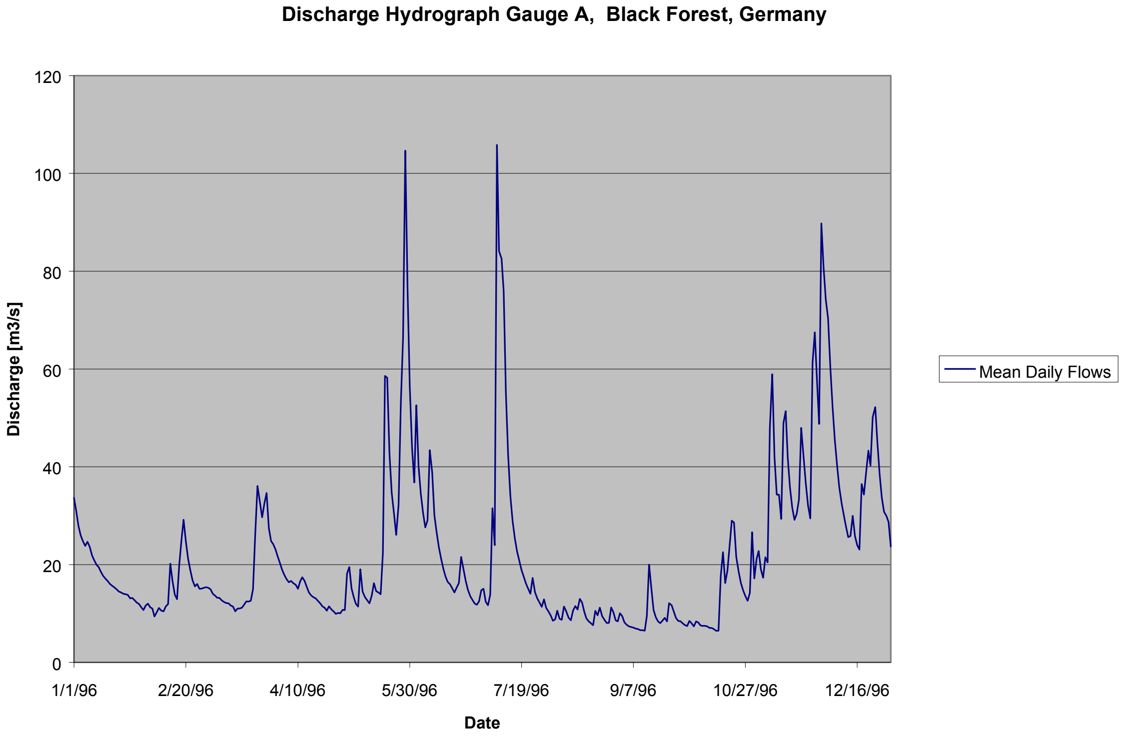


Fig. 3.9: Germany Mean daily discharge of Gauge A, Black Forest.

3.3.4 COMPARISON OF DISCHARGES UP AND DOWNSTREAM

Once the daily flows have been calculated, comparison of estimated flows of stations located on the same river may be undertaken. Provided that no water diversion or losses between the stations occur, the discharges calculated upstream have to be smaller or equal to the ones measured downstream. If the stations are located on tributaries and on the main stream, estimated discharges calculated for the tributaries are added up and compared with the estimated discharges at the point downstream of the confluence.

If the calculated discharges upstream of the confluence happen to be larger than the calculated discharges downstream, the records for this period have to be thoroughly reviewed and corrected. Most likely the problem lies in the extrapolation of the rating curve. Comparing the records for each month of the year can easily check this.

Comparison of discharges up and downstream is a complex task and once a station is changed the whole process of comparison up and downstream has to be reviewed.

3.3.5 PREPARATION FOR PUBLISHING

Before the preparation of a yearbook can be started, a uniform system of units (metric or British) has to be agreed upon for all parameters to be included in the publication.

Once the conversion of daily flows and sediment and quality data of all stations has been completed, the information undergoes a final processing in order to present the data in a comprehensive form.

Following information is included in the table summarizing the flows of the year:
- Salient features of the stations (code, name, location, elevation, river, basin, catchment area, installation date, year of the data).
- Summary of daily flows of the year.
- Summary of monthly flows (given in m^3/s, $lt/(s\text{-}km^2$, mm, maf).
- Summary of extreme flows during the year (daily maximum and minimum, and instantaneous maximum discharge during the year).

Following information is included in the table summarizing the available sediment data:
- Date of the sample.
- Discharge while taking the sample.
- Temperature of water if available.
- Total parts per million (ppm) by weight.
- Percentages of sand, silt and clay

Following information is included in the table summarizing the water quality data:
- Concentration in milli equivalent per liter of following elements:

Ca, Mg, Na, K, CO_3, HCO_3, Cl, SO_4, NO_3 and F.
- Total cations and anions.
- Concentration in parts per million of: SiO_2, Fe, B, dissolved solids by evaporation
- electric conductivity at 25 ^{o} C.
- PH.
- Residual CO_3 in me/l.
- Sodium Adsorption Ratio (SAR).

If sediment and water quality data are available for the same station, two tables (one for sediment samples and one for water quality data) containing the data of the available samples are recommended. The tables presenting sediment and water quality data are presented after the summary of flows of each station.

A front page, preface text, staff involved in the preparation of the yearbook, table of contents, explanatory text, summary of stations and maps showing the location of the stations are prepared.

Once the above mentioned items have been prepared and after final review, the yearbook is ready for printing and reproduction.

3.3.6 HYDROLOGICAL DATA BANK DBHYDRO

The hydrological data bank presented here has been developed during the last years and summarizes a series of programs and methodologies that have been used in many countries.

Development of the hydrological data bank has been necessarily a dynamic process in order to be able to adapt its concepts to a technologically changing environment. Technological improvements in hardware include for hydrological purposes more powerful computers, data loggers and memory cards. Similarly, more sophisticated software for handling of data and programs is now available to enhance the capabilities of the processing tools. Both aspects have been and continue to be revised with the final aim of improving the collection, processing, publication and storage of hydrological data. The concept behind the hydrological data bank is to facilitate the collection, processing, publication and storing of hydrological data in an user friendly environment to speed up the availability of data and to improve its quality.

3.4 APPLICATION

3.4.1 DESIGN PARAMETERS

The analysis and synthesis of discharge data implies the determination of flows in terms of their magnitude, seasonal distributions and multi-annual variations. Discharge records constitute a fundamental input in the identification and evaluation of potential sites for hydropower development.

Hydrological stations are frequently not at the same place as the potential sites to be investigated. Therefore, hydrological parameters estimated for the sites of the gauging stations have to be adjusted, interpolated, extrapolated and synthesized as required to estimate the design parameters at the site of the potential power development.

The following paragraphs address the estimation of flows from available records. Later, methods for estimation of design parameters for ungauged sites will be discussed.

3.4.1.1 MEAN ANNUAL FLOW

The most stable hydrologic parameter is the mean annual flow. It constitutes always the first parameter to be investigated.

The mean annual flow can only be calculated from stations with at least one complete year of record. Although, taking into consideration the variability of the hydrologic regime, longer records are always required to achieve reliable estimates.

Figure 3.10 shows the relationship between mean annual flow and record length at various gauging stations. As expected, the mean annual flow varies significantly during the initial years of operation and becomes more stable after some time.

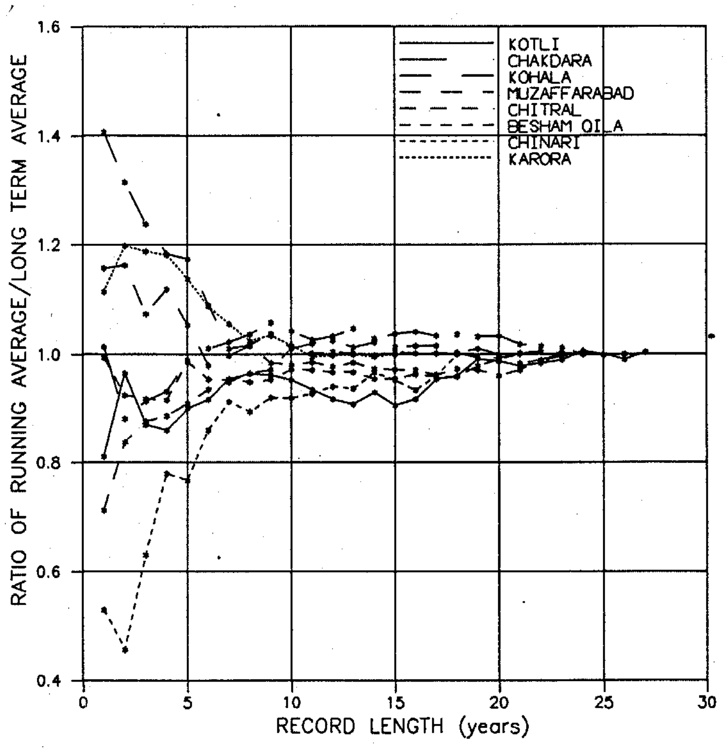


Fig. 3.10: Variation of the mean annual flow with the record length

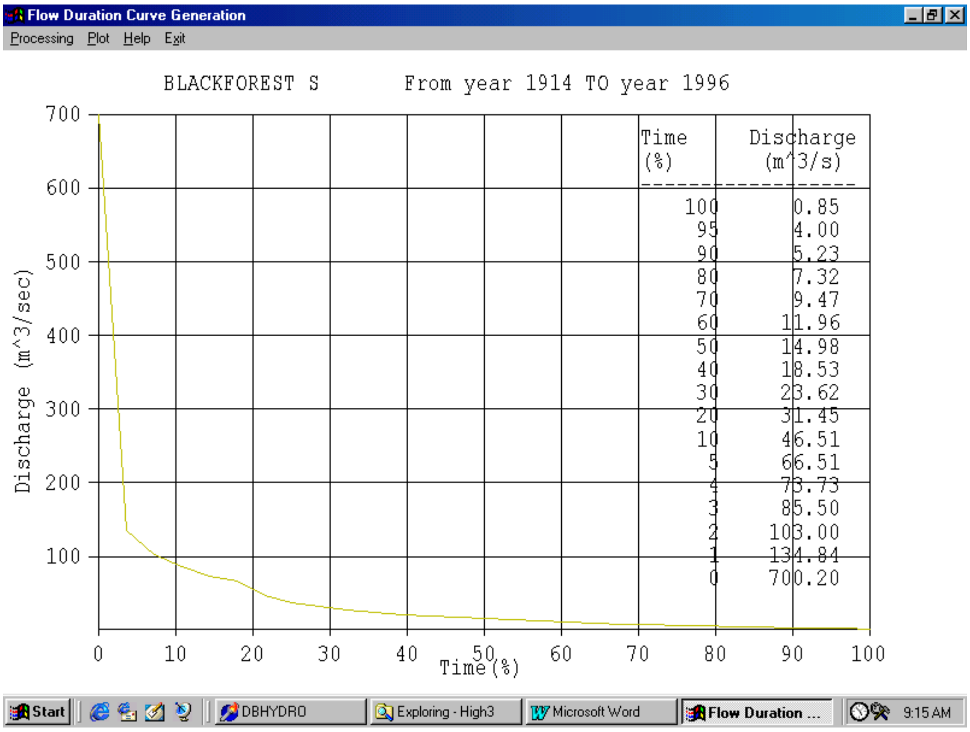
3.4.1.2 MEAN MONTHLY FLOWS

Mean monthly flows are the mean values of the mean daily flows recorded during each particular month. Mean monthly flows are used to determine the degree of variability of the flows throughout the year of a particular river.

3.4.1.3 FLOW DURATION CURVES

Flow duration curves show the percentage of time that flow is equaled or exceeded. A duration curve is generally constructed by counting the number of days with flows in various class intervals. The selection of the time unit of the class intervals depends on the purpose of the curve. If a project for diversion without storage is under study, the time unit should be the day, so that absolute minimum flows will be indicated. For reservoir design, a lesser number of intervals (100 to 200) may be sufficient depending upon reservoir size in relation to inflow.

The main drawback of the flow duration curve as a design tool is that it does not present the flows in their chronological sequence of occurrence. It is not possible to tell whether the lowest flows occurred in consecutive days or scattered throughout the record.



Time (%)	Discharge (m^3/s)
100	0.85
95	4.00
90	5.23
80	7.32
70	9.47
60	11.96
50	14.98
40	18.53
30	23.62
20	31.45
10	46.51
5	66.51
4	73.73
3	85.50
2	103.00
1	134.84
0	700.20

Fig. 3.11: Flow Duration Curve for a Gauge in the Black Forest, Germany, 1914-1996.

3.4.1.4 MONTHLY SERIES OF STREAM FLOWS

Monthly series of flows are useful when evaluating hydroelectric projects that include seasonal reservoirs. Monthly series of flows comprise the series of monthly values calculated from the daily flows. If the available record is long enough, analysis can be performed directly from the observed series. However, if the available record is short, completion and/or extension of the recorded series can be undertaken as explained in later paragraph.

3.4.1.5 LOW FLOWS

In order to analyze the severity of droughts in a proper manner, it is important to consider also their magnitude and duration. For this purpose, the lowest consecutive flows in given period during each year are considered. The minimum discharge is defined as the average minimum discharge for the period of time within a year. The period of time is generally taken as one or several days.

