Appendix C
Hydrology

FEASIBILITY STUDY
ON
THE DEVELOPMENT OF MUNDA DAM MULTIPURPOSE PROJECT
IN
ISLAMIC REPUBLIC OF PAKISTAN

FINAL REPORT
VOLUME III
SUPPORTING REPORT

Appendix C : Hydrology

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APPENDIX C HYDROLOGY

C1 Basin Description

C1.1 Physical Features

The proposed Munda Dam site is located on the Swat River, which is a major tributary of the Kabul River at approximately coordinates of 34° 21' N and 71° 32' E as shown in Figure C1.1. Up to the proposed Munda Dam site, the total catchment area of the Swat River basin is 13,650 km^2 and can be divided among three major subbasins of upper and lower Swat (6,579 km^2), Panjkora (5,724 km^2) and Ambahar (1,347 km^2) river subbasins. The basin lies between latitude of 34° 20' N to 35°56' N and longitude of 71° 20' E to 72° 50' E with about 137 km in length and 110 km in width. The Swat River originates from a confluence of Gabral and Ushu at Kalam in the Swat Kohistan with an average elevation of 4,500 m. Below Kalam, the upper Swat forms a well marked longitudinal valley; taking a southerly course that further joins the drainage of Dir Kohistan and the Buner State and basin elevation decreases from 3,050 to 1,520 m or less. The lower Swat flows through the broad valley at an elevation of 910 – 1,220 m. The Panjkora River, also rising in the Swat Kohistan, meets the river Swat below Kalangai. After their confluence, the river turns southwestwards, enters the Peshawar valley and meets the Kabul River at Misatta. Munda Headworks is located approximately 5 km downstream of the proposed dam site and the Swat River, of which the name is changed as the Khiali River at the Munda Headworks, joins the Kabul River at about 35 km further downstream of the headworks.

C1.2 Climatic Features

The climate varies considerably over the catchment. In the upper basin the winter is very cold and freezing weather prevails from November to March with snowmelt temperatures occurring between April and September. The snow line descends to 2,500 m during the winter and recedes to about 4,000 m during the summer. In the lower basin the winter is less cool and the summers are hotter. Figure C1.2 shows the satellite image map indicating the snow-covered regions in November 1976 for the entire basin. The Swat River consequently carries perennial flow, which is generated from snowmelt and rainfall.

On average, the rainfall over the catchment varies from 500 mm to 1,500 mm. Rain occurs over the basin in both summer and winter with two maximum occurring in March and August. In summer, rainfall is largely due to monsoon influences and storms, which produce significant runoff, and occur mainly at the central and lower basin. The monsoon rainfall far exceeds the winter precipitation both for the daily normal average and the recorded intense falls (ref. 1, pp. 3). In the remainder of the year, rainfall can occur over a wider area and is largely affected by the influence of westerly disturbances. The winter rainfall in the lower catchment is generally less intense than the summer rainfall. In the upper part of the basin, winter precipitation occurs almost entirely as snowfall.

C1.3 Present Development

The first significant water resources development on the Swat River took place in 1885 when the Lower Swat Canal (LSC) was opened to irrigate 510 km^2 with a designed capacity of 29.9 m^3/sec as seen in Figures C1.1 and C4.5. During 1915-19 the canal was renovated by additional barrage to provide extra 23.5 m^3/sec discharge from the left bank. Simultaneously, Doaba Canal with a designed capacity of 10 m^3/sec was constructed to be fed from the right-bank of the barrage and hence increased the total command area to about 650 km^2. In 1914, the Upper Swat Canal (USC) was completed to take off from Amandara Headworks to irrigate 1,117 km^2 with 50.9 m^3/sec-designed discharge. In 1938 a small hydropower plant was set up on USC near Jabban with an installed capacity of 9,600 kW which was raised to 19,600 kW in 1951. Another 20,000 kW plant was completed on the same canal near Dargai in 1954 (ref. 2, pp. 8-9).

C2 Hydro-meteorological Data

C2.1 Rainfall Data

In Pakistan, provincial authorities such as the Irrigation Department, the Revenue Department, and the Forest Department operated the rainfall gauging stations before the Independence of Pakistan. The Indian Meteorological Service used to assemble and collect data from monthly provincial returns and published the information in annual volume entitled "Daily Rainfall of India" which dates as old as 1866. Following the independence, the operation of some of the rainfall gauging stations was taken over by Pakistan Meteorological Service (PMS). The records for these stations are held in Lahore and are published in a series of volumes entitled "Daily Weather Reports". For other stations, control was not maintained and the availability of records depends amply on the arrangements made by individual departments (such as Pakistan Forest Institute at Peshawar). To date, daily rainfall of these stations not controlled by PMS can only be obtained from local offices of the provincial departments.

Water and Soil Investigation Division (WASID) of Water and Power Development Authority (WAPDA), or its Surface Water Hydrology Project (SWHP) as it is known at present, have set up a number of recording and non-recording rain gauges since 1960 to supplement rainfall records within PMS.

C2.2 Other Meteorological Parameters

In addition to rainfall information, PMS also collects and publishes other climatic parameters within their "Daily Weather Reports". These reports include records of air temperature, pressure, humidity, and wind speed. A number of climatological stations were set up by SWHP/WAPDA since 1960 to record daily data of temperature, evaporation, humidity, and wind.

The meteorological data were collected during the field investigation of the Study from several agencies responsible for maintaining meteorological data within and around the Munda catchment area. Principal sources are listed as follows:

- Pakistan Meteorological Service (PMS)
- Irrigation Department at NWFP (ID)
- Provincial Authorities at NWFP (PRO)
- Surface Water Hydrology Project at WAPDA (SWHP)
- Pakistan Forest Institute at Peshawar (FOR)

Stations maintained within and around the Munda catchment area by PMS and other provincial departments are listed in Table C2.1. The locations of these stations are shown in Figure C1.1. Rainfall records are available within all the meteorological stations. Peshawar station has records for 7-climatic parameters and is considered a synoptic station. For the Study, records of daily / hourly rainfall and daily / monthly meteorological data were collected and encoded by the Study Team during the site investigations. Inventory of the collected meteorological data is shown in Figure C2.1.

C2.3 Flow Data

Prior to the mid 1950s the Irrigation Department (ID), mainly through its two agencies of the Irrigation Research Institute and the Hydrology Directorate, was the only organization which collected river stage and discharge data on a regular basis. The Railways Department and the Public Works Department also maintained gauges at existing or planned bridge sites but flow records are available on discrete condition on high flood stages rather than on continuous record of river levels. Within the Swat River basin, ID maintained flow data at Chakdara since 1911 and Munda Headworks since 1927. The observations practice carried out by ID consists of staff gauge readings taken once, twice or three times a day during normal flows and more frequently, but insufficient, during floods. This principal practice brings fair records during normal flow condition and poor records for high and low flow periods (ref. 3).

An organized program of countrywide hydrologic observations and data collection using methods developed by the United States Geological Survey (USGS) was undertaken after the establishment of WAPDA in 1959. In January 1960 the Surface Water Circle was created by WAPDA solely for the management and operation of hydrological stations. This organization was later merged into Water and Soil Investigations Division (WASID) and now operates under the name of Surface Water Hydrology Project (SWHP). Hydrological data collected by SWHP consists of river stage and discharge, suspended sediment concentration and water quality data.

Computed mean daily flows based on stage and discharge observations along with the sediment and water quality analysis data are published in SWHP annual reports.

Standard SWHP practice at discharge measurement stations is to measure river levels at several times a day during low flow periods and more often during high flow. At some important stations such as Nowshera, observations are carried out hourly round the clock during high flow period (July – September). This principal practice brings fair records for both high and low water record periods. In July 1962 all stations located in the foothills and mountain areas were transferred to WASID, while those in the plains remained with the ID. Following this principal, in the Swat River basin, the station of Munda Headworks remained in ID Charsadda District of NWFP.

Inventory of the water level stations maintained within and around the Munda catchment area by SWHP and ID is listed in Table C2.2. The locations of these stations are shown in Figure C1.1 along with the meteorological stations.

During the field investigations of the Study, hydrological data were collected and encoded by the Study Team for five stations and two diversion canals. Inventory of the collected hydrological information is shown in Figure C2.2.

In summary, within the catchment of Swat River basin up to the proposed dam site, the hydro-meteorological data are available from eight rain gauging stations and three water level gauging stations as shown in Figure C1.1. As shown in the figure, the existing rain and water level gauging stations are inconsistently located along the main stem of the Swat River with no single station available in the Panjkora River basin, which represents approximately 40% of the total catchment area of the proposed Munda Dam. To supplement the hydrological information for the Project, new rainfall and water level gauging stations were recommended by the Study Team as shown in Figure C1.1 and are currently under construction by WAPDA at:

1) Approximately 2 km downstream of the proposed dam site where the river channel is relatively straight and narrow, and
2) Near existing Zulam Bridge in the Panjkora River basin.

