TECHNO-ECONOMIC ASSESSMENT STUDY FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

PHASE II: PROJECT DEFINITION OPTIONS

Volume 2: Basic Data

Chapter 5: Meteorology, Hydrology and Climate Change

August 2014

Report No. P.002378 RP 07 rev. F

F	19/08/2014	Final – August 2014	H. GARROS	LBO	LBO
E	31/03/2014	Final	H. GARROS	NSA	NSA
D	15/01/2013	Draft Version for Disclosure	H. GARROS	NSA	NSA
C	07/01/2013	Final	H. GARROS	ALA	NSA
B	10/08/2012	Rev B	H. GARROS	R. ALBERT	NSA
A	11/07/2011	First Draft	H.GARROS	R.ALBERT	R ALBERT
Revision	**Date**	**Subject of revision**	**Drafted**	**Checked**	**Approved**

CONTENTS

REFERENCES

Author(s)	Date	Title
Palgov, N. N.	1947	Relationship between air temperature and melting of glaciers in Zailiyskiy Alateau. Vestnik of Academy of Science of Kazakhstan SSR, n°10(10).
Shults, V.	1958	Hydrography of Central Asia. Tashkent: CAGU publishers.
Krenke, A. N., & Khodakov, V. G.	1966	Relationship between glacier surface melting and air temperature. Materials of glacier studies, chronicles of discussions n°12.
Tronov, M. V.	1966	Glaciers and climate. L. Gidrometeoizdat.
Francou, J., & Rodier, J.	1967	Essai de classification des crues maximales observées dans le monde. Cahier O.R.S.T.O.M. série hydrologie, Vol IV n°3.
UNESCO	1976	World Catalogue of Very Large Floods.
Krenke, A. N.	1982	Mass exchange in glacier systems in the USSR territory. L. Gidrometeoizdat.
Rodier, J. A., & Roche M.	1984	World Catalogue of Maximum Obseved Floods. IAHS Publication n°143.
WMO	1986	Manual for Estimation of Probable Maximum Precipitation.
World Meteorological Organisation	1986	Intercomparison of models of snowmelt runoff, report n°23. Genève.
Hydrometheoizdat, L.	1988	Applied scientific Reference Book on Climate of the USSR, issue 31.
Garros-Berthet, H	1994	Station-Year Approach: A Tool for Estimation of Design Floods.Journal of Water Resources Planning and Management 120(2), 135–160.
Kuchment L.S.	1997	Estimating the risk of rainfall and snowmelt disastrous floods using physically-based models of river runoff generation.
Garros-Berthet, H.	1998	Station-year and Lombardi's approach: tools for estimation of design floods. ICOLD Barcelona Symposium on Dam Safety. Barcelona.
Gibb and al.	2000	Nurek Dam - Safety Assessment Refort.
Ohmura, A.	2001	Physical basis for the temperature-based melt method. Journal of Applied Meteorology, 40(4), 753-761.
Makhmadaliev, Novikov and al.	2002	The First National Communication of the Republic of Tajikistan on the UN Framework Convention on Climate Change.
Makhmadaliev, Novikov and al.	2003	The First National Communication of the Republic of Tajikistan on the UN Framework Convention on Climate Change. Phase 2. Capacity Building in Priority Areas.
Savoskul	2003	Water, Climate, Food and Environment in the Syr Darya Basin.
Homidov A.	2006	Field Research of glaciers and glacial lakes located in Karatag, VakhshAnd Zeravshan river basins.
Lahmeyer	2006	Volume 3 D - Hydrology.
Christensen and al.	2007	Climate Change 2007 - Chapter 11 - Regional Climate Projections.
Perelet	2007	Central Asia: Background Paper on Climate Change.
Makhmadaliev, Novikov and al.	2008	The Second National Communication of the Republic of Tajikistan on the UN Framework Convention on Climate Change.
Hydroproject	2009	Final Design - Hydrometeorological Conditions.
Roy	2009	Potential impacts of Climate Change on the hydrological regime of Tajikistan and the Kyrgyz Republic at the horizons 2050 and 2080.
World Meteorological Organisation.	2009	Manual on Estimation of Probable Maximum Precipitation, WMO n°1045. Geneva.
Siegfried and al.	2010	Will Climate Change Exacerbate or Mitigate Water Stress in Central Asia?
Siegfred and al.	2010	Coping with International Water Confloct in Central Asia: Implications of Climate Change and Melting Ice in the Syr Darya Catchment.
Yasinkiy V.A, Mironenkov A.P, Sarsembekov T.T	2012	Priorities for cooperation in transboundary river basins in Central Asia - Eurasian Development Bank - Almaty

NOTATIONS

A Catchment area (km^2).