A frequency analysis is performed on the series of minimum flows for the period or for the various periods of time, to determine magnitude, duration and recurrence of the droughts.

3.4.1.6 FLOODS

Estimations of floods for different return periods are required to establish dimensions and costs of river diversions during construction and of permanent relief structures (bottom outlets, spillways, etc.).

The phenomena, which every year give origin to floods in general, comprise:

- Precipitation, as in case of storms and tropical cyclones. In the subcontinent, high precipitation intensities during monsoon are the cause for the largest recorded floods.
- Ice and snowmelt during spring and summer months.

3.5 METHODS FOR ESTIMATION OF DESIGN PARAMETERS

3.5.1 FLOWS

Normally, when long term hydrological stations were installed, the location of potential hydropower schemes was still unknown. On the other hand, due to data scarcity stream flow records will most likely not be available for the identified sites. Therefore, various procedures to estimate the mean flows (annual, monthly, daily flows and flow duration curves) at ungauged sites exist and are mentioned in the literature. In general, independently of the method adopted, the estimates strongly rely on morphometric parameters, such as catchment area, catchment elevation, etc. The most common procedures for estimation of flows, but not by way of limitation, adopted in practice are:

- Estimation on basis of ratio of catchment areas
- Multiple regression models
- Simulation

A brief discussion of these methods is given below.

3.5.1.1 RATIO OF CATCHMENT AREAS

Estimation on basis of ratio of catchment areas is the simplest method and implies the determination of catchment areas for both the gauging station and the point of interest. Other way of looking at this approach is that specific discharges at gauging stations are determined and then used to estimate the discharges at ungauged sites. The procedure is:

$$\frac{Q(station)}{A(station)} = \frac{Q(site)}{A(site)} \qquad \textbf{(3.1)}$$

$$q(station) = \frac{Q(site)}{A(site)} \qquad \textbf{(3.2)}$$

where,

Q(station)	= mean annual flow at gauging station
A(station)	= catchment area up to gauging station
q(station)	= specific discharge up to gauging station
Q(site)	= estimated mean annual flow at site
A(site)	= catchment area up to the site

By applying this method one assumes that the hydrologic conditions in the catchment where estimations are required are similar to the one of the catchment where the station is located. Therefore one or the two of the following conditions have to be fulfilled in order to obtain reliable results:

- Hydrologic regime is homogeneous in the catchment
- The site should be close to the gauging station.

- The catchments have to be climatologically and morphometrically homogeneous.

An example of the third condition is offered by the catchment of Swat river in Pakistan. Figure 3-9 presents specific discharges calculated at the stations Batal Khwar at Utror, Ushu river at Jildat and Swat river at Kalam. The three stations are located in the Swat river catchment within the catchment drained to the gauging station Kalam. The three stations have a different catchment area. However as shown on Figure 3-12, the specific discharges of the three rivers at their respective stations are remarkably similar.

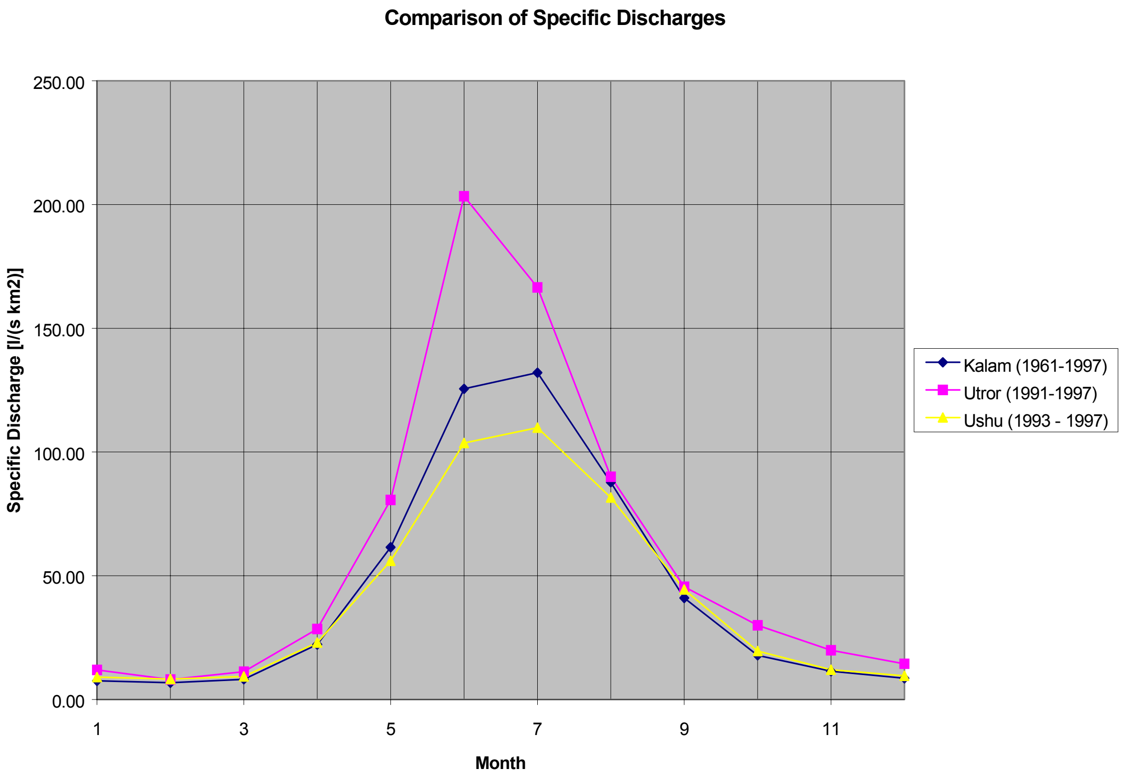


Fig. 3.12: Comparison of Specific Discharges in Swat River Catchment, Hindukush.

3.5.1.2 MULTIPLE REGRESSION MODELS

Multiple correlation models are basically an extension of the previous method. Besides catchment area, these models include other parameters, climatologic and morphometric ones. The procedure requires the determination of the basic parameters for all gauging stations considered. Various functions are fitted, most likely by the method of least squares, to determine those functions, which show the best fit. Usually the parameter which function fits best is the correlation coefficient.
The functions fitted may be of the form:

$$Q = A + B * x + C * y + ... \qquad \textbf{(3.3)}$$

where
Q = river flow
A,B,.. = fitted coefficients

x,y,... = independent variables

It is always important to confirm that the variables are in fact independent to avoid spurious correlations, which may result in high correlation coefficients but unreliable results when applied to estimate discharges at ungauged sites.

In any case, sufficient and reliable information of all independent variables must be available at the ungauged sites to allow the application of the derived functions.

Multiple regression models have been applied in various countries, mostly for regional studies. Estimation of following parameters has been undertaken in an example:

- Annual flows
- Floods
- Minimum run-off available during 7, 15, 50, 100 and 150 consecutive days

Following parameters are normally used as independent variables:

- Catchment areas
- Mean elevation of the catchments
- Geographical latitude and longitude of the center of the catchments
- Temperature
- Mean annual precipitation within the catchments
- Slope
- Exposure of the catchments to solar radiation
- Hypsometric curves

3.5.1.3 SIMULATION

There is a large variety of simulation models, which can be applied. The choice normally depends on the purpose of the work in hand, availability of basic data, manpower, time and financial resources.

The simulation model WAPPO (Water and Power Potential) used for the determination of discharges is described below. The first version of the model was developed in 1976 and has been extensively used in Central and South America, Africa and Asia. Details of the program are given in the manual.

The model allows the determination of discharges on basis of the following parameters:

- Morphometric : area and mean elevation
- Climatologic : precipitation and temperature
- Hydrologic : discharges at gauging stations

The catchment is subdivided in as many sub-catchments as possible to ensure a proper discretization and representativeness of the morphology. The scale of the topographic maps used is 1:50,000, which are available in almost every country. As a rule of thumb, the area of the sub-catchments varies between 5 and 10 km^2. Therefore, a catchment area of 3000 km^2 will be subdivided in approximately 300 to 600 sub-catchments.

After subdivision of the catchment, a topologic diagram showing the elements of the river is prepared. Elements of this diagram are explained on Figure 3.13. This diagram constitutes the basis to establish the topology of the river, which is presented in terms of nodes and branches. The branches correspond to river reaches, while nodes are either the connecting points between 2 or more catchments or the location of control points (gauging stations).

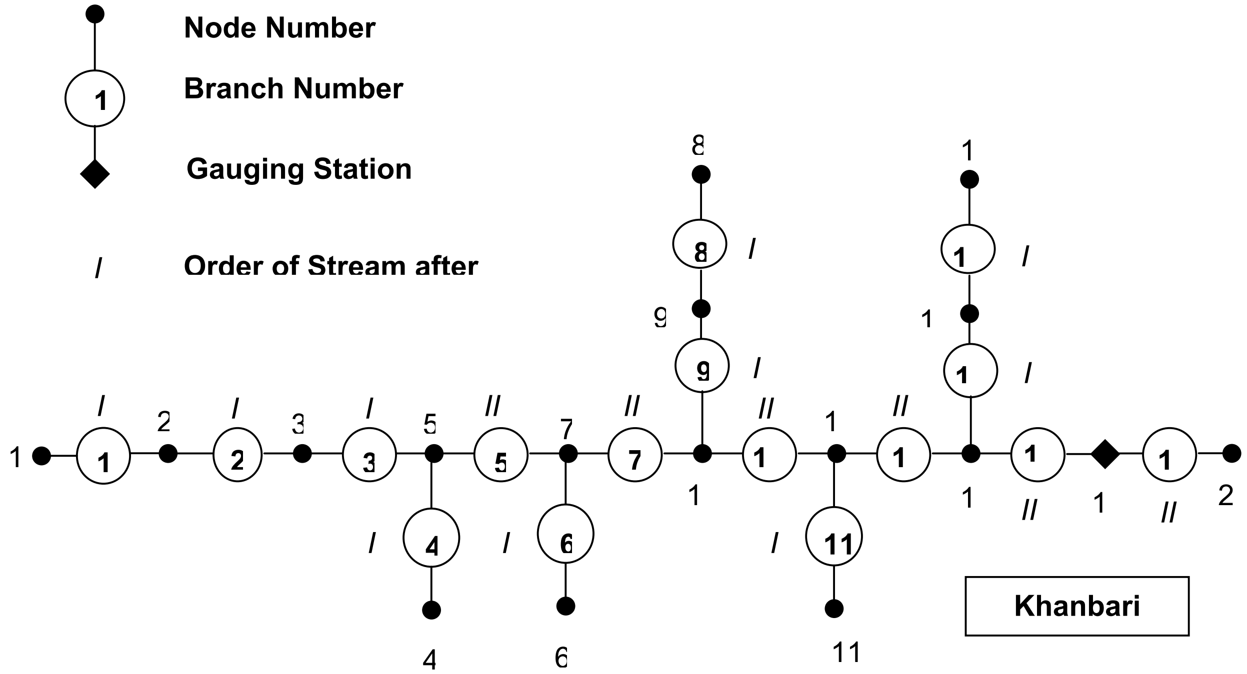


Fig. 3.13: Sample Model of a Catchment for Simulation Model WAPPO

For each sub-catchment, the area and the mean elevation are determined. Help can be taken from the work published by the National and Atmospheric Administration (NOAA-USA), which has published the data from the Global Land One-Kilometer Base Elevation (GLOBE) project, which provides elevations of the surface of the earth. The density of the grid of points is of one point every kilometer as defined by the UTM coordinate system. From this files area and mean elevation of catchments can be calculated. Coordinates defining all sub-catchments in which the catchment has been divided are taken from the 1:50,000 topographic sheets. For large catchments the number of sub-catchments is normally more than 1,000. In order to avoid errors in such amount of coordinate points, a computer program scrutinizes the file containing the coordinates to avoid missing or duplicated values. Once the file is clear of errors, the program calculates area and mean elevation of the sub-catchments.

Through observations in various parts of the world, good correlation has been obtained between elevation and climatic parameters, which constitute the basis to establish the variability of precipitation, specific discharges and temperature with elevation.