C2.4 Flow Records at Upstream of Existing Munda Headworks

There are daily flow records at the upstream site of the existing Munda Headworks, which are annually compiled as an annual data book, "Stream Flow and Rainfall Data, Peshawar Zone" published by Hydrology Division, Irrigation Department, NWFP. These records can be of crucial help for the assessment of water availability passing the dam site. However there are some disputable records and ambiguity involved regarding application of rating curve, frequency of discharge measurement, backwater effects from the headworks etc. The following statements were carried over from the previous studies and available reports that indicate some reasons of the dubious records maintained by ID at Munda Headworks gauging station:

- A great discrepancy was noted when the records of Swat River flows at Munda Headworks as observed by the Irrigation Department were checked against the SWHD discharge figures of Kabul river both above and below the confluence with Swat River. (ref. 2, pp. 18)
- Discharge at Munda Headworks since 1927 until recently have been computed by the Irrigation Department on the basis of gauge height observations and discharge rating tables developed using rod and float measurements. These records are considered to be only approximate since

the gate regulation and water diversions into Lower Swat and Doaba Canals in low-flow periods occasionally influence the river stage. (ref. 3. pp. I-4)

- About 500 m upstream of Munda Headworks there is a gauge maintained by the Hydrology Division, Irrigation Department, Peshawar. At this section, there is an old cableway, which is out of function. There is no arrangement of measurement of velocity and a proper rating curve is not available for the section. The discharge values are estimated against the gauge observations on the basis of the previous discharge values, which were recorded in the past when occasional measurement of velocity was also practiced. During low or medium flow period the gauge observations may be affected by the closure of gates at the headwork, which may involve error in the discharge data. Sometimes gauge observations are taken at Munda Headworks and the Hydrology Division, Peshawar also uses the corresponding discharges, instead of observations at their own section (ref. 4, pp. 4)
- A stream bifurcates from Swat River about 500 m upstream of the present cableway and downstream of the gauge site, with the result that the whole discharge cannot be measured at high stages due to the spill in the side stream. However it can be estimated. Gauge is affected when the gates of Munda Headwork are lowered during low stages of the river to supply water to Lower Swat Canal. It is difficult to shift the gauge site further upstream due to the disturbances in the tribal area (SWHP annual reports)

Based on the site observations, the results of interviews carried out during the field investigations, and the above perceptions concluded that the flow records at the existing Munda Headworks are not reliable and cannot be adopted for the hydrological study for the Project.

C2.5 Flow Records at Other Stations

There are four other flow gauging stations in and near the Swat River basin. These stations are Kalam (Swat River), Chakdara (Swat River), Warsak (Kabul River), and Nowshera (Kabul River). The four stations are in operation by the Surface Water Hydrology Project (SWHP) of WAPDA since 1960 up till now, except Warsak, which was abandoned after the construction of Warsak Dam in 1970. As described above, SWHP follows the procedures used by US Geological Survey, and standard SWHP practice at gauging stations is to measure river level several times a day during low flow periods and more frequently during those of high flow periods.

In order to compare the daily flow trends among the different stations, daily records from 1990 and 1991 at Kalam, Chakdara, and Nowshera were extracted from the available data and plotted as shown in Figures C2.3, C2.4 and C2.5 respectively. It can be noticed that maximum daily flow occurred within the summer season for the three stations in both 1990 and 1991. Mean monthly discharges for the period 1960 to 1991 at Kalam, Chakdara, Nowshera, and Warsak are shown in Figure C2.6.

Discharge measurements are generally made twice a month during low flows and more frequently during high flows. The average number of discharge observations during the period from 1961 to 1981 (for Warsak, 1961 to 1971) is as follows:

Average number of discharge observation

Gauge	Nos./Year
Kalam	26
Chakdara	42
Warsak	21
Nowshera	28

Source: ref. 5 Technical Memo 7, Table 9, pp. 27

During the first field investigation stage, rating curves for Kalam (1965-1988), Chakdara (1964-1988) and Nowshera (1964 – 1987) stations were collected and are shown in Figures C2.7, C2.8, and C2.9, respectively.

To investigate and find out the relationship between these flow patterns within the Swat and Kabul basins, correlation analysis was carried out on the basis of the monthly flow data. Cross correlation among each pair of stations was calculated and results are shown in Figures C2.10 and C2.11, and tabulated below.

Correlation Coefficient for Monthly Discharge
Among Water Level Gauging Stations

Name of Station (Catchment Area)	Kalam (1961-1995)	Chakdara (1961-1995)	Warsak (1961-1971)	Nowshera (1961-1995)
Kalam (2,020 km^2)	-	0.9445	0.9165	0.9086
Chakdara (5,766 km^2)	-	-	0.9743	0.9716
Warsak (67,340 km^2)	-	-	-	0.9914
Nowshera (88,578 km^2)	-	-	-	-

Based on the correlation coefficient results, the correlation is quite high among monthly flow data at the four stations, especially between Chakdara, Warsak and Nowshera for which the correlation coefficients are more than 0.97.

Furthermore, the correlation analysis of the monthly flow data at the above stations was carried out with Munda Headworks Station as shown in Figure C2.12, which indicates low correlation coefficients of 0.68 – 0.83.

Analysis of the records within the four stations, Kalam, Chakdara, Warsak, and Nowshera, maintained by SWHP-WAPDA revealed that flow records are reliable and acceptable based on the following reasons:

- Standard practice of flow measurements of US Geological Survey
- Number of the flow measurements are sufficient
- Updating of the respective rating curves
- High correlation coefficients among records of each gauging station

The records within the four stations were utilized to estimate the monthly flow data at the dam site based on regional analysis as will be described later.

In order to obtain long-term monthly flow data at Munda Dam site, available records at Kalam, Chakdara, Nowshera, and Warsak were utilized. Analysis of the available records revealed some missing records from 1961 to 1997 as shown in Figure C2.2. Review of available reports and studies were conducted to provide some of these monthly missing records (e.g. for the period 1956 – 1961 from ref. 3). The remaining missing records for the years 1973, 1974, 1991 and 1992 at Kalam, Chakdara and Nowshera stations were supplemented using means of serial correlation method. Because of the large documentation of serial correlation methodology description and material involved, only the outline of the methodology will be described. Details of the approach can be found in "Applied Modelling of Hydrological Time Series" (ref. 6). In brief, the following equation was applied:

$$Q_{i+1}=MQ_{j+1}+b_j(Q_i - MQ_j)+d_{j+1}t_i(1-r_j^2)^{1/2}$$

Where Q_{i+1} and d_{j+1} are the discharge and standard deviation during i and j months respectively. MQ_j and MQ_{j+1} are the mean of i and j months respectively. The b_i and r_j are the regression coefficient and the random normal-independently distributed variates (zero mean and unit variance) during the j month. During the model computation, the index j ran cyclically from 1 to 12 months. Given a table of normal random deviates and the 36 calculated statistical parameters of monthly flow (MQ_j and d_j for each month and r_j for each pair of consecutive months), the computation of Q_{i+1} is a straight forward matter of arithmetic.

The long-term flow records (available and supplemented) at Kalam, Chakdara and Nowshera are listed in Tables C2.3, C2.4, and C2.5, respectively.

C3 Meteorology

C3.1 General Climatological Characteristics

The climate of the Swat River basin is classified as sub-humid tropical continental high lands. The topographic features, especially the altitudes, influence the climatic conditions significantly. Precipitation over the catchment area is the only source of moisture and it is received in the form of both rain and snow. Rainfalls occur within two seasons, monsoon (July to September) and spring (February to May). The monsoon rain brings 30% of annual rainfall in the basin and prevails with moisture brought by winds from Arabian Sea and the Bay of Bengal. In the upper region, monsoon rain brings 15% of annual rainfall and the rest is due to snowmelt that takes effect during summer. The Panjkora basin is fairly well oriented and exposed to the monsoon incursion, which invades it from the south and southeast, as the southwest is primary blocked by Safed Koh Hills boarding the Peshawar Valley. Besides, rainfall in the summer season is occasionally associated with the eastward passage of active western disturbances, which reach West Pakistan from the west. This passage strengthens and induces the activity of the Arabian Monsoon and causes rain to fall over the drier parts of the basin (ref. 1). According to the normal isohyetal map prepared by PMS, the annual rainfall within the catchment area varies locally from 380 mm to 1,270 mm with 810 mm average annual rainfall (ref. 4). Monthly rainfall distributions indicate two existing peak seasons, in March and in August for most of the stations. However, significant variations in rainfall distributions can be noticed among the different stations.

Temperature varies within the region extensively. The upstream region of Swat River at Kalam has a very cold and freezing temperature in winter from November to March. In the downstream, winter is warmer and summer is hotter. The maximum temperature usually occurs in July and minimum in January. Based on the collected data, the long-term average annual temperature values at four meteorological stations are listed below:

Long-term Mean Monthly Maximum and Minimum Temperatures

Units: °C

Station	Maximum	Minimum	Average	Period
Kalam	19.2	-1.1	10.6	1986 - 1996
Saidu Sharif	28.7	8.2	19.1	1974 - 1991
Mardan	31.9	9.2	21.1	1985 - 1996
Peshawar	33.1	11.2	22.7	1961 - 1991

C3.2 Rainfall Analysis

In Swat River basin, generally the months of July and August have the highest magnitude of rainfalls, while November has the lowest rainfall throughout the year. Based on the collected data, monthly rainfall at 7 gauging stations are listed in Tables C3.1 to C3.7. The monthly rainfall distributions at Kalam, Charbagh, Malakand and Abazai stations are presented in Figures C3.1 to C3.4.

The long-term mean monthly and annual rainfalls at each respective station are summarized in Table C3.8 and Figure C3.5. Double mass curves among some selected stations are prepared and shown in Figure C3.6. As shown in the figures, intensive rainfall in the years 1987 and 1988 were encountered at Charbagh station.

C3.3 Evaporation

Evaporation records are available at Peshawar meteorological station, which is the closest station to the Project site. The annual/monthly pan evaporation records observed by Pakistan Forest Institute, Peshawar, for the period 1967 to 1985 are available from the Pre-Feasibility Report (ref. 4).

During the field investigation stage, additional monthly evaporation records for the period from 1986 to 1997 were collected and are listed in Table C3.9. These records were combined with the records of 1967 – 1985 to obtain monthly long-term evaporation time series for the period 1967 – 1997 and results are shown in Table C3.9. The results indicated that average annual pan evaporation based on 31 year data is 1,674.1 mm with a maximum of 275.8 mm in June and minimum 40.7 mm in December.

To estimate the evaporation loss from the reservoir, the values of monthly pan evaporation records were multiplied by the conversion factor of 0.7 to convert the pan evaporation to the reservoir evaporation. The converted data is used to estimate the evaporation loss from the Munda Dam reservoir for the different proposed water levels during the reservoir operation study.