Cv Coefficient of variation (Cv = S/M).

DDF Degree-Day factor (°C)

F Frequency.

K(Qp) Francou-Rodier's Flood Rating. $(Q/10^6) = (A/10^9)^{(1-01.K)}$.

M Average of sampled data.

Max Maximum of sampled data.

Me Median of sampled data.

Min Minimum of sampled data.

n Sample size.

PMP Probable Maximum Precipitation (mm).

PMF Probable Maximum Flood (m^3/s).

P(Oct/May) Seasonal Precipitation form October to May (mm).

P_{yr} Yearly precipitation (mm).

Q Discharge (m^3/s).

Q_d Daily discharge (m^3/s).

Q_{dmx} Maximum daily discharge (m^3/s).

Q_p Instantaneous peak discharge (m^3/s).

QFit Fitted discharge (m^3/s).

r Coefficient of correlation.

r^2 Coefficient of determination.

RF Daily rainfall (mm).

RH Relative humidity (%).

RO Runoff (mm).

RO Flood runoff, (mm).

S Standard deviation of sampled data

T Return Period (years).

V Volume (Mm^3).

V_{yr} Yearly inflow (Mm^3).

Z Elevation (m).

TABLES

FIGURES

1. INTRODUCTION

The following hydrological studies aim at a comprehensive review of all existing documentation provided by the Government / Barki Tojik (temperature, rainfall/snow fall/glacier melt, discharge…) as well as existing studies on Rogun Hydroelectric Project. This report therefore includes the following aspects:

- Assessment of the quality and reliability of data available,
- Review inflows assessment made for the project,
- Flood estimates with different return periods and the Maximum Probable Flood and corresponding flood hydrographs at the project site,
- Review existing climate change previsions and address possible scenarios.

The outcomes of this report are fundamental design parameters for the Techno-Economic Assessment Study for Rogun Hydroelectric Project.

2. GENERAL SITUATION

2.1 Geography

The proposed Rogun Dam site is located on the Vakhsh River which flows from the Pamir Mountains. The dam site is located 34 km downstream of the confluence of Surkhob and Obihingou Rivers, which are the two main tributaries of the catchment and join to form the Vakhsh River. At the proposed Rogun dam site the Vakhsh drains a catchment area of 30 390 km².

The Surkhob River flows from the east-northern part of the catchment, bordered to the north by the Pamir-Alai mountain system. The Obihingou flows from the east-southern part of the catchment (see Figure 2-2), drains high altitude mountains of the central Pamir, particularly the Somoni Peak Range (7495 m.a.s.l.).

Approximately 30% of the catchment lies above 4000 m.a.s.l. within the snow and glacier cover zone. Among the many glaciers which feed the Vahksh tributaries, it is worth mentioning the Fedchenko Glacier, currently extending to 77 km, which constitutes the world longest glacier outside the Polar Regions. Within the catchment the total glacier area is estimated between 3882 km² and 5000 km², which represent between 13 and 16% of the Vakhsh catchment at Rogun.

The projected dam site is located 74.6 km upstream of Nurek dam, and will constitute the most upstream dam of the current Vakhsh Hydropower Cascade System. Downstream hydropower facilities (constructed or under study) are: Nurek HEP, Shurob HEP, Baïpaza HEP, Sangduta HEP 1 & 2, Goluvnaya HEP, and with diversion from the Vakhsh: Centralnaya and Perepednaya HEP.