3.5.1.3.1 Precipitation Distribution

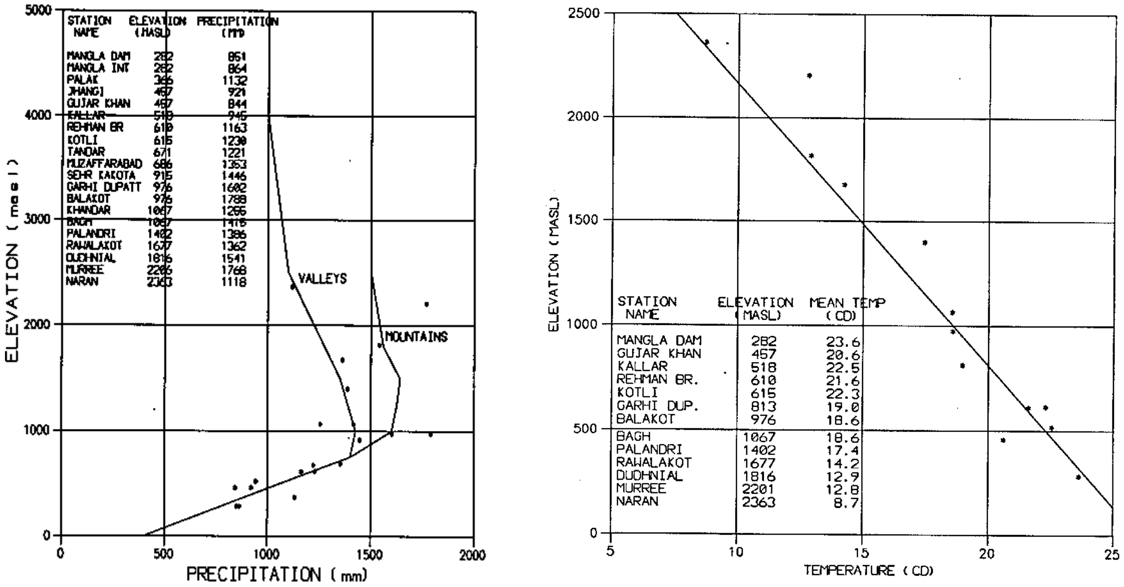
The characteristics of the available data have to be considered to calibrate the model. Similarly, characteristics of the hydro-climatologic events determining the precipitation-runoff process have to be given proper attention.

In relation to the available data, most of the precipitation stations have been installed near populated areas along river valleys. Consequently, climatologic data in the upper mountains is

very scarce and in most of the cases unavailable.
On the other hand, as observed in many parts of the world, precipitation on the mountains increases with the elevation. This has been observed in various regions, where the run-off recorded at the hydrological stations draining high-altitude catchments exceeds the precipitation recorded in the bottom of the valleys.

As a large amount of precipitation falls in form of snow, precipitation does not necessarily coincide with the place where run-off is produced. An unknown amount of snow moves, in the form of avalanches or slides, from the place where it falls to lower elevations. Run-off is not produced at the place where snow is available but where temperature is high enough to melt it.

Precipitation has been observed to increase with the elevation and temperature decreases almost linearly with the elevation. As a consequence of the relation of both parameters with the elevation, good agreement can be expected if elevation is properly used as parameter to estimate run-off. In fact, precipitation increases with the elevation, but run-off increases only up to a certain level. After this level, higher elevations are characterized by lower specific run-off.



STATION NAME	ELEVATION (MASL)	PRECIPITATION (MM)
MANGLA DAM	282	851
MANGLA INT	282	864
PALAK	366	1132
JHANGI	457	921
GUJAR KHAN	457	844
KALLAR	518	945
REHMAN BR	610	1163
KOTLI	615	1230
TANDAR	671	1221
MUZAFFARABAD	686	1353
SEHR KAKOTA	915	1446
GARHI DUPATT	976	1602
BALAKOT	976	1788
KHANDAR	1067	1266
BAGH	1067	1416
PALANDRI	1402	1386
RAWALAKOT	1677	1362
DUDHNIAL	1816	1541
MURREE	2206	1768
NARAN	2363	1118

STATION NAME	ELEVATION (MASL)	MEAN TEMP (CD)
MANGLA DAM	282	23.6
GUJAR KHAN	457	20.6
KALLAR	518	22.5
REHMAN BR.	610	21.6
KOTLI	615	22.3
GARHI DUP.	813	19.0
BALAKOT	976	18.6
BAGH	1067	18.6
PALANDRI	1402	17.4
RAWALAKOT	1677	14.2
DUDHNIAL	1816	12.9
MURREE	2201	12.8
NARAN	2363	8.7

Fig. 3.14: Typical relationship between precipitation – elevation and temperature – elevation in mountain areas.

To assess the variation of run-off with the elevation an algorithm has been developed to estimate the distribution of run-off by elevation bands, which are taken from the hypsometric curves up to the points of the gauging stations. Hypsometric curves can be prepared from the catchment area/mean elevation data available in the input data files of program WAPPO. The algorithm uses linear programming to find the optimal distribution of run-off by elevation bands that reproduces with the minimum error the mean annual run-off observed at the gauging stations.

The idea is to estimate the precipitation in each band minimizing matching errors for all stations used in the analysis. For exact matching of values and using the same number of stations and elevation bands, the problem could be solved as a system of linear equations as follows:

$$\Sigma a_{ij} * r_i = R_j \qquad \textbf{(3.4)}$$

where

a_{ij} = area of the elevation band i in percentages of total catchment area of station j.
r_i = run-off produced at elevation band i.
R_j = total run-off as recorded at station j.

It is important to have the possibility of using different number of stations and elevation bands and to account for errors in the estimates. The algorithm has an objective function the minimization of the sum of all matching errors, which will always occur in most practical cases. The formulation is as follows:

Objective function:

$$\text{Min}\, \Sigma (error)_j \qquad \textbf{(3.5)}$$

where

error =error of the estimate (difference between recorded and estimated run-off)
j = 1,......,n
n = number of gauging stations

Subject to:

$$\Sigma a_{ij} * r_i + (error)_j = R_j \qquad \textbf{(3.6)}$$

$$r_i \_ 0 \qquad \textbf{(3.7)}$$

$$(error)_j \_ 0 \qquad \textbf{(3.8)}$$

Precipitation for the lower elevations can be estimated from the precipitation records. However, precipitation has to be converted into runoff by subtracting the actual evapotranspiration. The later is required because annual discharge represents the total run-off in one year. Once the run-off - elevation relationship has been estimated by the program, equivalent precipitation-elevation can be prepared by adding the evapotranspiration at each elevation.

3.5.1.3.2 Mean Annual Flow

Location of climatologic stations in the Jhelum river catchment in Pakistan used to determine the precipitation and temperature-elevation relationship. Precipitation-elevation and temperature-elevation relationships used to simulate the catchment are shown in Figure 3-14 for Jhelum catchment.

When the precipitation-elevation relationship is ready the process of simulation of the catchment can be started. Through a water balance, the model estimates the net discharge for each sub-catchment independently. On basis of the river topology, discharges are accumulated in downstream direction. The hydrologic stations constitute control points and are used to calibrate the model and determine the reliability of the estimates

Using the WAPPO model, simulation of rivers of northern areas of Pakistan has been successfully undertaken. Catchments that have been simulated are shown in the table below. For these catchments simulations to estimate mean annual flow, mean monthly flow and flow duration curve have been performed.

Table 3.4: Simulated Catchments with model WAPPO

Sr. Nr.	Catchment	Number of Points
1.	Punch river	452
2.	Jhelum river	915
3.	Neelum river	764
4.	Chitral river	782
5.	Upper Indus (confluence with Gilgit)	1730
6.	Gilgit and Hunza	1605
7.	Lower Indus (Shatial-Besham)	1083

The experience accumulated during the execution of the work of simulation of the rivers in different mountainous areas of the world confirmed that the program can be successfully applied under extremely different climatologic conditions. As examples of the diversity of conditions on which the model can be applied, the Punch River and the Neelum River catchment in the Himalayas can be mentioned.

The Punch River catchment receives its precipitation mainly in the form of rainfall and very little amount of it is stored as snow during the winter months. The catchment receives large amount of precipitation during the monsoon because it is directly exposed to the winds coming from the south.

On the other hand, the Neelum river catchment receives less precipitation during the monsoon due to weaker and drier winds reaching the catchment. Precipitation during the winter months in form of snow is far more important than it is in the Punch River catchment. The water stored as snow is released during the summer months.

The program has been applied under conditions of extremely scarce information. In this regard, it can be mentioned that within the Neelum River catchment only two climatologic and two hydrological stations are located. The stations are located on the river valley, consequently no information is available from the mountainous area. In this case, the climatologic functions have been developed and extrapolated using records of stations located in the surrounding area.

From the previous discussion, it can be concluded that the WAPPO model has been a useful tool for the estimation of flows of the rivers in mountain areas. It is especially remarkable that the prevailing conditions in the catchments are those of extremely different climatologic conditions with limited data.

3.5.1.3.3 Mean Monthly Flows

Monthly time series are used to evaluate projects with seasonal reservoirs. Using the WAPPO program mean monthly flows are estimated on basis of recorded time series at gauging stations.

Following procedure has been adopted to estimate monthly flows by simulation using program WAPPO at each node:

- A relationship between the mean annual flow expressed in millimeters and the mean elevation of the catchments is developed from the results of the runs to simulate the mean annual flow.
- Mean monthly flows are estimated for all available hydrologic stations.
- Proportion of the mean annual flow is established for every month, dividing the corresponding flow by the mean annual flow.
- A relationship between the proportion of the mean annual flow for every month and the mean elevation of the catchments is established. At this point the sum of all flows should be established to avoid differences with the mean annual flow. Examples of these relationships as used during the simulation of the Jhelum River catchment are given in Figures 3.15 and 3.16.
- The relationship between the flow for every month, expressed in millimeters and the mean elevation of the catchments is established.
- Computation of flows is performed and a table summarizing the estimated monthly flows is prepared.

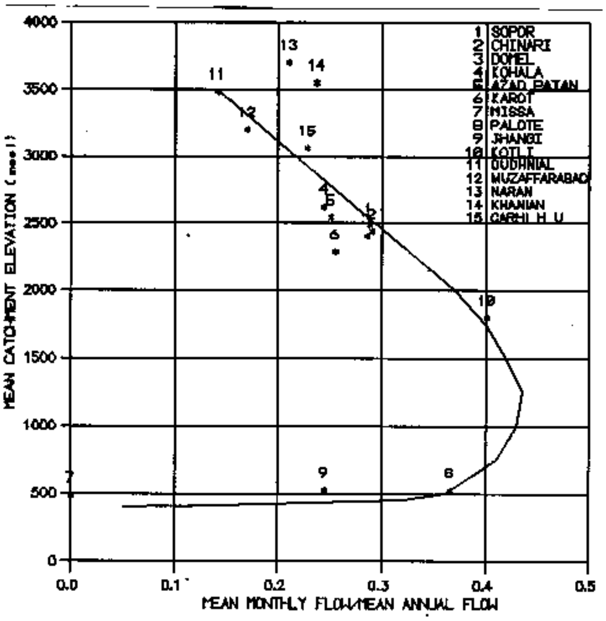


Fig. 3.15: Mean monthly flow – elevation relationship in January, Jhelum Catchment

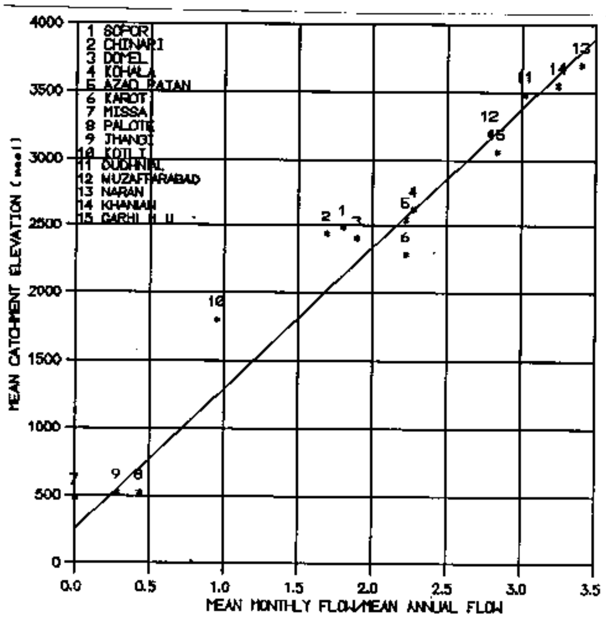


Fig. 3.16: Mean monthly flow – elevation relationship in June, Jhelum catchment

3.5.1.3.4 Flow Duration Curve

Flow duration curves can be determined through various runs of WAPPO model, as has already been satisfactorily done in the Andes and Himalayas. The program is run as many times as discharge durations are decided. The proper input data has to be prepared in every case.

Following procedure has been adopted to estimate flow duration curves by simulation using program WAPPO at each node:

- A relationship between the mean annual flow expressed in millimeters and the mean elevation of the catchments is developed from the results of the runs to simulate the mean annual flow.
- Flow duration curves are developed for all available hydrologic stations and flow for every desired duration is determined.
- Proportion of the mean annual flow is established for every given duration, dividing the corresponding flow by the mean annual flow.
- A relationship between the proportion of the mean annual flow for every duration and the mean elevation of the catchments is established. At this point the sum of all flows should be established to avoid differences with the mean annual flow.
- The relationship between the flow for every duration, expressed in millimeters and the mean elevation of the catchments is established.
- Computation of flows is performed and a table summarizing the estimated flows for different durations is prepared.

After completion of the simulation work, flow measurements made during the low flow season are used to check the goodness of the estimations. With this purpose the daily hydrographs are analyzed to establish the period of occurrence of the lowest flows, which vary according to their location (position and elevation) of the catchment.

For example, in the Punch River catchment the lowest flows occur during late December or

January, while in the Neelum catchment located further north and at higher elevation the lowest flows are recorded during January or at the beginning of February.