C4 Stream Flow

C4.1 Analysis of Available Data

The Munda Dam Project is proposed on the Swat River basin with a catchment area of 13,650 km^2 and traverses a river length of about 250 km. The catchment area was calculated and examined by dividing the total basin into four regions as illustrated in Figure C4.1. Based on the calculated catchment areas for each region, the upper Swat catchment area up to Chakdara water level station (region B1, 5,776 km^2) together with the Panjkora River basin (region B2, 5,724 km^2) form about 85% of the total catchment area. Flow from Panjkora River basin, which alone forms about 40% of the total catchment area and contributes an average of 50% runoff to the Swat River, is not being monitored. Flow records at the Munda Headworks are believed to have a low degree of reliability as discussed in the previous section. Therefore, alternative methodologies that included rainfall-runoff and regional analysis were investigated in order to estimate the long-term flow values passing the Munda Dam site.

Analysis of flow records indicates no direct relationship between rainfall and the corresponding runoff on both a monthly and annual basis. To illustrate this, the runoff coefficients at Kalam and Chakdara water level stations were calculated based on the relationship between annual rainfall and corresponding annual specific runoff as shown in Figure C4.2. The average annual runoff coefficients at Kalam and Chakdara, as shown in the figures, were calculated as 1.47 and 1.03, respectively. These values are impractical and the most likely reasons are (i) intensive rainfall and snowfall at the upper basin of Swat and Panjkora are not observed, (ii) locally intensive rainfall is not properly observed. With this fact in mind, application of rainfall-runoff methods and models (such as Tank model) cannot be utilized in this Study.

With the limited rainfall and snow information, the regional analysis was destined to be the most suitable procedure to be applied for water availability estimates at the dam site. In order to carry out regional analysis, the flow records of Kalam and Chakdara at the Swat River basin, and Nowshera and Warsak at the Kabul River basin were utilized.

Procedures of the regional analysis are outlined in the following Figure C4.3:

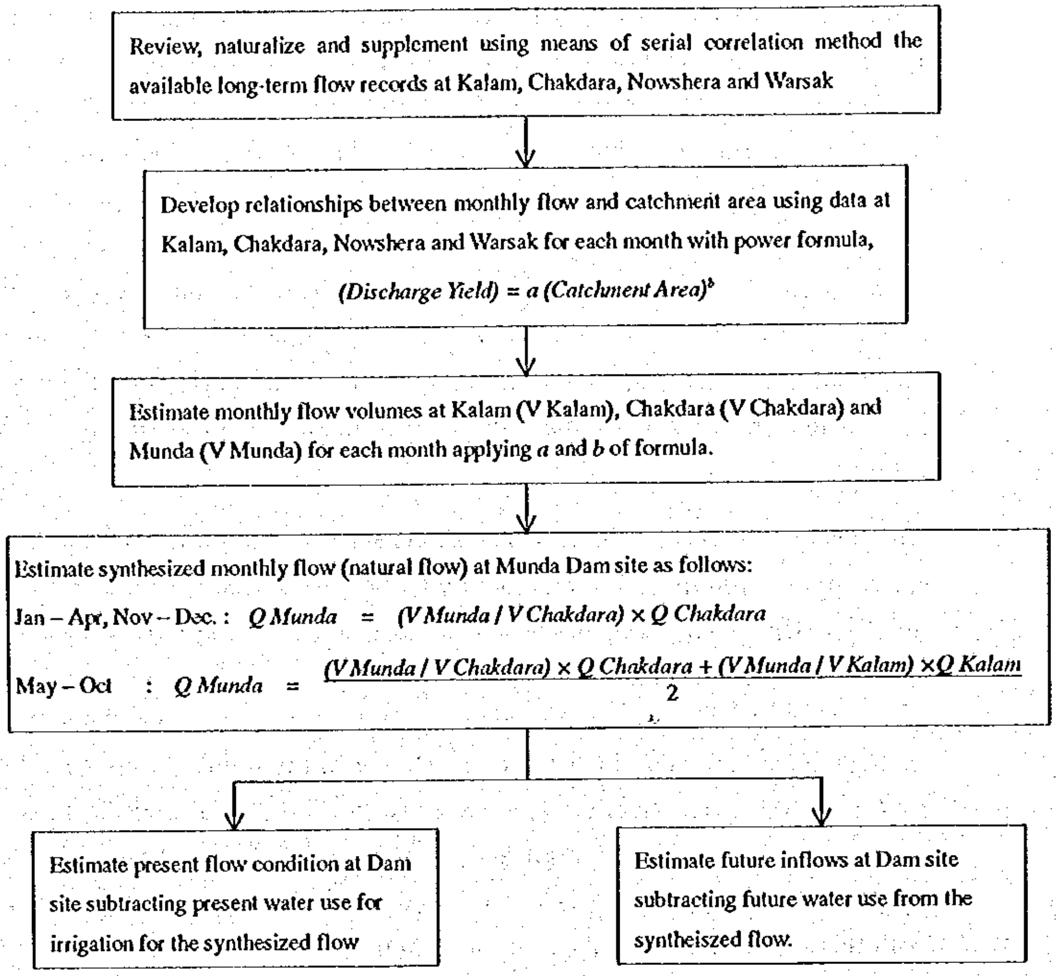

Figure C4.3 Procedures of the Regional Analysis

C4.2 Flow Estimation at Munda Dam Site

Flow estimation was carried out based on flow-catchment area relationships using flow records at the four stations of Kalam, Chakdara, Nowshera, and Warsak. The relationships have been developed for each month based on average monthly records in each station.

Figure C4.4 presents the relationships between the monthly discharge yield and corresponding catchment area in each station. As shown in the figure, all the relationships were best fitted using power formula in the form:

$$(Discharge\ Yield)_I = a_I\ (Catchment\ Area)^{b_I}$$

Where *discharge yield* is the specific flow volume per catchment area at month I expressed in mm. For each month, values for a_I and b_I were estimated as shown in the figure. Having the monthly relationships, monthly discharge yield at Munda Dam site can be then estimated. With a catchment area of

13,650 km², average monthly flow volume at Munda Dam site can be calculated as shown in the following table.

Monthly Estimated Parameters for Discharge Regional Analysis

Month	Power parameters		Discharge Yield mm	Flow Volume 10^6 m^3	V Munda / V Kalam	V Munda / V Chakdara
	a	b				
Jan.	143.91	-0.256	12.6	172	4.24	1.66
Feb.	163.84	-0.263	13.3	182	5.53	1.62
Mar.	227.18	-0.213	29.8	407	9.30	1.59
Apr.	517.91	-0.218	64.9	887	7.88	1.77
May	34523	-0.385	88.2	1,205	3.54	1.54
Jun.	8037	-0.439	123.5	1,686	2.56	1.54
Jul.	11904	-0.469	137.1	1,872	2.52	1.56
Aug.	7235	-0.463	88.1	1,204	2.46	1.47
Sep.	3066	-0.458	39.1	534	2.34	1.40
Oct	1296	-0.436	20.3	278	2.91	1.51
Nov.	472.89	-0.361	15.2	208	3.40	1.61
Dec.	262.81	-0.308	13.9	191	3.90	1.58
Average	3065	-0.356	53.8	736	4.21	1.57

The monthly natural discharges at Munda can be then estimated by using the following relationships:

$$(Q\ Munda)_{I,j} = (V\ Munda\ /\ V\ Chakdara)_I \times (Q\ Chakdara)_{I,j} \quad \text{for I=1,2,3,4,11,12}$$

or

$$(Q\ Munda)_{I,j} = [(V\ Munda\ /\ V\ Chakdara)_I \times (Q\ Chakdara)_{I,j} + (V\ Munda\ /\ V\ Kalam)_I \times (Q\ Kalam)_{I,j}]/2 \quad \text{for I=5,6,7,8,9,10}$$

Where I is the monthly index (1, 2, ... 12) and j is the annual index (1956, 1957, ... 1997). In each month, volume ratios of Munda to Chakdara, as indicated in the above table, can be applied to the flow records at Chakdara to obtain flow records at Munda Dam site.

Taking into consideration the fact that natural discharge volume during the period from May to October is strongly influenced by snow water from the upper basins, the effect of flow records at Kalam, which is located in the mountain region was acquainted as shown in the second equation.

To estimate the flow at the Munda Dam site, present and future water diversions in the basin for irrigation schemes shall be taken into consideration. The schematic diagram of irrigation schemes is shown in Figure C4.5 and the water use of each scheme prepared by Swabi SCARP is listed in Table C4.1.

Since the existing irrigation schemes such as Nipkikhel and Fatehpur are located in the Chakdara basin, the diverted water of these schemes was first added to the Chakdara historical flow records in order to estimate the natural flow. Results of the adjusted flow are listed as shown in Table C4.2. Following these adjustments, the monthly synthesized flow at the Munda Dam site was estimated utilizing the above equations and is shown in Table C4.3. This estimated flow represents the natural flow at the Munda Dam site and to estimate the present (historical) flow condition at the Munda Dam site, the diverted water at USC and various existing irrigation schemes are to be subtracted from the synthesized flow (natural flow).

Table C4.4 shows the historical diversions to USC at Amandara Headworks. Where diversion records to USC are missing, those were supplemented by the average of the records during the period 1956 – 1964 (ref. 3) so that the diversion records were available as a continuous chronicle. It is to be noted that some of the historical diversion record were slightly adjusted so that the diversion volume to USC does not exceed the recorded inflow volume at the Chakdara gauging station.

The estimated monthly flow records at the Munda Dam site (present condition), after subtracting all the above present water use, were then calculated and the results are shown in Table C4.5. The long-term average annual inflow at Munda Dam site can be estimated as 7,208 MCM (million m^3) with a maximum of 20,175 MCM in July and a minimum of 906 MCM in January.

It is planned that diversions to USC as well as other water uses will be substantially increased in the future as shown in Table C4.1. Therefore, the available flow at the Munda Dam site will be reduced once such extension plans are implemented.

Table C4.6 shows the monthly expected diversion flow rates to USC in the future. The estimated values were based on the assumption that the maximum water use for USC during the dry season is limited to the difference of the inflow at the Chakdara station and the water use by locals at the downstream of the Amandara Headwork. The water use by locals was assumed to be 5.66 m^3/sec.

The extended water uses of the irrigation schemes in the basin and extended diversion to USC are then subtracted from the synthesized flow (natural flow). The estimated future monthly inflows at the Munda Dam site after the extension of these schemes are shown in Table C4.7.

Since the extension of USC is expected to be implemented soon, the estimated flow at the Munda Dam site after the extension of these schemes should be applied for optimization study of the Munda Dam.

C5 Flood Studies

The prime objective of the flood studies is to estimate a series of flood values for the design of the various structures of the Project. There are two principal flood calculation requirements for the design of the dam and spillway, and the design of the other relevant structures including river diversion arrangement. In view of the large scale of the Project (both financial and physical), considerable care is required in the study of flood hydrology and the selection of the appropriate design floods as the risk of overtopping the dam embankments is of significant importance. Because of these two principles, it was decided to estimate probable maximum flood (PMF) based on probable maximum precipitation (PMP) for the dam and spillway design. On the other hand, probable flood calculations based on rainfall frequency analysis for different return periods were considered for the design of powerhouse, downstream structures of spillway and the diversion facilities.

C5.1 Procedure of Flood Studies

The proposed Munda Dam is considered as a major structure that requires estimation of flood values for dam and spillway design based on probable maximum flood (PMF) that may be expected from the most possible severe combination of critical meteorological and hydrological conditions in the region. The estimate of probable floods is also required. The physical-based procedures shown in the following Figure C5.1 are applied for PMF and probable floods estimates:

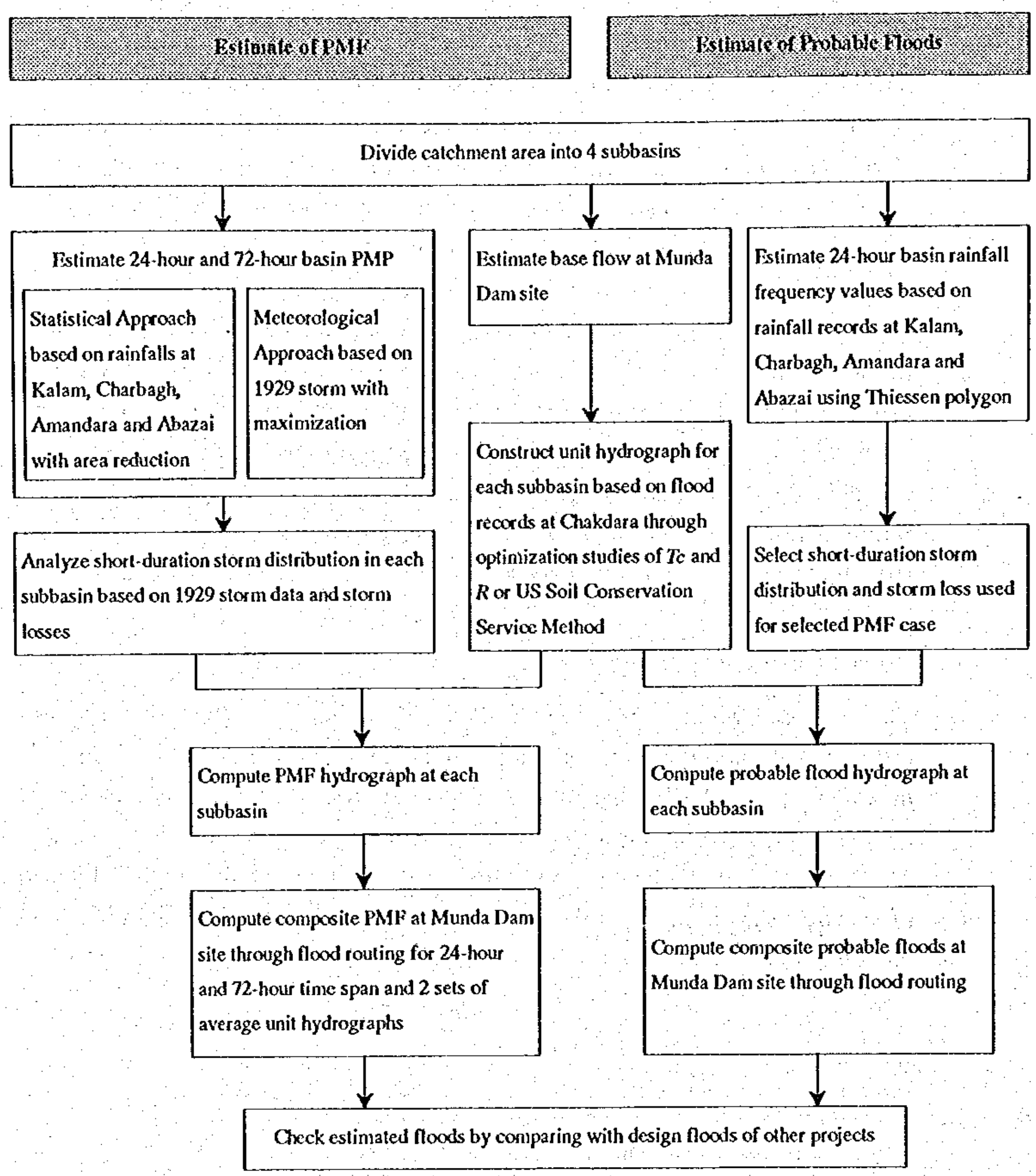

Figure C5.1 Procedures for PMF and Probable Flood Estimates

C5.2 Computation of Composite PMF

C5.2.1 Catchment Area Division to Subbasins

In this Study, the total catchment area of the Swat River up to Munda Dam site can be divided into four subbasins. The boundary of each subbasin is shown in Figure C4.1 and the catchment area of each one is listed in the following:

Catchment Area of each Subbasin

Index	Name of the Subbasin	Catchment Area, km²
B1	Upper Swat	5,776
B2	Panjkora	5,724
B3	Ambahar	1,347
B4	Lower Swat	803
Total		13,650

C5.2.2 Estimation of Probable Maximum Precipitation (PMP)

PMP can be defined as "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year" (ref. 7). The more common methodologies to estimate PMP are the meteorological and statistical approaches. The statistical approach may be used wherever sufficient historical rainfall data are available or where other meteorological data such as dew point and wind speed are lacking. The statistical approach is of particular importance for making quick estimates for PMP and provides a check guide for the estimated values by the meteorological approach. In this Study, both of the approaches were applied to predict the most relevant PMP value for PMF estimate at Munda Dam site.

(1) Statistical Estimates of PMP

The statistical methodology for estimating PMP is based on statistical analysis of maximum rainfall records within gauging station. The methodology is to yield only point PMP estimates and thus requires area-reduction factor for converting to basin PMP. The methodology is documented in the report of World Meteorological Organization (WMO) (ref. 8) and the presented procedure in the report is based on the general frequency equation:

$$X_m = \mu_n + K_m \sigma_n$$

Where X_m is the maximum rainfall; μ_n and σ_n are respectively the mean and standard deviation of a series of n annual maximal 24-hours rainfall; K_m is a common statistical variable, which varies with different frequency distributions fitting extreme-values and represent the physical characteristics of the location.

Extreme rainfall amounts of rare magnitude or occurrence (outliners), about 500 years or more, are often found to have occurred at same time during a much shorter period, about 30 years or less. These outliners have significant effect on the mean and standard deviation of the annual series. Therefore, series of adjustments will be applied to the records mean and standard deviation as well as estimated PMP using standard charts (Figures 4.1 to 4.4 – ref. 8):

Following the procedure presented in WMO Report, estimations of PMP were carried out for four rainfall gauging stations located in Munda Dam basin. These stations were Kalam, Charbagh, Amandara, and Abazai. These stations were selected as they divide the total catchment area, almost equally, and do have long time daily records (about 32 years) from 1961 to 1997. In order to perform PMP calculations, maximum annual 24 hours rainfalls for the period 1961 – 1997 were extracted for each station and results are shown in Table C5.1. The steps used to estimate PMP for each station are as follow (case of Charbagh station):

- Mean Calculations and Adjustments:

  n= 32

  μ_n = 69.88 mm

  $C2$= Mean μ_n and record length n adjustment = 1.01 (Figure C5.2)

  μ_{n-m} = 66.90 mm

  μ_{n-m}/μ_n = 0.96

  $C1$= Relative mean μ_{n-m}/μ_n adjustment = 0.99 (Figure C5.2)

  Final Mean Value = 69.88 x 1.01 x 0.99 =69.87 mm

- Standard Deviation Calculations and Adjustments:

  n=32

  σ_n = 31.92 mm

  $C4$= Standard deviation σ_n and record length n adjustment = 1.02 (Figure C5.2)

  σ_{n-m} = 27.56 mm

  σ_{n-m}/σ_n = 0.86

  $C3$= relative standard deviation σ_{n-m}/σ_n adjustment = 0.91 (Figure C5.3)

  Final Standard Deviation Value = 31.92 x 1.02 x 0.91 =29.63 mm

- PMP Calculations and Adjustments:

  K_m = 16 corresponding to 69.88 mm mean rainfall (Figure C5.3)

The final point probable maximum precipitation value of 24 hours can be estimated as: PMP = 69.87 + 16 x 29.63 =543.9 mm.