In the above examples, comparison of estimated flows with measured flows show good agreement, provided that no precipitation in the form of rainfall occurred during or before the flow measurement. The measured flows taken during the low flow season under no rainfall conditions are close to the estimated 95 % duration flow and measured low flows do not exceed the estimated 70 % duration flow.

Alternatively, dimensionless flow duration curves can be derived for different parts of the catchment. These curves are determined for all gauging stations by dividing the ordinates of the curve by the mean annual flow. The discharges at ungauged points are then determined by multiplying the estimated mean annual flows with the ordinates of the dimensionless flow duration curves.

3.5.2 MONTHLY SERIES OF STREAM FLOWS

Time series (in this case monthly series of flows) can be either observed or synthetic. Observed series of monthly flows are calculated from the available daily flows. On the other hand, synthetic series of monthly flows are generated on basis of records of other stations or using statistical parameters of the observed series. When the available series of monthly flows is long enough, the studies can be performed using only the available data. When the series is not long enough, it will have to be completed or extended with help of records of other stations having concurrent but longer periods of record. To undertake a confident completion of time series, good correlation coefficients have to be obtained between the time series.

Synthetic flows can be generated from the statistical parameters of the observed series of data when the series of data is not long enough and no station is available for completion of the data. Synthetic flow series are expected to preserve the statistical properties of the series of observed flows. Synthetically generated data provide other possibilities of analysis, as compared with analysis based only on recorded series of flows. However, completion or extension of the time series based on the recorded data of other stations normally provides a more adequate basis for analysis, especially concerning the critical period of the series.

The program HEC-4 developed by the Hydrologic Engineering Center of the US Army Corps of Engineers has been extensively used for completion and generation of flows. The program analyzes monthly stream flows at a number of interrelated stations to determine their statistical characteristics and generates a sequence of synthetic stream flows of any desired length preserving the basic characteristics of the original series. The program reconstitutes missing stream flows on the basis of concurrent flows observed at other locations. It also has the capability to use a generalized simulation model for generating monthly stream flows at ungauged locations based on regional studies.

Time series analysis is required for the design of water resources projects, especially those which foresee seasonal reservoirs. There are many methods to estimate the required capacity of a reservoir. However, with the modern computational facilities, simulation of reservoirs with existing or generated monthly series of flows is part of normal practice. Other time discretization may also be adopted (i.e. 10-daily or weekly), especially in case of multiple purpose reservoirs.

The simulation of reservoir operation is based on the solution of the continuity equation for each time step over the total simulation period. The mathematical models used simulate the operation of the reservoir assuming the existing or generated monthly flows as inflows into the reservoir. Evaporation from the free surface of the reservoir is calculated and subtracted as water loses. Releases from the reservoir are simulated according to the requirements for energy generation, irrigation, etc. Finally, to ensure conservation of mass, surpluses are accounted as spill water.

3.5.3 ANALYSIS OF LOW FLOWS

As already discussed, analysis of low flows is required in order to determine the magnitude, duration and recurrence of droughts. For this purpose, the series of minimum flows for various durations have to be determined from the daily series of flows. One value is normally determined for each duration and recorded year. After the series of minimum flows has been obtained, a frequency analysis is performed to determine the lowest flows for different return periods as necessary. Extreme value distributions, such as Gumbel and Pearson Type III have been found to provide satisfactory results.

Table 3.5: Minimum flows of Khan Khwar River

PERIOD	**Logarithms of the Mean Minimum Row for the Indicated Number of Days (m^3/s)**										
	1	3	7	15	30	60	90	120	150	183	274
1975/76	0.57	0.58	0.58	0.60	0.64	0.68	0.73	0.79	0.88	1.00	1.26
1976/77	0.59	0.60	0.60	0.61	0.64	0.87	0.70	0.76	0.84	0.96	1.33
1977/78	0.68	0.68	0.70	0.71	0.74	0.82	0.89	0.93	0.96	1.09	1.40
1978/79	0.70	0.72	0.77	0.81	0.84	0.86	0.87	0.91	0.95	1.05	1.26
1979/80	0.57	0.57	0.57	0.60	0.61	0.83	0.67	0.70	0.75	0.85	1.12
1980/81	0.53	0.58	0.61	0.62	0.63	0.64	0.67	0.72	0.79	0.90	1.13
1981/82	0.45	0.47	0.47	0.48	0.50	0.53	0.56	0.61	0.67	0.78	1.02
1982/83	0.74	0.74	0.76	0.78	0.82	0.88	0.92	0.93	0.96	0.98	1.16
1983/84	0.49	0.50	0.50	0.51	0.53	0.54	0.56	0.60	0.67	0.86	1.18
B229W pQ1984/85	0.66	0.66	0.66	0.67	0.71	0.79	0.81	0.85	0.89	1.07	1.23
1985/86	0.62	0.62	0.63	0.65	0.69	0.75	0.80	0.81	0.84	0.89	1.12
1986/87	0.64	0.65	0.65	0.72	0.76	0.88	0.94	0.91	0.94	1.00	1.22
1987/88	0.61	0.61	0.62	0.64	0.67	0.72	0.76	0.82	1.08	1.07	1.15
1988/89	0.87	0.89	0.71	0.71	0.73	0.78	0.80	0.82	0.88	0.96	1.25
1989/90	0.65	0.65	0.66	0.68	0.71	0.75	0.79	0.84	0.91	1.02	1.25
1990/91	0.79	0.81	0.86	0.88	0.91	0.98	1.03	1.07	1.08	1.13	1.26
1991/92	0.37	0.38	0.40	0.49	0.73	0.81	0.87	0.93	1.00	1.12	1.30
1992/93	1.03	1.03	1.04	1.05	1.07	1.11	1.12	1.15	1.22	1.30	1.40
Mean	0.63	0.64	0.65	0.68	0.72	0.77	0.81	0.84	0.90	1.00	1.23
StDv	0.14	0.14	0.14	0.14	0.13	0.14	0.14	0.14	0.14	0.12	0.09
High Thr	8.99	9.15	9.64	10.02	10.50	12.59	13.81	14.57	16.69	19.36	27.97
Low Thr	2.03	2.09	2.11	2.27	2.60	2.72	2.97	3.33	3.86	5.19	10.26

Table 3.5 shows the logarithms of the minimum flows recorded on Khan Khwar at Karora in the Karakoram Mountains. On the same table the analysis of outliers is performed on one particular

flow that was found to be extraordinarily high. The recorded low flows are presented in Table 3.6 ranked from largest to smallest. Finally, the estimated minimum flows from the frequency analysis are presented on Table 3.7 for various durations and return periods.

Table 3.6: Ranked minimum flows of Khan Khwar River

Sr. Nr	Prob (%)	Ranked Mean Minimum Flows for the Indicated Duration (m^3/s)										
		1-Day	3-Day	7-Day	15-Day	30-Day	60-Day	90-Day	120-Day	150-Day	183-Day	274-Day
1	94.74	6.14	6.50	7.17	7.67	8.11	9.64	10.79	11.88	11.97	13.61	24.92
2	89.47	5.48	5.52	5.86	6.42	6.86	7.65	8.65	8.91	11.95	13.25	21.41
3	84.21	5.02	5.27	5.70	6.05	6.66	7.53	8.41	8.56	9.92	12.28	19.92
4	78.95	4.78	4.86	5.07	5.21	5.73	7.22	7.75	8.54	9.77	11.82	18.34
5	73.68	4.71	4.83	4.98	5.17	5.45	6.63	7.39	8.50	9.18	11.71	18.28
6	68.42	4.60	4.60	4.60	5.14	5.43	6.45	7.38	8.22	9.02	11.13	18.22
7	63.16	4.45	4.50	4.59	4.77	5.31	6.16	7.28	8.20	8.82	10.90	18.16
8	57.89	4.38	4.42	4.48	4.67	5.10	5.98	6.53	7.14	8.61	10.57	17.70
9	52.63	4.16	4.16	4.23	4.48	5.08	8.85	6.37	6.94	8.19	10.01	17.68
10	47.37	4.06	4.09	4.15	4.35	4.90	5.68	6.37	6.67	7.85	9.90	16.97
11	42.11	3.93	3.96	4.12	4.24	4.68	5.56	6.12	6.61	7.65	9.50	16.63
12	36.84	3.88	3.90	4.04	4.17	4.48	5.20	5.80	6.40	7.25	9.15	16.31
13	31.58	3.69	3.77	3.98	4.11	4.39	4.82	5.38	6.17	6.98	9.11	15.14
14	26.32	3.69	3.76	3.82	3.99	4.32	4.69	5.03	5.76	6.94	7.94	14.43
15	21.05	3.40	3.70	3.75	3.95	4.23	4.37	4.72	5.27	6.18	7.84	14.22
16	15.79	3.07	3.14	3.16	3.22	4.12	4.26	4.71	5.02	5.56	7.21	13.43
17	10.53	2.85	2.92	2.94	3.06	3.40	3.48	3.66	4.07	4.73	7.11	13.04
18	5.26	2.33	2.42	2.51	3.03	3.17	3.37	3.62	4.00	4.64	5.78	10.42

Table 3.7: Estimated minimum flows of Khan Khwar after Gumbel distribution

Duration	**Mean Minimum Flow for the Indicated Return Period (m^3/s)**					
	2-Year	**5-Year**	**10-Year**	**20-Year**	**50-Year**	**100-Year**
1-Day	4.02	3.24	2.91	2.67	2.42	2.27
3-Days	4.12	3.31	2.96	2.71	2.46	2.30
7-Days	4.25	3.33	2.94	2.65	2.36	2.18
15-Days	4.50	3.51	3.09	2.78	2.47	2.28
30-Days	4.93	3.92	3.49	3.18	2.86	2.66
60-Days	5.57	4.24	3.68	3.27	2.85	2.59
90-Days	6.12	4.60	3.95	3.48	2.99	2.70
120-Days	6.65	5.07	4.40	3.90	3.40	3.09
150-Days	7.66	5.93	5.20	4.66	4.11	3.78
183-Days	9.55	7.73	6.95	6.38	5.81	5.45
274-Days	16.39	13.62	12.45	11.58	10.71	10.17

3.5.4 ESTIMATION OF FLOODS

Estimation of floods for different return periods are required to establish dimensions and costs of river diversions during construction and of permanent relief structures (bottom outlets, spillways, etc).

The phenomena, which every year give origin to floods in general, comprise:

- Intensive precipitation, as in case of storms, tropical cyclones and typhoons.
- Ice and snow melt

- Tropical cyclones in Central America, typhoons in the Far East and monsoon rains in the Indian subcontinent have caused the largest recorded floods.
- In Europe combinations of intensive rains, ice and snowmelt have been the cause of flooding.

Figure 3.17 shows the mean monthly flows recorded at Kotli, Karora, Chitral and Yugo gauging stations in Hindukush, Karakoram and Himalayas Mountain Range. The recorded flows at the stations located to the South (Kotli and Karora) report two yearly peaks. The first peak is firstly due to precipitation and secondly to some snowmelt during the late winters months. The second and largest peak is due to monsoon rains and is recorded in August. On the other side, the stations located to the North report a single peak discharge caused by snowmelt during the summer months (July and August).

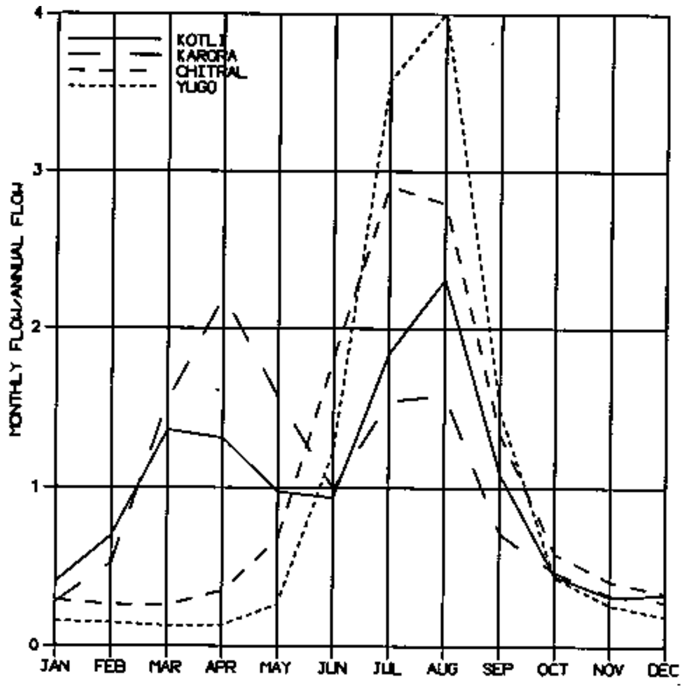


Fig. 3.17: Comparison of flow regime at various stations in mountain areas

Main parameters determining the hydrologic regime are precipitation and temperature. The figure shows that total annual precipitation determines the total runoff, while the distribution of both rainfall and temperature determines the pattern of flows throughout the year.

Extraordinary events may also originate floods. These are mostly related to geodynamic activity, such as landslides which may impound a river during some time until overtopping occurs and a surge or water wave moves in downstream direction, similar to the case of a dam failure (dam break).

Due to lack of data, the case of extraordinary floods due to landslides is studied only in very special cases. The type and amount of data needed is such that intensive field and desk studies are needed to arrive at reliable results.