The same steps were applied to the other three stations, and the results are summarized below:

Statistical Parameters for PMP estimates

Variable	Abazai	Amandara	Charbagh	Kalam
n	30	32	32	32
μ_n	59.55	63.22	69.88	61.75
σ_n	22.78	27.52	31.92	25.79
μ_{n-m}	57.40	61.41	66.90	59.27
σ_{n-m}	19.84	25.98	27.56	22.03
μ_{n-m}/μ_n	0.96	0.97	0.96	0.96
σ_{n-m}/σ_n	0.87	0.94	0.86	0.85
$C1$	0.99	0.99	0.99	0.99
$C2$	1.01	1.01	1.01	1.01
$C3$	0.95	1.04	0.91	0.91
$C4$	1.03	1.02	1.02	1.02
Km	17	16	16	17
PMP	438.47	530.34	543.92	468.77

Where

$C1$= Relative mean μ_{n-m}/μ_n adjustment (Figure C5.2)

$C2$= Mean μ_n and record length n adjustment (Figure C5.2)

$C3$= Relative standard deviation σ_{n-m}/σ_n adjustment (Figure C5.3)

$C4$= Standard deviation σ_n and record length n adjustment (Figure C5.2)

Km= Statistical Variable based on annual mean (Figure C5.3)

According to the estimated PMP for each station, the calculated value for Charbagh station was the highest value among the other stations, therefore, the PMP for calculation will be considered as 544 mm. The final step is to apply the area reduction factor to convert PMP from point rainfall to average basin PMP. The area reduction factor will be estimated as will be discussed later.

(2) Meteorological Approach

The meteorological approach relies on the theoretical interrelation of convergence, vertical motion and condensation of the air mass in the atmosphere. Briefly summarized, the assumption is that PMP can be computed from optimum storm maximization by moisture maximization factor and storm transportation of wind coverage. Moisture maximization factor depends on the specific humidity that maintains precipitable water in ratio to the storm holding humidity capacity. For estimation of PMP the most severe mechanism by which moisture is converted from water vapor into rain or snow is considered with the maximum moisture content in the air. As the precipitation efficiency of storms cannot be estimated directly, a series of major historic storms should be examined to indicate the extreme historical storm event. Once the largest storm can be identified, maximization based on moisture content represented by dew point temperature effect can be applied.

a) Review of historical storm in the basin

The rainfall and storm records were reviewed from the available previous studies to indicate the largest storm over the Swat River basin. The principal storms identified in the review process are as listed below:

Principal Historical Storms

27-29 July 1882	8-10 August 1940	15-17 July 1958
25-27 August 1910	9-11 July 1942	3-5 July 1959
23-28 July 1924	19-23 August 1948	31 July – 3 August 1976
26-29 August 1929	1-3 August 1950	2-7 August 1987

Source: Reference 5) Appendix B.2

From the storms listed above, it is evident that all the critical storms occurred during July and August principally due to monsoons in the summer season. Inspection of these storms from the available reports revealed that the storms of August 26 – 29, 1929 and July 31 – August 3, 1976 were outstanding extreme storms compared to the other recorded storm events.

To illustrate this fact, the Pakistan Meteorological Department (PMD) in 1966 had prepared probable maximum precipitation study (ref. 1) over the Swat River basin in connection with the proposed Munda Dam project at that time. In their study, a detailed analysis of 300 storms in which about 37 storms were selected for preliminary analysis and finally 10 storms were found significantly important. The study indicated that the maximum depths of the storm of August 26 – 29, 1929 were the highest among other observed storms.

Also, according to the Kalabagh Consultant Study (KCS) in connection of the Kalabagh Dam Project (ref. 5), daily rainfalls were collected for the dates in the listed storms above. Storm total rainfalls were plotted on maps and analysis confirmed that the floods of August 26 – 29, 1929 and July 31 – August 3, 1976 were the highest among the other storms. Moreover, the study indicated that the storm of 1929 produced higher floods than the storm of 1976 in the Indus at Kalabagh (the study area of Kalabagh Dam Project). Also, as indicated in the Kalabagh study, the 1929 storm has the largest 3-day storm of record in the northern region (which includes the Swat River basin) and the 1976 storm was greater in the southern part (paragraph E.3.10 pp. E.12).

Based on these reviews, the storm of August 26 – 29, 1929 is clearly a candidate for the assessment of the PMP value in the Swat River basin.

- Isohyetal of the August 26 – 29, 1929

  The isohyetal map for the storm of 1929 was available from both of the studies mentioned above of PMD (ref. 1) and KCS (ref. 5). However, significant differences can be noticed between both of the maps as shown in Figure C5.4 (ref. 1) and Figure C5.5 (ref. 5). For the sake of comparison, the Study Team redrew the map developed by the PMD study (Figure C5.4) based on the original map without changing its original storm patterns. The major difference can be noticed in the Panjkora River basin, in which the PMD study indicated more rainfall amounts than KCS. Due to the significant importance of the storm distribution in the study, a detailed review of each study was conducted and the following principles in providing the map were identified:

- In PMD study, precipitation data at 52 rainfall stations were obtained from the WAPDA published reports for the period 1931 – 1946 and rainfall data form Tarbela studies (in association with Tarbela Dam) was also utilized. Using these data and double mass curve technique, seasonal map (June – October) was prepared and adjusted for topographical features of the Swat River basin. In preparation of 1929 storm isohyetal map, storm totals of the known stations, isopercental analysis of the pattern for 1929 storm, elevation-precipitation-barrier curve and seasonal precipitation distributions were used to develop the storm isohyet pattern.
- In KCS study, an effort to update the storm map of 1929 for the Kalabagh Dam basin was conducted in association with PMP estimates. The initial effort was lacking the interest regarding the Swat River basin, in which more work was given to the region downstream Attock. A great deal of attention was given to this feature in the later stages of their study and the isohyets for the ungauged portion of the Swat basin were adjusted. Major guidelines for the adjustment were to obtain storm distribution that fit with: 1) total storm rainfall over 13,000 mile^2 above Attock, 2) storm runoff from this area as estimated from the hydrograph of the Indus at Attock, and 3) rational rainfall loss assumptions (paragraph E.2.4 pp. E.6).

Although it seems that during the 1929 storm, the upper Swat was almost lacking in rain gauges, the practice provided by PMD for the storm pattern estimates seems to be more reliable. The direct reason is the great efforts that were contributed to the physical characteristics of the rainfall over the Swat River basin and its subbasins. On the other hand, efforts of KCS may be appropriate for storm estimation from the Swat River basin as a whole but were lacking local characteristics of the Swat River subbasins, especially for Panjkora where isohyet lines were inadequate. Also, adjusting the rainfall patterns based on observed flood hydrograph at Attock can not be reliable with the fact that many principal features of the storm over the Swat River were not considered.

From the above discussion, it was decided to adopt the isohyetal map provided by PMD study for the 1929 storm shown in Figure C5.4 for the PMF estimates.

b) Storm Moisture Maximization Factor

Moisture maximization of storms in place, i.e., without change in location, consists simply of multiplying the observed storm rainfall amounts (storm of 1929) by the ratio (R_m) of the maximum precipitable water (W_m) indicated from the storm location to the precipitable water (W_s) estimated for the storm (ref.8), or

$$R_m = W_m / W_s$$

In order to compute storm moisture maximization factor (R_m), 12-hour 1,000-mb storm dew temperature and maximum 1,000-mb dew point temperature should be available from meteorological stations. These data were obtained from the KCS report (ref. 5) as follows:

Dew point station constants, 1929 storm

Station	Elevation (m)	Max. 12-hr persisting dew point on August 31 (°C) 1000-mb	station
Gilgit*	1,454	25.6	20.2
Khushab	188	28.3	27.6
Lahore	214	28.3	27.5
Peshawar*	360	27.8	26.5
Rawalpindi	375	28.3	26.4
Sialkot	253	28.3	27.4
Srinagar	-	26.9	20.5
Average*	907	26.7	23.35

Source: ref. 5, pp. B.41

In view of station location and approximate elevation of the Swat River basin (1,000-m), dew points data from Gilgit and Peshawar meteorological stations were considered. Their corresponding average values are listed in the table. The representative persisting 12-hour 1,000-mb of 1929 storm dew point is 23.35 °C and the maximum is 26.7 °C and the rain area is at 907 m above the mean sea level (always assumed to be at 1,000-mb, ref. 8). With no inverting topographic barrier between the rain area and the moisture sources, the moisture maximization ratio (R_m) is computed from precipitable water values obtained from Table C5.2 (ref. 8) as 92.6 and 69.1 mm for W_m and W_s respectively.

Elevation adjustment values can be obtained from Table C5.3 (ref. 8) as 20.88 and 17.10 mm for W_m and W_s respectively. Thus for W_m = 92.60 – 20.88 = 71.17 mm; W_s = 69.10 – 17.10 = 52.00 mm; and R_m = 71.17 /52.00 = 1.38.

It should be noted that the estimated moisture maximization ratio (R_m) is identical to the value estimated by the PMD study (ref. 1, Table-II). However, dew points data from four meteorological stations of Peshawar, Khushab, Multan and Lahore were applied with no consideration for elevation adjustment. Therefore, the equivalent estimated values W_m and W_s were 88.646 and 64.008 mm respectively and R_m was 1.38. With this result, the estimated PMP values by PMD were considered in the present Study as it reveals the same moisture maximization factor and principle of storm isohyetal distributions.

c) Depth-Area-Duration for PMP

In the PMD study, spatial and temporal storm analysis was carried out in order to estimate the Depth Area Duration (DAD) curves for probable maximum precipitation including the moisture maximization factor of 1.38 and 1929 storm isohyetal distributions. The methodology was obtained by applying the standard procedures of US Weather Bureau " Manual for Depth-Area-Duration Analysis of Storm Precipitation" and results are listed below:

Depth-Area-Duration Data for Probable Maximum Precipitation (mm)

Area, km²	Duration in Rainfall in Hours							
	6	12	18	24	30	36	42	48
26	304	462	483	487	504	578	588	606
129	283	430	447	453	470	542	550	567
259	270	411	427	435	453	523	533	552
1,295	224	327	348	371	391	459	489	511
2,590	204	291	315	342	358	423	458	482
5,180	177	254	280	301	318	371	402	418
7,770	150	217	239	255	270	318	340	358
10,360	125	180	199	215	227	264	283	293
12,950	106	150	168	182	191	223	239	251

Source: Ref. 1 Table III, pp. 13

From the DAD table, the 24 hour PMP at Munda Dam site can be estimated by linear extrapolation of the table value between areas of 10,360 and 12,950 km² up to the catchment area of 13,650 km² at Munda Dam site. The estimated value can be calculated as:

$$PMP = 215 + [(13650 - 10360) \times (182 - 215) / (12950 - 10360)] = 173.08 \text{ mm}$$

Hence, the final PMP for the PMF calculation can be considered 174 mm.

In order to compare this value with the statistically estimated point PMP value of 544 mm (section 3.3.5 (2) ii-a), an area reduction factor should be estimated to convert point PMP to its equivalent basin PMP. The area reduction factor can be calculated from the above table by extrapolation of the 24 hour storm values for 25 km^2 (base for no-reduction) and for the total catchment area up to Munda Dam site (13,650 km^2) as 530 and 173 mm respectively. Therefore, the area reduction factor can be estimated as 0.326. With this value, the estimated basin PMP can be calculated as 544 × 0.326 = 177.34 mm which shows that the estimated PMP value of 174-mm for the Project is relevant and acceptable.

C5.2.3 Estimation of Short-Duration Storm Rainfall

In order to estimate flood hydrograph, a short-duration of 6-hour rainfall or less should be estimated. Different areal rainfall patterns and storm profiles could produce the average 72 hour design storm rainfalls, but for a short-duration, pattern information and review of storm characteristics should be investigated. Information on 6-hour storm increments were available mostly for the recent storms but with less reliability than those for older ones. After detailed review of the available materials, the values from DAD table developed by PMD study were found more reliable and applicable. Considering the case of 5,180 km^2 (average area of major subbasins), the short duration for the storm distribution values for 24-hour and 72-hour cases can be summarized as below:

6-hour Storm Distributions cases of 24-hour and 72-hour storms

Hours	6	12	18	24	30	36	42	48	72
24-Hours	0.58	0.84	0.93	1.00	0	0	0	0	0
72-Hours	0.42	0.61	0.67	0.72	0.76	0.89	0.96	1.00	1.13*

* Value estimated from the Mass Rainfall Curves of 1929 Storm; ref. 1 Exhibit VII

C5.2.4 Storm Distribution Among the Subbasins

The calculation of the composite flood hydrograph is more dependent on how the basin total storm can be distributed among the different subbasins. Using the isohyetal map of 72-hour 1929 storm (Figure C5.4), the basin as well as subbasins rainfalls were estimated by calculating the area Aj between each pair of isohyets within the basin (or subbasins) boundary and multiplying by the average rainfall depths Pj of the two boundary isohyets. The final areal rainfall P can be calculated from the following equation:

$$P = 1/A\ (\sum A_j \times P_j)$$

Detailed calculations are shown in Table C5.4 and summary results of calculating rainfall for each subbasin are shown below:

Summary of Rainfall Calculation Based on 3-Days 1929 Storm

Subbasin	Catchment Area km^2	3-day [1] 1929 Storm, mm	Ratio to Basin Storm	1-day [2] PMP mm	3-day [3] PMP mm
B1	5,776	161.5	0.93	161.8	226.5
B2	5,724	181.8	1.05	182.7	255.8
B3	1,347	115.1	0.66	114.8	160.7
B4	803	270.8	1.56	271.4	380.0
Total Basin	13,650	173.2	1.00	174.0	243.6

1) Values calculated from the 3-days 1929 storm isohyetal map (Figure C5.4)
2) Values adopted based on estimated basin 24-hours PMP value of 174 mm
3) Values adopted based on maximization of 24-hours PMP by 1.4

The 72-hour PMP can be estimated by maximizing the 24-hour PMP value by 1.4. This value can be calculated from the DAD table, in case of 5,180 km^2 as follows:

Maximization Ratio = 48 hours rain (418) / 24 hours rain (301) = 1.4

The value for 72-hour PMP can be estimated as 243.6 mm. The estimated value of PMP for 24 hours and 72 hours can be distributed among the subbasins based on the relative rainfall distributions as shown in the above table.

C5.2.5 Estimation of Storm Losses

Studies of daily rainfall values carried out by KCS (ref. 5) suggested that the storm rainfall during the August 1929 event was particularly concentrated in the 24 hours to 8:00 am on August 28. As indicated in the KCS study, the 72-hour losses above Attock (including the Swat River basin) were about 84 mm. This value was indicated as relatively low and was adopted for the Kalabagh Dam project to increase the volume of runoff downstream Attock. On the other hand, the storm losses estimated in Tarbela design flood studies were slightly greater (105 mm). It is evident from both studies that antecedent rainfall was not severe and substantial initial losses and the storm losses were prolonged rather than in bursts. In the present Study, rainfall losses were estimated from available flood record and corresponding storm value and distribution using means of optimization technique. In view of the data availability, the flood of July 25, 1995 was considered to provide the necessary data for the rainfall loss estimates. The hourly flood records were available at Chakdara water level station and hourly storm distributions were available at Kalam and Mardan rainfall gauging stations. The optimization processes were carried out with the

HEC-1 model (ref. 11) in which initial and uniform loss rate values were calculated after several optimization trials. The initial loss and the constant loss rate were best optimized as 5.5 mm and 4.5 mm/hour, respectively.

C5.2.6 Estimation of Maximum Snowmelt Rates and Base Flow

Although snowmelt has significant impacts on flood hydrograph especially during monsoon season, snow data and information within the Swat River basin are not available. In the upper Swat region, the snow starts to melt from the middle of April and reaches its maximum during June, July, and early of August. This region in general does not receive significant monsoons. Therefore, the recorded runoff at Kalam can be considered entirely comprised of snowmelt where almost 50 % of the average annual runoff occurs during June and July. In the middle and southern region, recorded flows during June and July are mainly due to monsoon rainstorms with a portion accumulated from snow melt of the upper region. Due to the lack of snow data, it is difficult to identify accurately the portion of the snowmelt that may contribute to the design flood at the proposed Munda Dam site.

In the present Study, snowmelt effect is considered as the base flow for the calculation of PMF and its flood routing among the different basins. After review of the available methodologies and appropriate techniques, it was decided to adopt the average of estimated long term flow records (1956 – 1997) at Munda Dam site (Table C4.5) for July as base flow and snow effect when performing PMF estimates. This value can be considered as 650 m^3/sec and will be distributed between Upper Swat and Panjkora river subbasins (B1 and B2) as 400 and 250 m^3/sec. The value adopted for Upper Swat River basin was based on the long term flow records (1956 – 1997) at Chakdara station (450 m^3/sec) after subtracting the diversion water for Upper Swat Canal and local users (50 m^3/sec).

C5.2.7 Construction of Unit Hydrograph

To estimate the probable maximum flood passing the Munda Dam site, the unit hydrograph at each subbasin should be constructed based on recorded floods and storm events. The Swat River basin up to Munda Dam site was divided into three subbasins of Upper Swat, Panjkora and Ambahar and one region contributes inflow directly to the river (Lower Swat). The boundaries of these divisions are shown in Figure C4.1.

The unit hydrograph for Upper Swat was constructed using data of five flood hydrographs observed at Chakdara station for the years 1985, 1986, 1988, 1991 and 1995. The hourly hydrograph distributions of the five floods for 48 hours are listed in Table C5.5 and shown in Figure C5.6. As shown in the figure and listed table, all five floods occurred in July basically due to monsoons of the summer season. The flood of 1995 is the most significant as it has the maximum value (2,772 m^3/sec) and the shortest time to peak (6 hours) compared to the other flood events. The flood of 1991 had the largest base flow of 1,366 m^3/sec and undefined sudden drop after 24 hours from 1,156 m^3/sec to 829 m^3/sec.

Storm data during the five floods were obtained from the available rainfall records. Equivalent 24-hour rainfalls were estimated from the rainfall records at eight rainfall stations while their hourly distributions were assumed based on the hourly rainfall records from Kalam and Madran rainfall stations.

The unit hydrographs of 1985 and 1986 were adopted following the estimated values by the Pre-Feasibility Study (ref. 4). The unit hydrographs of 1988, 1991 and 1995 were calculated using HEC-1 model (ref. 11). Using data of the 1995 flood, unknown parameters of unit hydrograph and rainfall loss were estimated using the optimization capabilities of HEC-1. The unit hydrograph parameters were optimized based on Clark unit hydrograph method. The rainfall loss parameters were optimized based on uniform loss rate method. The optimization results of the unit hydrograph time of concentration (*Tc*) and storage coefficient (*R*) were best estimated as 3.0 and 8.0 hours, respectively (ref. 19). The initial loss and the constant loss rate were best optimized as 5.5 mm and 4.5 mm/hour respectively. It should be noted that the base flow was considered to be on recession equation of starting base flow (833 m^3/sec), with ratio to the peak (0.48) and recession power coefficient (1.0). The estimated flood flow compared to the observed one is presented in Figure C5.7 for the 1995 flood.

Having obtained the rainfall loss parameters for the Upper Swat subbasin based on characteristics of the 1995 flood, HEC-1 model was applied to estimate the unit hydrograph parameters for 1991 and 1988 flood events. After several optimization trials, the unit hydrographs for each flood event were determined and results of hourly ordinates are tabulated in Table C5.6. The hourly distributions of each of the estimated unit hydrograph are presented in Figure C5.8. The estimated unit hydrograph results show that the unit hydrographs of 1991 and 1995 are quite similar. On the other hand, the unit hydrographs of 1985, 1986, and 1988 are also similar in their shape. Therefore, in the present Study, two sets of average unit hydrographs were adopted and applied to estimate the design flood. The hourly ordinates of these two sets of unit hydrographs are listed in Table C5.7 and presented in Figure C5.9.