Many methods have been derived to estimate floods. They can be classified into three groups:

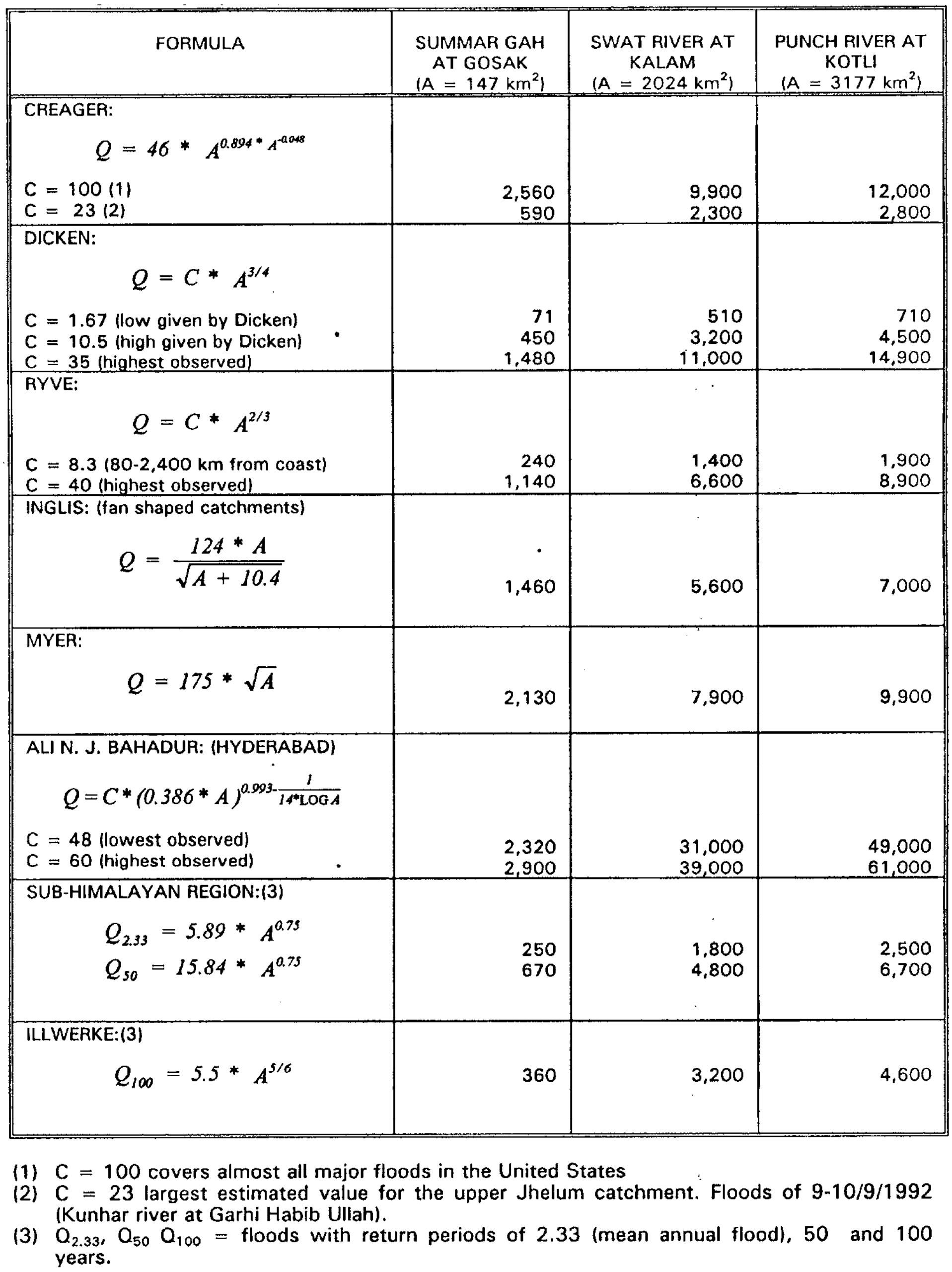
- Empirical or semi-empirical formulae

- Probability analysis
- Precipitation - runoff models

3.5.4.1 EMPIRICAL OR SEMI-EMPIRICAL FORMULAE

Empirical formulae rely normally on one or more geomorphologic parameters (primarily the catchment area) for the assessment of the magnitude of floods. Empirical formulae are developed keeping in view various physical and climatic conditions. These include vegetation cover, weather, catchment morphology, geologic setup and other. The applicability of particular formula depends on the conditions giving origin to the maximum floods for which the formula has been developed. These conditions should be similar to the ones at the place for which estimation of floods is required. In this regard, selection of an appropriate formula is extremely difficult, because the conditions vary from place to place.

Table 3.8: Estimation of floods by empirical formulae for some catchments



FORMULA	SUMMAR GAH AT GOSAK ($A = 147\ km^2$)	SWAT RIVER AT KALAM ($A = 2024\ km^2$)	PUNCH RIVER AT KOTLI ($A = 3177\ km^2$)
CREAGER: $Q = 46 * A^{0.894 * A^{-0.048}}$			
C = 100 (1)	2,560	9,900	12,000
C = 23 (2)	590	2,300	2,800
DICKEN: $Q = C * A^{3/4}$			
C = 1.67 (low given by Dicken)	71	510	710
C = 10.5 (high given by Dicken)	450	3,200	4,500
C = 35 (highest observed)	1,480	11,000	14,900
RYVE: $Q = C * A^{2/3}$			
C = 8.3 (80-2,400 km from coast)	240	1,400	1,900
C = 40 (highest observed)	1,140	6,600	8,900
INGLIS: (fan shaped catchments) $Q = \frac{124 * A}{\sqrt{A + 10.4}}$	1,460	5,600	7,000
MYER: $Q = 175 * \sqrt{A}$	2,130	7,900	9,900
ALI N. J. BAHADUR: (HYDERABAD) $Q = C * (0.386 * A)^{0.993 - \frac{1}{14 * \mathrm{LOG} A}}$			
C = 48 (lowest observed)	2,320	31,000	49,000
C = 60 (highest observed)	2,900	39,000	61,000
SUB-HIMALAYAN REGION:(3)			
$Q_{2.33} = 5.89 * A^{0.75}$	250	1,800	2,500
$Q_{50} = 15.84 * A^{0.75}$	670	4,800	6,700
ILLWERKE:(3) $Q_{100} = 5.5 * A^{5/6}$	360	3,200	4,600

(1) C = 100 covers almost all major floods in the United States

(2) C = 23 largest estimated value for the upper Jhelum catchment. Floods of 9-10/9/1992 (Kunhar river at Garhi Habib Ullah).

(3) $Q_{2.33}$, Q_{50} Q_{100} = floods with return periods of 2.33 (mean annual flood), 50 and 100 years.

Table 3.9: Flood frequency analysis for two different catchments with Gumbel

Return Period (Years)	Swat River at Kalam (1973 – 85) (m^3/s)	Punch River at Kotli (1961 – 90) (m^3/s)
2	390	4120
5	490	6410
10	550	7920
20	620	9380
50	700	11260
100	760	12670
1000	960	17320
10000	1160	21970

To illustrate the later, a series of floods have been calculated for catchments in the Himalayas in which floods are originated by different climatic conditions. The floods have been calculated using empirical formulae normally applied in the sub-continent and elsewhere. The formulae have been taken from different references. The catchments selected for the calculations are: Summar Gah at Intake, Swat river at Kalam and Punch river at Kotli. Results of the calculations are presented on Table 3.8 and estimation of floods for Swat river at Kalam and Punch river at Kotli applying the Gumbel distribution are shown on Table 3.9. Comparison of Tables 3.8 and 3.9 indicate that some of the formulae may give reasonable estimations in some cases but they completely fail in other cases when the climatic conditions which originate the floods change.

Selecting a coefficient of 100 (a Creager coefficient of 100 envelopes almost all major floods in the United States), the estimated flood for Punch river at Kotli using the Creager formula coincides with the 100-year flood estimated for the same station by frequency analysis. However, the estimated flood for Swat river at Kalam using the same Creager coefficient and formula is nine times larger than the 10,000-year flood estimated by frequency analysis. Using the same formula with a coefficient of 23 (minimum observed in the tributaries of the Jhelum river during the 9-10/9/1992 floods) the estimated flood is two times the 10,000-year flood at Kalam estimated by frequency analysis. The value obtained by the Creager formula for Punch river at Kotli using the same coefficient does not even meet the lowest recorded flood.

When compared with floods estimated from actual records, other formulas show similar results. The Illwerke formula for example, gives an estimation of the 100-year flood for the Swat river at Kalam, which is three times larger than the 10,000-year flood for the same station estimated by frequency analysis. However, the estimated 100-year flood for Punch river at Kotli using the same formula is comparable with the 2-year flood estimated by frequency analysis.

From the above discussion, it has to be concluded that estimations by empirical formulae estimated for different climatic conditions as the ones originating floods in northern areas of Pakistan, show poor correlation with the floods estimated from flood records. This poor correlation occurs because the formulae are only suitable for the places for which they have been developed. Consequently, whenever possible, estimation of floods by empirical formulae developed for other places with different climatic conditions as the ones giving origin to floods in area of interest should be avoided.

3.5.4.2 PROBABILITY ANALYSIS

Determination of design floods can be made on basis of analysis of maximum instantaneous flows for each year of record. More attention will be paid here to this method as it has been considered to be suitable to establish the design floods when data is scarce. The classical analysis considers the fitting of an extreme value distribution to the annual floods. The distributions used in flood analysis are the following:

- Pearson Type 3
- Log Pearson 3
- Gumbel
- Log Gumbel
- Gamma
- Log Gamma
- Normal (Gauss)
- Log Normal

In most cases, the symmetrical Gaussian normal distribution is not suitable to assess the return periods of floods because it does not regard the asymmetry (skewness) of the observed series.

Since the distribution function of the infinite number of all random events-in this case all possible annual maximum discharges- is not known, we stand in need of approaching the true distribution function on the basis of a sample and by application of various methods.

In practice, the statistical parameters of the true distribution, the so-called moments have to be estimated from the sample; such moments are the arithmetic mean, the variance and the skewness:

mean:

$$\overline{Q} = \frac{1}{n} \sum^{n} Q_i \qquad \textbf{(3.9)}$$

variance:

$$\overline{Q} = \frac{1}{n} \sum^{n} Q_i \qquad \textbf{(3.10)}$$

Coefficient of variation:

$$C_V = \frac{S}{\overline{Q}} \qquad \textbf{(3.11)}$$

Coefficient of skewness:

$$C_S = \frac{n \sum_{i=1}^{n} (Q_i - \overline{Q})^3}{(n-1)(n-2)\, S^3} \qquad \textbf{(3.12)}$$

where,
Q_i = annual maximum discharge in the year i within the n-year observation period.

It should be strongly emphasized that in some cases the deviation of results obtained by the application of different distributions may be of considerable magnitude. Therefore a characterization of the design flood simply by its exceedance frequency may be very elusive.

Therefore it is necessary that, if a flood discharge is characterized on probability basis, besides its exceedance frequency (or recurrence interval) also the distribution should be given.

3.5.4.2.1 Direct Estimation from the Records

When the period of record of the station is long enough, floods for different return periods can be calculated directly with confidence from the records. An example of the estimation of floods directly from the records is given in Figure 3.24 as estimated for Jhelum river at the multipurpose project Mangla Dam in Pakistan.

3.5.4.2.2 Extension of Flood Records

As already discussed, short records is one of the problems normally faced when determining hydrologic design parameters. In this regard, estimation of design floods with confidence requires observation of floods during a long period, which normally is not available at the sites of the projects. Consequently, the available information, including the information of other stations located nearby the point of interest should be analyzed in detail to obtain the most reliable estimation of floods.

When analyzing the flood information available within the Jhelum river in Pakistan, two methods have been applied to improve the frequency curves and consequently the estimation of floods:

- Comparison with a long-term record station. The statistical parameters of the logarithms of the series of recorded floods (mean, standard deviation and skewness coefficient) are adjusted on basis of a regression analysis with a long-term record. The floods for various periods of return are determined from the adjusted statistical parameters using the log Pearson 3 distribution.
- Adjustment of frequency curve by a high outlier. The statistical parameters of the logarithms of the series of recorded floods without the outlier are adjusted assigning a weighting factor to the outlier that depends on the years of record and the period for which the outlier is the maximum. The floods for various periods of return are determined from the adjusted statistical parameters using the log Pearson 3 distribution.

An example of comparison of a gauging station with short record and a gauging station with long records is given in the paragraphs dedicated to the estimation of floods from mixed population. It has to be emphasized that to perform any of the two analyses mentioned in the previous paragraphs, the series of floods have to be similar in origin.

3.5.4.2.3 Floods From Mixed Population

As already discussed, floods can be originated mainly from rainfall or snowmelt. Due to the morphologic characteristics of the catchments and the natural phenomena producing floods in the Himalayan Range, it has been established that rainfall and snowmelt produce floods of quite different magnitude.

Floods produced by rainfall are more intense and frequent in the catchments to the South that are directly exposed to the prevailing winds during the monsoon season. These catchments do not have a significant snowfall in winter and therefore floods from snowmelt origin are almost negligible. In this case floods can be estimated directly from the records if they are available. An example of such catchment is the Punch River.