In view of the limited storm and flood data at Panjkora and Ambahar subbasins, the unit hydrograph of Panjkora subbasin was considered identical to the estimated unit hydrograph of Upper Swat assuming both subbasins are physically the same (ref. 4). For Ambahar subbasin, a synthetic unit hydrograph was derived using the US Soil Conservation Service method (ref. 12 and 13). The HEC-1 model was applied using data input of lag parameter L to compute peak flow and time to peak. The lag parameter L is estimated from the time of concentration (Tc) with the equation $L = 0.6\ Tc$. The time of concentration represents the amount of time required for water to flow from the most upstream point in the watershed to the watershed outlet. In efforts to estimate the time of concentration (Tc), the following six empirical formulas were used:

Empirical Formulas for Time of Concentration Estimates

Method	Formula	Tc (minutes)	Parameters
Izzard	$41\ K\ L^{1/3}/ i^{2/3}$ and $K = (0.0007i + Cr)/S^{1/3}$	359.7	L = 30,000 m S = 0.01 i = 2.2 mm/hr Cr = 0.008 C = 0.8 n = 0.005 A = 1347 km² Ct = 0.5
Kerby	$C(LN/S^{1/2})^{0.467}$	470.5	
Kirpich	$0.0078\ (L^{0.77}/S^{0.385})$	321.2	
Kinematic	$0.93\ (L^{0.6}n^{0.6}/i^{0.4}S^{0.3})$	406.2	
Bransby Williams	$21.3\ L/5280\ (1/A^{0.1}\ S^{0.2})$	533.6	
FAA – Fedral Aviation Agency	$1.8\ (1.1 - Ct)\ L^{0.5}/ S^{0.33}$	338.8	
Avera;; Time of Concentration		405	

From the above formulas, an average time of concentration was estimated as 405 minutes (6.75 hours). Hence, lag parameter L was calculated as 4.05 hours. Having obtained lag parameter L, the time to peak and peak discharge can be calculated as:

$$Tp = dt/2 + L \quad \text{and} \quad Qp = 484A/Tp$$

Where dt is the time interval in hours, and A is the subbasin catchment area in square-miles. The final estimates of the time to peak and peak discharge were 4.55 hours and 61.67 m^3/sec/1-mm rainfall. The ordinates of the unit hydrograph are determined through interpolation of the dimensionless unit hydrograph curve (ref. 12) at hourly points. The final estimated unit hydrograph ordinates are shown in Figure C5.10.

C5.2.8 Computation of Composite PMF

The principal procedures used to estimate the composite PMF at Munda Dam site include:

- Calculation of PMF hydrographs at each subbasins utilizing calculated PMP and storm characteristics, loss rate, base flow and unit hydrograph data. The storm characteristics of short-duration storm rainfall and storm distribution among the subbasins were based on the 1929 storm data.
- Flood routing in stream reaches between confluence points (junctions) to the proposed dam site. Based on the subbasins distribution, flood routing were carried out for three stream reaches in the Swat River. These reaches were considered from Upper Swat to Panjkora as reach 1, from Panjkora to Ambahar as reach 2 and from Ambahar to the Munda dam site as reach 3.

The HEC-1 model was used to carry out these procedures through construction of a stream network representing the watershed up to the proposed dam at Munda. The storm-flood characteristics utilized for the stream network were explored in the above sub-sections and can be summarized as follow:

- Base flows in each subbasin were assumed to be in constant rates of 400 m^3/sec and 250 m^3/sec for Upper Swat and Panjkora subbasins, respectively (section C5.2.6))
- The loss rate of rainfall was considered to be on initial of 5.5 mm and hourly uniform loss rates of 4.5 mm/hour for the three subbasins (section C5.2.5)). Incremental hourly distributions were carried out by HEC-1 model based on the principal "All rainfall is lost until the volume of initial loss is satisfied. After the initial loss is achieved, rainfall is lost at a constant rate" (ref. 11 pp. 17)
- The PMP 6-hour distributions for 24-hour and 72-hour flood estimates were calculated from the Depth-Area-Duration values of the 1929 storm (sections C5.2.3). Incremental hourly distribution was carried out by HEC-1 model based on Southwestern Division Criteria for PMP (ref. 11 Table 3.1, pp. 11).
- The PMP distribution among the subbasins was considered similar to the distribution of the 1929 storm. Based on the 1929 storm isohyetal map, PMP distribution ratios were estimated as 0.93, 1.05 and 0.66 for Upper Swat, Panjkora and Ambahar subbasins respectively (section C5.2.4)
- Flood routing was carried out based on the Muskingum routing procedure with equal number of sub-reaches between junctions and 0.5 Muskingum coefficient. The K coefficients of each subbasin were assumed to be as 1.0 hour (reach 1), 2.0 hour (reach 2) and 2.0 hours (reach 3)

In the present Study, PMF values were calculated for 24-hour and 72-hour time span and two sets of average unit hydrographs of 1991 and 1995 and 1985, 1986 and 1988. The combination of these sets leads to four case result sets to be examined in estimation of PMF. These cases are as follows:

- Case 1: using average unit hydrograph of 1991 and 1995 with 24-PMP
- Case 2: using average unit hydrograph of 1985, 1986 and 1988 with 24-PMP
- Case 3: using average unit hydrograph of 1991 and 1995 with 72-PMP
- Case 4: using average unit hydrograph of 1985, 1986 and 1988 with 72-PMP

Table below summarizes the PMF estimates at Munda Dam site for each case:

Estimated Probable Maximum Flood Values

Case	Probable Maximum Flood (PMF), m³/sec	
	Peak	Time to Peak
1	18,170	11
2	19,390	16
3	15,990	13
4	16,710	18

Ordinate of the computed PMF at Munda Dam site for the above four cases are tabulated in Table C5.8 and illustrated in Figure C5.11.

From the estimated values of PMF, it is evident that 24-hour PMP cases (Case 1 and Case 2) are more critical for the purposes of the dam design than the 72-hour cases and Case 2 has the highest peak. Therefore, Case 2 will be considered as PMF value used for the design of the dam and spillway.

Figure C5.12 illustrates specific design floods for dam and hydropower projects in Pakistan as well as Munda Dam. The estimated Munda PMF peak of 19,390 m^3/s (1.42 $m^3/s/km^2$) falls in the reasonable range in this Figure. Therefore, the Munda PMF of 19,390 m^3/s is considered acceptable.

C5.3 Estimates for Probable Flood Frequencies

The purpose of the probable flood frequency study is to obtain a range of floods of various magnitudes and probabilities of exceedence for different return periods for the purpose of design of structures other than dams. Flood frequency analysis is usually carried out by utilizing the annual instantaneous maximum flow records. In case such flow records are not available, flood frequency values are to be obtained erased on rainfall frequency values converting the results to equivalent flood values using rainfall-runoff relationship. In view of flow records at Munda Headworks, erasing insufficient it was decided to carry out the flood frequency analysis based on rainfall frequency analysis. Rainfall frequency values for different return periods were estimated based on basin 24-hour maximum rainfall. The rainfall duration of 24-hour was applied for the flood estimates since the study of PMF revealed the maximum peak discharge for 24-hour PMP and recorded maximum 1929 storm shows the principal duration of 24-hour. In order to estimate basin 24-hour maximum rainfall, rainfall records from four stations during the period 1961 – 1997 were selected (Kalam, Charbagh, Amandara and Abazai). The total basin catchment area up to the Munda Dam site was divided based on Thiessen polygon as shown in Figure C5.13. For each year four trials were examined to check the possible maximum basin result considering effect of each station to produce maximum case. The final results of annual maximum 24-hour basin rainfall are shown in Table C5.9.

Having the annual series of basin maximum daily rainfall, frequency analysis using six distributions were examined. These distributions were: Normal, Log-Normal type II, Log-Normal type III, Pearson type III, Log-Pearson type III, and Gumbel Extreme type I. Among the six distributions, Pearson type III distribution was selected as it produced the best fitted results compared to the recorded data with a correlation coefficient of 0.9869. The frequency curve and estimated values for different return periods are listed in Figure C5.14.

Maximum flood and flood hydrograph for each return period were calculated using the HEC-1 model by utilizing the basin characteristics based on case 2 (i.e. Unit hydrograph, base flow, rainfall losses, rainfall hourly distribution, etc.). Figure C5.15 presents the hourly flood hydrograph distribution for each return period. The more pertinent results are shown in Table C5.10 and summarized as follows:

Probable Flood for Different Return Periods

Return Period, (Years)	24-Hour Basin Maximum Rainfall, (mm)	Probable Flood, (m^3/sec)
2	35.7	1,050
5	46.3	2,050
10	53.1	2,740
20	59.4	3,400
25	61.2	3,630
50	67.4	4,370
100	73.3	5,010
200	79.1	5,720
500	86.9	6,610
1,000	92.7	7,280
10,000	112.6	10,050

C6 Sedimentation

C6.1 Suspended Load

In the published reports of Hydrology Division, Irrigation Department, the suspended sediment records at Munda Headworks are available for 6 years within the period 1964 to 1973. However there are various examples of discrepancy in these data that raise doubts about the accuracy of the records especially during high flow period records. An example that shows this discrepancy can be noticed from the recorded sediment on July 1, 1964 compared to the one in July 13, 1964. Within these two dates, the recorded sediment concentrations were 3,121,524 and 28,527 ton/day whereas recorded flow rates were 851 and 1,478 m^3/sec respectively. This is a very high range of sediment inflow that is not reliable. With this fact in mind as well as the doubts of flow accuracy, the recorded suspended sediment at Munda Headworks cannot be utilized in the preseur Study. According to the availability of the data, it was decided that the most appropriate method to estimate the sediment inflow at the Munda Dam site is to carry out the regional analysis based on the available sediment records at the four gauging stations of Kalam, Chakdara, Warsak and Nowshera.

During the field investigation stages, daily-suspended sediment records at Kalam and Chakdara were collected from SWHP of WAPDA for the period 1960 – 1995 (ref. 14, pp. 31 - 40). Also, annual sediment load records at Kalam, Chakdara, and Nowshera stations for the period 1961 – 1990, and that of Warsak station for the period 1961 – 1970 are available. The annual water yield and suspended sediment for these stations are shown in Table C6.1 (ref. 14, pp. 141 – 145)

Using these data, sediment concentration at the Munda Dam site was computed by establishing relationship between sediment and water yields. The annual average values of each gauging station is given below:

Average Annual Sediment and Water Yields

Station	Catchment Area CA km^2	Annual Flow[1] Q m^3/sec	Water Yield Q/A m^3/sec/km^2	Sediment Load[2] Qs ton/day	Sediment Yield Qs/A ton/day/km^2
Kalam	2,020	92	0.0455	789	0.3906
Chakdara	5,776	180	0.0317	3,305	0.5722
Warsak [3]	67,340	706	0.0105	46,667	0.6930
Nowshera	88,578	858	0.0097	100,767	1.1376

1) Based on records of 1956 – 1997
2) Based on records of 1961 – 1990
3) Based on records of 1961 – 1970

Average annual sediment and water yields for the period 1961 – 1990 at the four stations are plotted, and the regression analysis was carried out as shown in Figure C6.1.

For the Munda Dam site with average annual inflow of 228.58 m^3/sec and a catchment area of 13,650 km^2, the sediment yield of 0.85 ton/day/km^2 can be estimated based on the regression formula (Y=-16.635 X + 1.1307) shown in the Figure C6.1. Where Y and X are the sediment and water yields in units of ton/day/km^2 and m^3/sec/km^2, respectively.

The equivalent average annual suspended sediment value is then estimated to be 311 ton/km^2. The long-term average annual suspended sediment values for the period 1956 – 1996 are tabulated in Table C6.2.

C6.2 Bed Load

Up to date, no bed load measurements have been performed in the Swat River basin therefore the bed load is to be estimated based on suspended load value. For preliminary estimation, bed load can be estimated from the following table:

Bed Load Preliminary Ratios to Suspended Sediment Load

Case	Concentration of suspended load (ppm)	Type of material forming channel of the stream	Texture of suspended material	Percent bed load in terms of suspended load
1	< 1000	Sand	Similar to bed material	25 to 150
2	< 1000	Gravel, rock or consolidated clay sand	Small amount of sand	5 to 12
3	1000 to 7500	Sand	Similar to bed material	10 to 35
4	1000 to 7500	Gravel, rock or consolidated clay	25 % sand or less	5 to 12
5	> 7500	Sand	Similar to bed material	5 to 12
6	> 7500	Gravel, rock or consolidated clay	25 % sand or less	2 to 8

Source: ref. 15, pp. 842

Since the average sediment load is valued as 535 ppm (in equivalent to 11,630 tons/day sediment and 228.56 m^3/sec flow), the estimated rate of bed load is about 5 to 12 % of the total sediment load (case 2 in the above table). In the present Study, with safety consideration, the proportion of bed load was conservatively assumed to be 20 % of the suspended sediment load. Therefore, the annual bed load yield at the Munda Dam site was estimated to be 62 ton/km^2.

C6.3 Total Sediment Inflow

The total sediment yield can be estimated as the sum of suspended load and the bed load. In this way, the annual total load can be estimated to be 373 ton/km^2.

The geological condition of the basin was reviewed in order to evaluate the estimated total sediment inflow. The geological condition of a catchment area is one of the influential factors on sedimentation as well as other factors such as precipitation, vegetation, river gradient, and pitch of uplift. Geologically the catchment area of Munda Dam seems to have different geological conditions compared with neighboring dams of Tarbela and Warsak. In the area of Tarbela dam, unconsolidated sand of terrace deposits is widely distributed on the relatively higher portions of the catchment area. Due to the erodible nature of the sand, it seems that sedimentation problem has arisen in the Tarbela reservoir. The upstream area of Warsak Dam lies in rocky desert containing a huge amount of loose sand, and sedimentation problem has occurred in the Warsak reservoir due to the erosion of the loose sand. In contrast with the geological condition of the above two areas, the catchment area of Munda Dam lies in rocky mountains covered with few erodible deposits. Although unconsolidated river deposits are distributed on a wide and gentle river plain in the middle reaches of the Swat River between Chakdara and Mingora, the river plain looks relatively stable and looks like a trap of eroded materials from the upstream mountains without intense erosion. Considering these geological factors, the estimated annual total sediment of 373 ton/km^2 for the Munda Dam site is considered to be reliable.

C6.4 Fresh Sediment Density

The initial specific weight (fresh) of sediment density can be estimated based on the ratios of the clay, silt and sand contents in the sediment load using the following equation (ref. 16, eq. 12.8.2, pp. 12.38):

$$W_o = p_c W_c + p_m W_m + p_s W_s$$

Where W_o, W_c, W_m and W_s are the densities (kg/m^3) for initial clay, silt, and sand respectively, and p_c, p_m and p_s are the percentages of the corresponding total sediment composition. Based on the mode of reservoir operation, the values of W_c, W_m and W_s can be estimated as 416, 1,120, 1,550 kg/m^3 respectively (ref. 16 pp. 12.39). According to the collected sediment data for the four stations, average percentages of clay, silt and sand in the sediment load were estimated as 0.30, 0.53, and 0.17 as shown in the table below:

Percentage of Clay, Silt and Sand in Sediment

Station	Clay	Silt	Sand
Kalam	31	45	24
Chakdara	39	49	12
Warsak	28	60	12
Nowshera	24	57	19
Average	30	53	17

Source: Ref. 15

Using the above mentioned formula and percentage of clay, silt and sand contents in the sediment load, the initial sediment density was estimated to be 982 kg/m³.

C6.5 Compacted Sediment Density

Since the density of the deposited sediment will increase each year, the specific weight of sediment must be predicted in order to estimate the storage space in the reservoir which will be replaced by sediment in a given period of time.

The average density of sediment accumulation W_T after T years of reservoir operation is given by Miller's formula (ref. 16, eq. 12.8.3, pp. 12.39) as follows:

Where W_o is initial specific weight and K_o is a constant it depends on mode of

$$W_T = W_o + 0.4343 \quad K_o \left[\frac{T}{T-1} (\ln \quad T) - 1 \right]$$

the reservoir operation. In case of Munda Dam, the sediment is considered always submerged or nearly submerged. Therefore, the mode of the reservoir operation can be considered as type 1 (ref. 16, Table 12.8.1, pp. 12.38). For the present case of the reservoir type, K_o can be taken as 256, 91, and 0 (ref. 16, Table 12.8.2, pp. 12.39) for each of the sediment type of clay, silt, and sand respectively. With an average of K_o as 173.5 and estimated value of W_o as 982 kg/m³, the average density of sediment accumulation W_T after 100 years (T) can be calculated as 1,257 kg/m³.

C6.6 Bed Load Density

For bed load, accumulated permanently submerged specific weight can be considered as 1,760 kg/m³ according to recommended range values (listed below case of poorly sorted sand and gravel) by U.S. Soil Conservation Service for General Design Purposes.

Ranges of Specific Weight Used in US Soil Conservation Services for General Design Purposes

Grain Size	Permanently submerged kg/m³	Aerated kg/m³
Clay	640 - 960	960 - 1280
Silt	880 - 1200	1200 - 1360
Clay-silt mixtures (equal parts)	640 - 1040	1040 - 1360
Sand-silt mixtures (equal parts)	1200 - 1520	1520 - 1760
Clay-silt-sand mixtures (equal parts)	800 - 1280	1280 - 1600
Sand	1360 - 1600	1360 - 1600
Gravel	1360 - 2000	1360 - 2000
Poorly sorted sand and gravel	1520 - 2080	1520 - 2080

Source: ref. 17, Table 17-I-5, pp. 17-18

C6.7 Trap Efficiency

Not all sediment passing through the dam section will be deposited in the reservoir because part of it will pass through sluices, spillways, waterway, and other diversion flow releases from the reservoir.

The most commonly used relation for determining sediment trapping is the sediment trap efficiency curve developed by Gunner Brune (ref. 16, Figure 12.8.2, pp. 12.38), where the trap efficiency is defined as the ratio between sediment trapped in the reservoir and the total sediment entering the reservoir. Dendy added more data to Brune' s curve and developed a prediction equation for the median curve as follows (ref. 18, pp. F-2):

$$E = 100 \times 0.97^{0.19^{\mathrm{Log}(C/I)}}$$

Where, E is the trap efficiency, C is the reservoir storage capacity and I is the flow inflow rate. As the storage capacity changes with the operation period, trap efficiency will be calculated for a 10-year interval as will be discussed later.

C6.8 Accumulation of Sediment in the Reservoir

In order to estimate the sediment accumulation in the reservoir, a 10-year calculation period was considered. For each period, cumulative sediment values were calculated based on trap efficiency and suspended and bed sediment unit weight estimations. Four cases of the reservoir scales were examined as follows:

- Case 505: FLS 505 m and gross storage 690 million m³
- Case 530: FLS 530 m and gross storage 1,070 million m³

- Case 555: FLS 555 m and gross storage 1,590 million m^3
- Case 580: FLS 580 m and gross storage 2,340 million m^3

The calculations for 500 years are listed in Tables C6.3 for each of the four cases of reservoir scales. The more pertinent results are summarized as follows:

Sediment Accumulation in the Reservoir

Period	Sediment Accumulation million m^3			
	Case 505	Case 530	Case 555	Case 580
10	40.7	42.6	43.9	44.8
20	77.1	80.8	83.3	85.2
30	112.0	117.6	121.4	124.2
40	146.0	153.6	158.7	162.3
50	179.2	188.8	195.3	199.9
60	211.7	223.6	231.5	237.0
70	243.6	257.9	267.3	273.8
80	275.0	291.8	302.7	310.3
90	305.7	325.4	337.8	346.4
100	335.8	358.5	372.7	382.3

From the above table, it can be seen that the reservoir would lose 49, 33, 23 and 16 % of its capacity of 690, 1,070, 1,590 and 2,340 million m^3, respectively after 100 years.

The plan formulation study was concluded with the optimum case of 555. The estimated sediment accumulation after 100-year is 373 million m^3 for the case 555. Figure C6.2 shows specific sediment discharges for various dam and hydropower projects in Pakistan as well as Munda Project. The Munda sediment accumulation of 0.94 ton/day/km^2 falls within a reasonable range in Figure C6.2. Therefore, the estimated 100-year sediment accumulation of 373 million is considered acceptable.

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