Catchments located towards the north present an increasing area covered by snow. Additionally monsoon events are weakened along their path and rainfall produced as consequence of these monsoon events is normally moderate. Under these conditions the population of flood events is of mixed origin. However, strong monsoon events can penetrate further into the upper catchments producing heavy rains and high floods. The frequency of these heavy rains depends upon the importance of the mountainous barriers protecting the catchment from the southern monsoon winds. When effect of the mountain is not very important, heavy rains are recorded frequently and maximum floods are from rainfall origin. Otherwise, if the mountainous barrier is relevant, heavy rains are recorded seldom and floods are normally originated from snowmelt. However, strong monsoon events or climatologic conditions supporting the movement of the disturbance in direction of the catchments with high mountain barriers can produce heavy precipitation and originate high floods of a magnitude not related to the floods originated from snowmelt. These monsoon events and the related floods do not occur frequently and in many cases they have not been recorded at the hydrological stations.

During September 1992 extraordinary high floods were observed in the northern areas of Pakistan. Many of the hydrological stations, especially those in the Jhelum catchment, were destroyed. The level reached by the flood raised well beyond the level of the gauges (at Kohala the highest staff gauge was 15 meters above the river bed, however the water level reached 30 meters above the river bed). However, the floods recorded at stations on rivers normally subject to severe monsoon rainfall like Punch at Kotli, Kanshi river at Palote and estimated by volume at Mangla remained within the limits of observed floods.

After the floods a party was sent to the field to measure the maximum water level during this flood at different stations in the catchment. The magnitude of the flood at Kohala, Domel, Azad Patan and Chinari was estimated with the help of cross sections surveyed before the floods occurred. Additionally, for estimation of hydraulic factors, flow measurements taken before the floods at the sites of the stations were provided by Surface Water Hydrology Project. Final check of the magnitude of the floods was made at Mangla with the estimated flood given in various WAPDA reports (this includes press reports).

Within the Jhelum river catchment, series of maximum floods are available at Mangla since 1922 (65 years), at Azad Patan since 1979 (13 years), at Kohala since 1970 (19 years), at Domel since 1976 (14 years) and at Chinari since 1970 (19 years). The estimated magnitude of the September 1992 floods exceeds by a factor that varies from 2 at Domel to 2.9 at Azad Patan the previously maximum recorded floods. Correlation of the historical series of floods observed at Mangla and at the stations on the main Jhelum was undertaken to extend the period of record at the stations on the upper catchment (Azad Patan, Kohala, Domel and Chinari), but poor correlation coefficients were obtained.

After comparing the date of occurrence of the maximum floods at Mangla and at the stations located in the upper catchment, it was found that they do not occur on the same date. Maximum floods recorded at Mangla occur normally during the monsoon season, while maximum floods in the upper catchment normally occur before the monsoon. In order to correlate comparable magnitudes, floods recorded at the stations in the upper catchment on the same day as recorded at Mangla were collected from Surface Water Hydrology Project. Floods recorded at the stations on the Main Jhelum river on the same day as at Mangla are included in Table 3.10.

Table 3.10:Recorded Floods at Main Jhelum River

YEAR	MANGLA DAM		CHINARI		DOMEL		KOHALA		AZAD PATAN	
	DATE	Q^{max}	DATE	Q^{max}	DATE	Q^{max}	DATE	Q^{max}	DATE	Q^{max}
1957	04/07	44.33								
1958	06/08	14727								
1959	04/07	23506								
1960	10/07	4262								
1961	22/07	4446								
1962	22/07	4390								
1963	00/00	2270								
1964	18/07	2413								
1965	25/04	2498					24/04	3738		
1966	09/09	2524					24/06	3285		
1967	15/07	4556					11/06	2753		
1968	22/08	7589					11/06	2608		
1969	00/00	6155					10/06	2775		
1970	01/09	7453	29/09	391			23/05	1713		
1971	23/06	6288	22/06	379			31/05	1869		
1972	16/08	10621	23/05	1037			23/05	3370		
1973	09/08	9385	17/08	926			14/06	2489		
1974	14/07	10375	24/06	711			24/06	1719		
1975	28/08	12900	28/08	1240			17/05	2826		
1976	02/08	16667	12/08	1124			02/08	3880		
1977	14/07	6415	05/05	663			30/06	2481		
1978	17/03	11228	18/08	986			25/05	2917		
1979	02/08	5327	20/04	685			30/06	2022	30/06	2203
1980	28/02	6960	27/06	753	26/06	861	24/06	2917	24/06	3370
1981	30/03	5705	21/04	1184	21/04	1473	21/04	3257	21/04	2974
1982	07/08	6876	18/04	810	17/04	909	07/05	2031	28/04	2130
1983	25/08	10131	22/05	1088	18/05	1306	04/08	2801	18/05	2656
1984	25/08	5549	02/04	869	01/04	1037	03/06	2280	07/06	2220
1985	07/08	9740	13/08	728	07/08	821	04/08	3682	07/08	2807
1986	04/08	11955	27/04	1456	27/04	1594	22/05	3965	04/08	4135
1987	23/05	3280	23/05	2243	23/05	1654	16/07	2591	23/05	3540
1988	16/07	12051	17/07	932	24/07	1150	NA	NA	01/08	3625
1989	31/07	4922	NA	NA	31/07	1158	NA	NA	31/07	3837
1990	18/05	4315	NA	NA	18/05	1386	NA	NA	18/05	2884
1992	10/09	30860	10/09	2792	10/09	3474	10/09	10888	10/09	12909

During the monsoon season heavy rains occur on the southern part of the Jhelum catchment (including Punch and Kanshi rivers). These rains give origin to the maximum floods recorded at Mangla. However as already discussed monsoon winds become weaker when they penetrate the upper catchment, and consequently they normally originate low to moderate rains. Floods in the upper Jhelum catchment originated by low to moderate rains during the monsoon produce floods of moderate magnitude. These floods are normally not the largest of the year, the bigger floods in the upper catchment are originated from snowmelt as suggested by the date of occurrence of the floods.

Table 3.11: Classification of Floods, Main Jhelum River

Date	Origin of Flood	Remarks
01-09-70	Rainfall	Fall in Temperature. Rainfall on the Catchment
23-06-71	Rainfall	Fall in Temperature. Rainfall on the Catchment
16-08-72	Snowmelt	Rise in Temperature. Negligible Rainfall on the Catchment
09-08-73	Rainfall	Fall in Temperature. Rainfall on the Catchment
14-07-74	Snowmelt	Rise in Temperature. Little Rainfall on the Catchment
28-08-75	Rainfall	Fall in Temperature. Rainfall on the Catchment
02-08-76	Rainfall	Fall in Temperature. Rainfall on the Catchment
14-07-77	Rainfall	Fall in Temperature. Rainfall on the Catchment
17-03-78	Rainfall	Fall in Temperature. Rainfall on the Catchment
02-08-79	Rainfall	Fall in Temperature. Rainfall on the Catchment
28-02-80	Rainfall	Fall in Temperature. Rainfall on the Catchment
30-03-81	Rainfall	Fall in Temperature. Rainfall on the Catchment
07-08-82	Rainfall	Fall in Temperature. Rainfall on the Catchment
05-08-83	Rainfall	Fall in Temperature. Rainfall on the Catchment
25-08-84	Rainfall	Fall in Temperature. Rainfall on the Catchment
07-08-85	Rainfall	Fall in Temperature. Rainfall on the Catchment
04-08-86	Rainfall	Fall in Temperature. Rainfall on the Catchment
23-05-87	Snowmelt	Rise in Temperature in the Upper Mangla. Little Rainfall is experienced. Seems to be mostly snowmelt generated.
16-07-88	Rainfall	Fall in Temperature. Heavy Rainfall on the Catchment
31-07-89	Snowmelt	Rise in Temperature in the Upper Mangla. Some Rainfall is also experienced. Seems to be snowmelt generated.
18-05-90	Snowmelt	Rise in Temperature in the Upper Mangla. Some Rainfall is also experienced. Seems to be snowmelt generated.
10-09-92	Rainfall	Fall in Temperature. Heavy Rainfall on the Catchment

Keeping in view that floods in the catchment can be of different origin, in order to correlate comparable floods, it was necessary to classify them according to their origin. Classification of floods was undertaken on basis of the following criteria:

- Date of occurrence of flood: floods occurring during the hottest months of the year (May and June) are probably snowmelt originated floods. On the contrary, floods occurring during the monsoon are probably rainfall originated floods.

- Precipitation and temperature records: Precipitation and temperature before and during the day of the floods were analyzed. In those cases when precipitation was recorded and a drop in the mean daily temperature was observed at the climatologic stations before and during the day of the flood, it was concluded that the flood was originated from rainfall. When no precipitation was recorded and a rise of the mean daily temperature was observed before and during the day of the flood, it was concluded that the flood was originated from snowmelt. However, coverage of the climatologic network is poor and in few cases it was not possible to establish the origin of the floods with certainty.

Classification of the series of floods recorded at the stations on the same or previous day as observed in Mangla is shown on Table 3.11.

On basis of the classification of floods, it can be concluded that the floods recorded at Mangla are mostly originated by rainfall. To extend the series of rainfall originated floods, those recorded on the previous or the same day as observed at Mangla were calculated. The long term series of floods at Mangla was used to extend the series of floods recorded at the stations on the main Jhelum river. Correlation coefficients obtained after comparison of the series of concurrent rainfall originated floods recorded at Mangla and at the stations on the main Jhelum river are quite high. Consequently, extension of the series of floods observed at the stations on the main Jhelum river can be undertaken with confidence.

Table 3.12 shows that the correlation coefficients between the series of rainfall originated floods are quite high, and therefore, the extrapolation of floods on basis of the long term series can be done with confidence. Table 3.13 presents the estimated floods for various return periods calculated from the extended flood records of rainfall origin. When comparing the values on Tables 3.13 and 3.14, it can be observed that the September 1992 flood has a return period close to one in 100 years at all stations but at Kohala, where the difference is apparently because of a wrong estimation of the September 1992 flood.

Table 3.12:**Extension of flood records at base station Mangla**

Short Term Station	Corr. Coeff.	Equip. Period	Short Term Series			Extended Series		
			Mean	St. Dev.	Skew	Mean	St. Dev.	Skew
Chinari	0.858	36	2.8018	0.2683	0.6518	2.640	0.308	0.337
Domel	0.800	16	2.9368	0.3004	1.0280	2.749	0.304	0.394
Kohala	0.879	39	3.2822	0.2639	1.4358	3.120	0.304	0.394
Azad Patan	0.903	30	3.3305	0.3940	0.7459	3.107	0.420	0.348

Table 3.13:**Frequency analysis of rainfall originated floods, Main Jhelum River**

Station	Floods with Indicated Return Period (m^3/s)							
	2-Y	5-Y	10-Y	20-Y	50-Y	100-Y	1000-Y	10000-Y
Chinari	420	782	1109	1497	2128	2713	5552	10429
Domel	536	993	1409	1908	2727	3494	7299	14046
Kohala	1250	2324	3320	4533	6561	8492	18409	36887
Azad	1209	2823	4546	6855	11098	15479	41373	98447

Table 3.14:**Frequency analysis of snowmelt originated floods, Main Jhelum River**

Station	Floods with Indicated Return Period (m^3/s)							
	2-Y	5-Y	10-Y	20-Y	50-Y	100-Y	1000-Y	10000-Y
Chinari	898	1259	1488	1701	1969	2164	2789	3394
Domel	1158	1427	1573	1695	1833	1925	2178	2377
Kohala	2579	3183	3542	3863	4252	4528	5377	6166
Azad	3098	3672	4023	4342	4737	5023	5936	6829

However, in the short term (return periods shorter than 10 years at Azad Patan, 20 years at Kohala, and 50 years at Domel and Chinari) floods estimated from rainfall origin are significantly smaller than the observed annual maximum floods. As already discussed, on the short return period floods of snowmelt origin are larger than the ones originated from rainfall. Therefore, to assess the magnitude of floods on the short term frequency analysis was performed from the recorded maximum floods at the stations on the main Jhelum river, excluding the September 1992 flood. Estimated floods for different return periods are given in Table 3.14.

From the above discussion, it has been concluded that floods in the Jhelum river catchment are from snowmelt and rainfall origin. Floods with short return periods are originated by snowmelt. Larger floods with longer return periods are originated by rainfall. This occurs due to the fact that the changes in thermal conditions in the catchment normally produce a larger release of water than the run-off produced by weak monsoon rains. However, in the long term, floods produced by strong monsoon rainfall are larger than the floods originated by snowmelt. A sample of the results of the frequency analysis of floods from mixed population is shown in Figure 3.25 for the station on Jhelum river at Azad Patan.

3.5.4.3 PRECIPITATION - RUNOFF MODELS

Precipitation-runoff models include all the methods that use precipitation to estimate floods. These comprise from the very simple models based on rainfall intensity and several catchment parameters, to the unit hydrograph used to obtain detailed flood hydrographs.

Example of the simple models is the so-called "rational formula". The formula is extensively used for calculation of maximum instantaneous discharges of small catchments where hydrological information is scarce or does not exist at all. The method determine the maximum instantaneous discharge with the formula:

$$Q = C * i * A \qquad \textbf{(3.13)}$$

where
Q = maximum instantaneous discharge
C = runoff coefficient
I = rainfall intensity, from a duration-intensity curve. Critical duration of storm is assumed to be the same as the time of concentration of the catchment.
A = catchment area

On the other hand, the unit hydrograph as proposed by Sherman is based on the fact that the hydrograph of outflow from a basin is the sum of the elemental hydrographs of the sub-areas of the basin modified by the effect of transit time through the basin and storage in the stream channels. Since the physical characteristics of the basin - shape, size, slope, etc.- are constant, one might expect considerable similarity in the shape of the hydrographs from storms of similar rainfall characteristics. The unit hydrograph is a typical hydrograph for the basin and is called unit because, for convenience, the runoff volume under the hydrograph is commonly adjusted to 1 cm (or 1 mm or 1 inch) equivalent depth over the catchment.

The unit hydrograph can be used in combination with other models to produce design floods. Storm models, for example the probable maximum precipitation, are used to produce maximum probable floods that can be used as design floods. Similarly, flood routing models are used to route the hydrographs of single sub-catchments and produce hydrographs of large basins.

Precipitation-runoff models have been used to estimate the design flood discharges for the Golen Gol Hydroelectric project. Computer program HEC-1, Flood Hydrograph Package developed by the Hydrologic Engineering Center of the US Army Corps of Engineers was used for the determination of design floods. In this case an extensive analysis of maximum precipitation for short and long periods of the stations Chitral was performed.

A detailed model including the morphometric characteristics of the Golen Gol catchment and hydraulic conditions of the channels was formulated. Series of runs of the program permitted to conclude that in the Chitral river catchment rainfall originated floods are important in small catchments in the short and long term. The Golen Gol catchment falls into this category. Design floods were estimated from the precipitation-runoff model.

Similarly, a computer model of the Mastuj river up to the confluence with Golen Gol was prepared to estimate the maximum level of the Mastuj river at the place of the power house. Because of the extension of the catchment of the Mastuj river (catchment area = 9676 km^2), it was divided into 8 sub-catchments for simulation purposes. The catchment was simulated using the synthetic unit hydrograph technique. After various runs of the computer program, it was concluded that for catchments of the size (or larger) of the Mastuj river rainfall originated floods are important only in the long term. 10,000-year flood was estimated to assess the maximum flood level of the Mastuj river at Golen Gol Power House.

The following was the procedure used to determine the maximum floods at the proposed weir site and the 10,000-year flood to determine the level of the power house of the hydroelectric project Golen Gol. The precipitation analysis was performed on basis of the station Chitral at Chitral town:

Precipitation analysis:

- Selection of maximum storms for reduction of available 3-hours precipitation data to 1-hour precipitation.
- Estimation of maximum precipitation for durations of 3, 6, 9, 12, 15, 18, 21 and 24 hours for each year of the precipitation record.
- Frequency analysis of maximum precipitation for the same durations.
- Reduction of estimated maximum precipitation for the mentioned durations to maximum precipitation for durations of 1, 2,...., 24 hours. Estimated maximum precipitation values are presented on Table 3.14.
- Processing and analysis of selected storms to obtain various possible hyetographs. Mass curves of selected storms are depicted on Figure 3.26.
- To reduce the maximum point precipitation to the area of the catchment of Golen Gol, a coefficient of 0.67 was adopted.

Table 3.15: Estimated maximum Precipitation for various duration and return periods

Duration (hrs)	Corr. Coeff.	Return Period (Years)							
		2	5	10	20	50	100	1000	10000
1	0.81	7.9	9.4	10.3	11.3	12.5	13.4	16.3	19.3
2	1.28	12.4	14.7	16.3	17.7	19.6	21.0	25.7	30.3
3	1.80	17.5	20.7	22.9	24.9	27.6	29.6	36.1	42.7
4	1.26	21.9	26.6	29.7	32.7	36.6	39.5	49.0	58.5
5	1.46	25.3	30.8	34.4	37.8	42.3	45.6	56.6	67.6
6	1.60	27.8	33.7	37.6	41.4	46.3	49.9	62.0	74.0
7	1.23	29.6	36.5	41.0	45.4	51.0	55.3	69.3	83.2
8	1.29	31.0	38.3	43.0	47.6	53.5	58.0	72.7	87.3
9	1.33	32.0	39.4	44.4	49.1	55.2	59.8	74.9	90.0
10	1.12	33.3	42.1	48.0	53.6	60.9	66.4	84.4	102.4
11	1.16	34.4	43.6	49.7	55.5	63.1	68.7	87.4	106.1
12	1.20	35.6	45.1	51.4	57.4	65.3	71.1	90.4	109.7
13	1.05	36.8	47.2	54.1	60.8	69.3	75.8	97.0	118.2
14	1.08	37.9	48.6	55.7	62.5	71.3	877.9	99.8	121.6
15	1.11	38.9	49.9	57.2	64.2	73.3	80.1	102.5	124.9
16	1.01	40.4	52.2	60.0	67.6	77.3	84.6	108.6	132.7
17	1.04	41.6	53.8	61.8	69.6	79.6	87.1	111.9	136.6
18	1.07	42.8	55.3	63.6	71.6	81.9	89.6	115.1	140.6
19	1.01	44.3	58.0	67.1	75.9	87.2	95.7	123.7	151.7
20	1.04	45.6	59.7	69.1	78.1	89.8	98.5	127.4	156.2
21	1.08	47.3	62.0	71.8	81.1	93.2	102.3	132.3	162.2
22	1.04	49.0	65.2	75.9	86.1	99.4	109.4	142.3	175.2
23	1.06	50.2	66.8	77.8	88.3	101.9	112.2	145.9	179.6
24	1.09	51.4	68.4	79.7	90.5	104.4	114.9	149.5	184.0

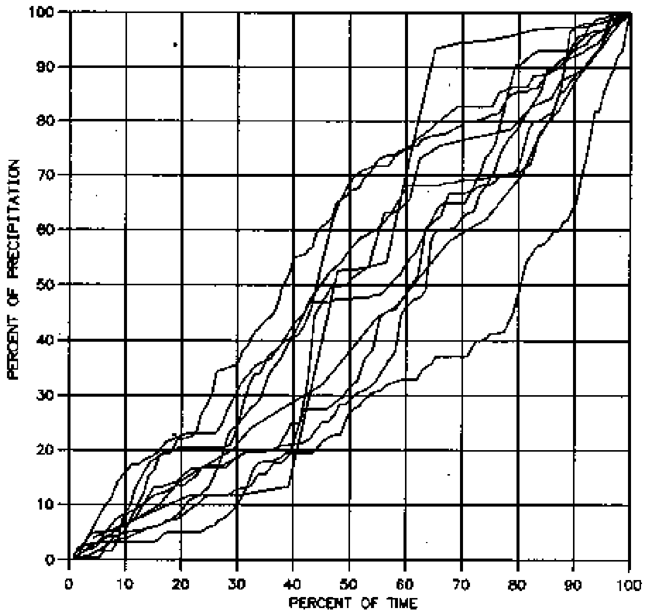


Fig. 3.18: **Dimensionless Precipitation Mass Curves, Chitral, Hindukush**

Flood model development of Golen Gol:

- Development of a flood model of the Golen catchment using the kinematic wave option available in HEC-1 flood package. The physical parameters of the model were obtained as follows:
    - The overland flow element is described by four parameters: a typical overland flow length, the slope (both obtained from 1:50,000 sheets), the roughness factor (assumed to be 0.15 corresponding to hard material with sparse vegetation) and the percent of the sub-catchment represented by these parameters (always 100%).
    - The channel elements are defined by their length, slope (both obtained from 1:50,000 sheets), roughness (assumed to be 0.043 for the upper part of the catchment and 0.039 for the middle and lower part), shape (assumed to be rectangular), width or diameter and side slope.

- The components of the flood hydrograph were determined as follows:
    - Snowmelt and base flow contribution was assumed to have the same specific discharge as the maximum base flow observed at Chitral during May.
    - The total loss to infiltration was adopted to be 3.1 mm/h corresponding to soils with slow infiltration losses when thoroughly wetted, and consisting mostly of soils with a layer that impedes downward movement of water.

- Various runs of the model were required to determine critical hyetograph and critical storm duration.

- Final runs to estimate design floods. Estimated maximum floods for various return periods are given on Table 3.16. Final estimation of maximum 1,000-year flood of Golen Gol at the confluence with Rogahil Gol.

Table 3.16: Estimated maximum floods of Golen Gol at confluence with Roghail Gol

Return Period (Years)	Maximum Flood (m^3/s)
5	380
10	465
100	809
1000	1156
10000	1501

- Mastuj river model development

- Geomorphologic parameters required to develop the flood model of the Mastuj river, namely sub-catchments area, length to the centroid of the catchment and weighted slopes were determined from the 1:50,000 sheets. Geomorphologic parameters of the sub-catchments are summarized in Table 3.17.

- The components of the flood hydrograph were determined as follows:
    - Snowmelt and base flow contribution was assumed to be the same as the estimated mean monthly flow during May from the simulation of flows. The mean monthly flow was affected by a coefficient calculated between the maximum daily flow during May and the mean monthly flow as observed at Chitral.
    - The total loss to infiltration was adopted to be 3.1 mm/h corresponding to soils 7ith slow infiltration losses when thoroughly wetted, and consisting mostly of soils with a layer that impedes downward movement of water.

Table 3.17:**Geomorphologic characteristics of sub-catchments, Mastuj River at confluence with Golen Gol**

Name	Area (km^2)	L (km)	Lca (km)	S (m/m)	Kn	Lg (hrs)
Upper Yarkun River	1763	93	40	0.009	0.039	5.9
Lower Yarkun River	1388	61	33	0.006	0.039	5.2
Laspur River	1235	66	32	0.020	0.039	4.3
Upper Mastuj River	305	30	15	0.003	0.039	3.5
Upper Turikho River	1825	64	24	0.016	0.039	4.0
Tirich Gol	1294	62	26	0.034	0.039	3.6
Lower Turikho River	435	33	20	0.007	0.039	3.5
Lower Mastuj River	1431	38	14	0.004	0.039	3.6

- Various runs of the model were required to determine critical hyetograph and critical storm duration.

- Final runs to estimate design floods. Final estimation of maximum 10,000-year flood of Mastuj river was calculated for the power house of Golen Gol HP.

A detailed explanation of the procedure of estimation of design floods for the Golen Gol Hydroelectric Project is given in feasibility report.

3.5.5 REGIONAL ANALYSIS

Very often, information on floods in a given region is restricted to short records if at all available. The reliability of estimates from short records is very low and not advisable. Although desirable when direct measurements do not exist, estimation of floods by precipitation - run-off models is not always possible. One common reason is the lack of continuously recorded precipitation data, which is necessary for the identification of storms capable of generating large floods in the catchment.

Consequently, in order to take into account the conditions originating floods in the area of interest and the magnifying effect of the area on the specific discharge of the floods as observed in the area, a regional approach was developed for estimation of floods.

Following are the main steps:
1. Flood frequency analysis is performed for all available stations in the area.
2. Specific discharge of estimated 100, 1,000 and 10,000-year floods are calculated.
3. Available flood data are classified according to the origin of floods in the catchment.
4. An enveloping curve is drawn to each set of specific discharges (100, 1,000 and 10,000-year floods), and a mathematical function is fitted to the curve.

Stations for which flood frequency analysis was performed are presented on Table 3.17, along with the estimated 100, 1,000 and 10,000-year floods. The specific discharges of the 100, 1,000 and 10,000-year floods have been plotted in Figures 3.19, 3.20 and 3.21. The mathematical function fitted to the enveloping curves is of the form:

$$Q_{\max} = C * A^n \qquad \textbf{(3.14)}$$

where

Q_{max} = maximum instantaneous discharge for the return period in m^3/s.

C,n = coefficients

A = catchment area in km^2

Table 3.18:**Estimated 100, 1.000, 10.000 – year floods after Gumbel for different rivers in Karakoram – Himalayan Mountain Range**

Station	Catchment Area (km^2)	Q_{100} (m^3/s)	Q_{1000} (m^3/s)	Q_{10000} (m^3/s)
Shyok at Yugo (78-83)	65025	3570	4275	4980
Indus at Kachura (73-80)	146100	8220	9970	11710
Hunza at Dainyor Br.(74-83)	13925	3750	4670	5580
Gilgit at Gilgit (80-85)	12800	4370	5150	5930
Gilgit at Alam Br.(73-83)	27525	4360	5150	5930
Indus at Partab Br. (73-83)	176775	12340	14680	17020
Astore at Doyian (74-87)	3750	1370	1770	2200
Gorband at Karora (75-84)	625	980	1330	1670
Indus at Besham Qila (73-83)	196425	15950	18890	21820
Brandu at Daggar (70-86)	598	640	990	1260
Siran at Phulra (73-83)	1057	1170	1530	1880
Chitral at Chirtral (73-84)	12425	1880	2320	2760
Swat at Kalam (73-85)	2024	760	960	1160
Swat at Chakdara (73-85)	5400	1980	2570	3170
Bara at Jhansi Post (73-83)	1846	1160	1660	2150
Kabul at Nowshera (73-88)	88540	7180	9320	11450
Haro at Khanpur (73-83)	777	2050	2890	3720
Jhelum at Chinari (70-90)	13735	2340	3080	3830
Jhelum at Domel (80-90)	14490	2410	3120	3820
Neelum at Muzzafarabad (63-90)	7275	2490	3050	3600
Kunhar at Naran (60-90)	1036	680	900	1120
Kunhar at Garhi Habib (60-88)	2382	1570	2080	2590
Jhelum at Kohala (65-90)	24769	5870	7530	9170
Jhelum at Azad Patan (79-90)	26289	5830	7320	8820
Kan shi at Palotel (70-90)	1111	2700	3600	4600
Ounch at Kotli (61-90)	3177	12700	17400	22000

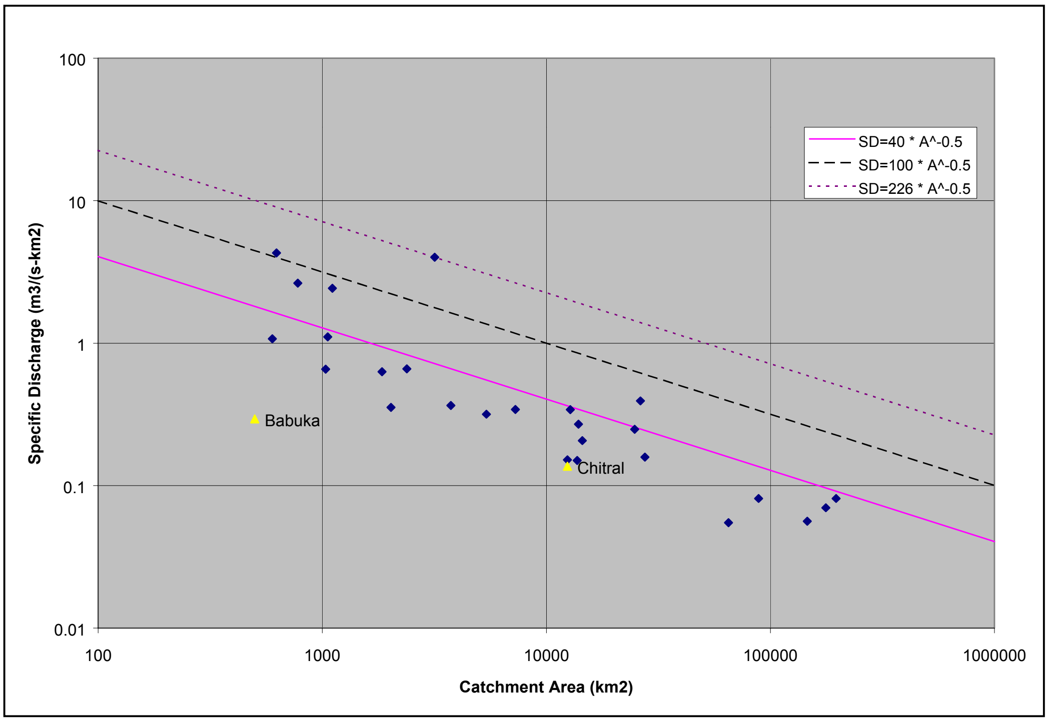


Fig. 3.19: Enveloping Curves to the 100 – year flood

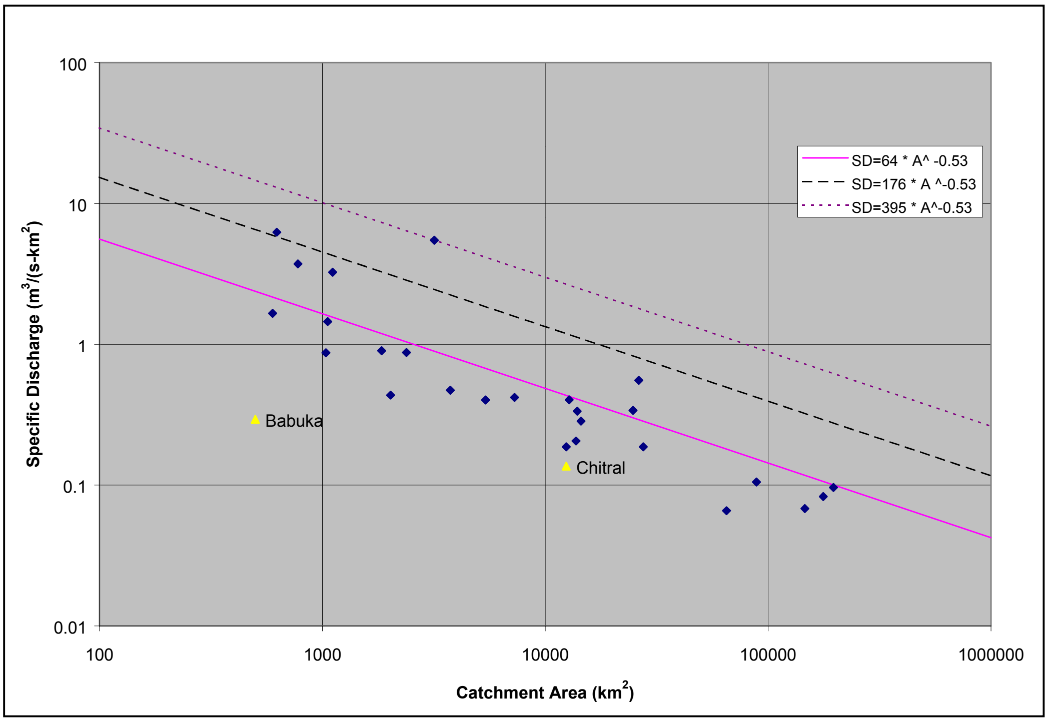


Fig. 3.20: Enveloping curves to the 1.000 – year flood

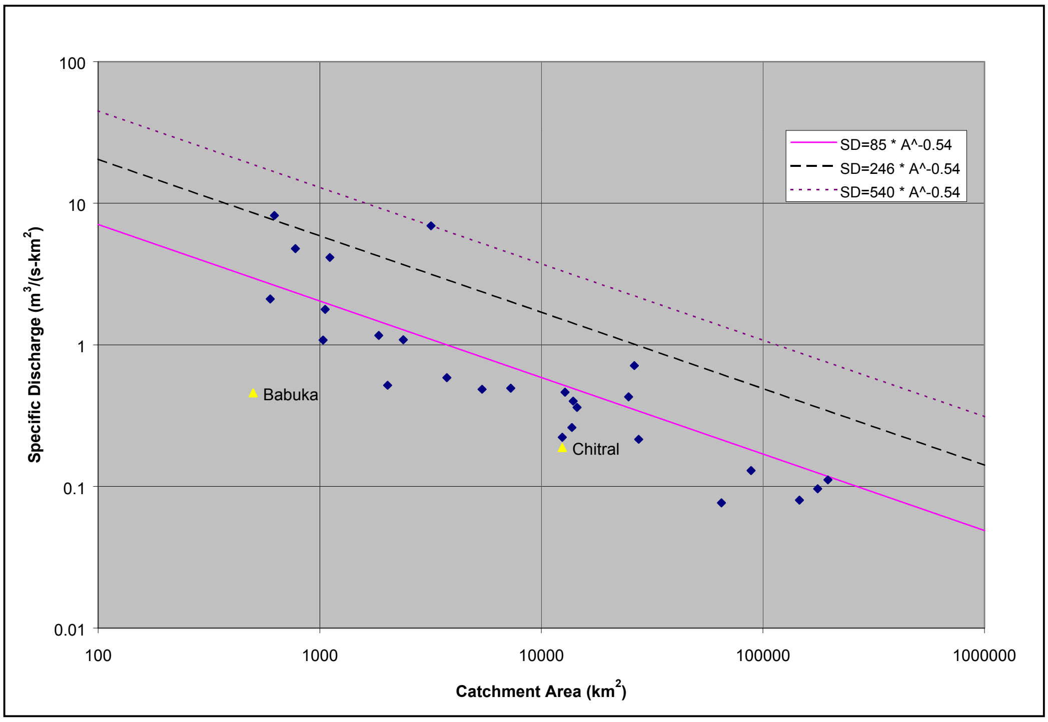


Fig. 3.21: Enveloping curves for the 10.000 – year flood

The equations enveloping the 100-years, 1,000-years, and 10,000-years maximum floods are given in the same Figures 3.19, 3.20 and 3.21, and are presented below:

For regions affected by monsoon rains:

$$Q_{100} = 226 * A^{0.5} \tag{3.15}$$

$$Q_{1,000} = 395 * A^{0.47} \tag{3.16}$$

$$Q_{10,000} = 540 * A^{0.46} \tag{3.17}$$

For regions frequently affected by monsoon rains:

$$Q_{100} = 100 * A^{0.5} \tag{3.18}$$

$$Q_{1,000} = 176 * A^{0.47} \tag{3.19}$$

$$Q_{10,000} = 246 * A^{0.46} \tag{3.20}$$

For regions moderately affected by monsoon rains:

$$Q_{100} = 40.45 * A^{0.5} \quad \textbf{(3.21)}$$

$$Q_{1,000} = 64 * A^{0.47} \quad \textbf{(3.22)}$$

$$Q_{10,000} = 84.85 * A^{0.46} \quad \textbf{(3.23)}$$

The coefficients of the equations presented above are in good agreement with the values obtained by other authors in previous studies. Creager in his remarkable work on floods found, with data available in 1926, a value of 0.5 for the exponent "n" of equations 3.15, 3.18 and 3.21. The values obtained for the same exponent through the regional analysis presented in this document are 0.5, 0.47 and 0.46 for the 100, 1,000, and the 10,000-year flood equations respectively (equation 3.15, 3.16 and 3.17, 3.18, 3.19, 3.20, 3.21, 3.22 and 3.23). Creager mentions that the value of the exponent "n" of equation 3.15, 3.18 and 3.21 have ranged between 0.3 and 0.8. Myer (see Table 3-4) found a "n" value of 0.5 and a value of 175 for the coefficient "C". The values for the coefficient "C" given in equations 3.15 to 3.23 vary between 40.45 to 226, 64 to 395 and 84.85 to 540 for the 100, 1,000 and 10,000-year flood equations respectively.

The coefficients of equations 3.15 to 3.23 are also comparable with the coefficients of formulas obtained in Europe. The Illwerke-formula assigns a value of 0.83 to the exponent "n", and a value of 5.5 to the coefficient "C" for the estimation of the 100-year flood. The value of "n" in the Illwerke formula is larger than the value presented in the corresponding formulas 3.15, 3.18 and 3.21 while the "C" value of the Illwerke formula is smaller than the one given in formulas 3.15, 3.18 and 3.21. However, estimated floods from both equations are comparable for catchments with an area up to 700 km^2.

The Hofbauer-formula, developed in Europe, is remarkably similar to the 100-year flood for areas moderately affected by monsoon rains obtained in this document. The values of the coefficients "n" and "C" as given by Hofbauer are 0.5 and 42 respectively, the exponent "n" being the same as presented in formula 3.21, and the "C" coefficient very close to the value given in formula 3.21.

The Melli formula gives 0.67 and 34 for the "n" and "C" coefficients, and floods estimated with this formula are larger than the floods estimated with the formula 3.21.

Similar relationships have been used in Pakistan in the past to estimate floods. Direct estimation of floods from the records by statistical methods has been considered to be inadequate in some cases, because the records may not include floods caused by extremely severe monsoon events. These events could penetrate the upper valleys and produce high floods that have not been recorded at the gauging stations. These extreme events have been considered here by including stations in areas where maximum floods are produced by monsoon rains. Stations in areas moderately affected by the monsoon and included in this analysis are: Swat river at Chakdara, Gorband river at Karora, Siran river at Phulra, Brandu river at Daggar and Bara river at Jhansi Post.

Maximum floods for areas affected by extreme monsoon rains can be calculated with the formulas (3.15), (3.16) and (3.17). Stations on rivers recording such floods include Punch river at Kotli, Kanshi river at Palote in the Jhelum catchment, and Haro river at Khanpur in the Indus catchment. The estimated 100, 1,000 and 10,000-floods estimated for those stations have the maximum specific discharges.

From the above discussion, it was concluded that at the present, the estimation of floods by the regional approach presented here gives reliable results. However, from the information included in Table 3.15, it becomes apparent that updating of the information is required, especially to include the floods occurred in September 1992. The estimated 100, 1.000 and 10.000-year floods of Summar Gah at the site of the intake (near Gosak), of the whole catchment of the Summar Gah and of the Indus river at the confluence with the Summar Gah are included as an example in Table 3.16.

Table 3.19:**Estimation of floods at intake and power house, Summar Gah, Kohistan**

Return Period (Years)	Summar Gah at Intake (A = 147 km^2) (m^3/s)	Summar Gah at Confluence (A = 160 km^2) (m^3/s)	Indus River at Confluence with Summar Gah (A = 188.563 km^2) (m^3/s)
100	500	160	17570
1000	670	520	19320
10000	850	700	22670

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