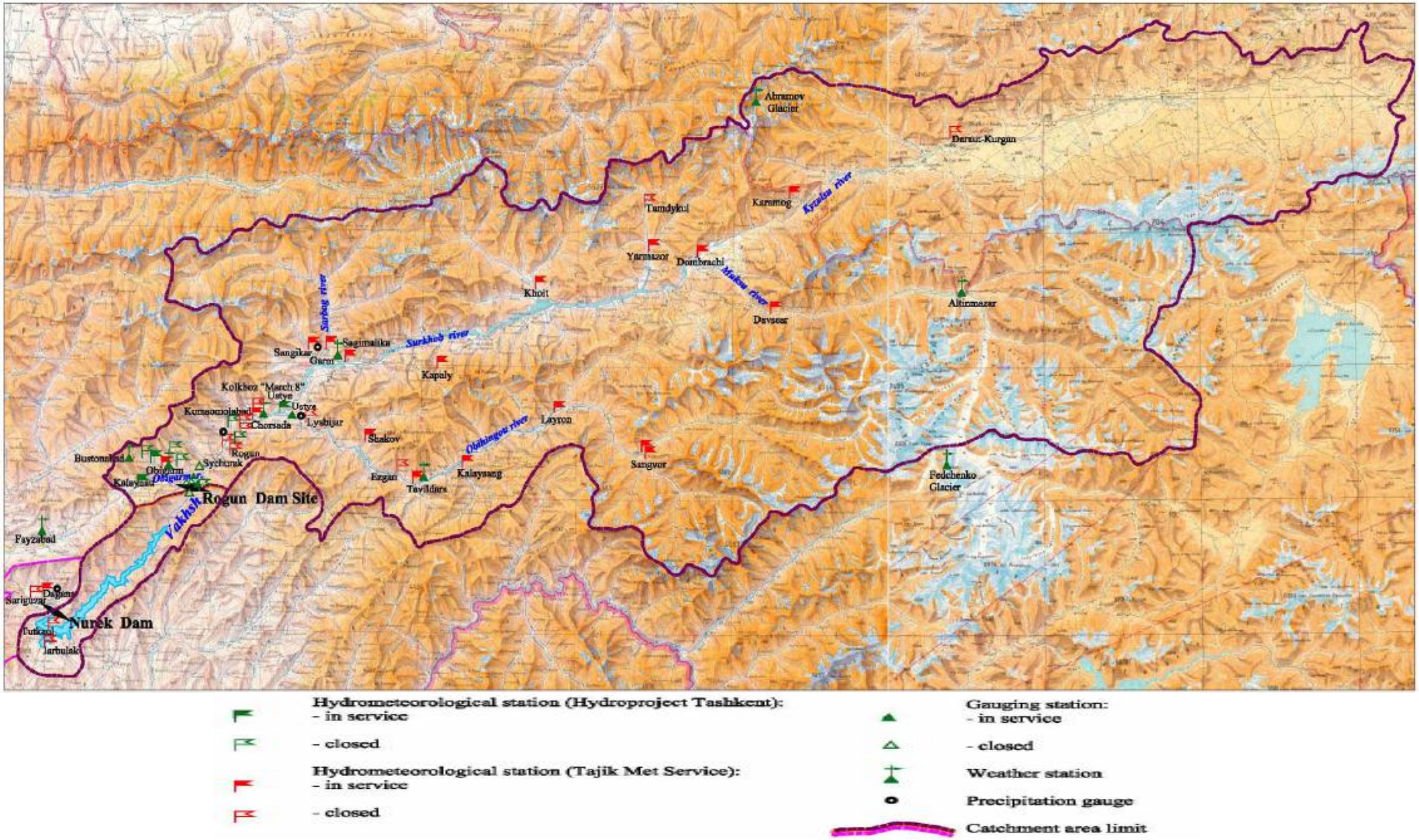
Further downstream, the Vakhsh River join the Panj River issued from central Pamir; together they form the Amu-Darya River, which is a main tributary of the Aral Sea.

2.2 Hydrological regime

Consequently to its catchment morphology located next to the high mountains of the Pamir range, the Vakhsh catchment is mainly controlled by snow melt and glacier contribution. The region is under the continental climate, which is characterised by a wide temperature range during the year. The coldest month occurs generally in January, with minimal temperature reaching -30°C at Komsomolabad and -32°C at Garm.

The yearly amount of precipitations in the lower part of the catchment ranges from 816 mm (Obigarm) to 936 mm (Komsomolabad). In the upper part of the catchment, the yearly amount of precipitations can be close to 2000 mm. A particularity of the climate of central Asia, is that the maximum precipitation amount occurs during winter. Approximately 60% of the annual precipitation falls during February and March. For this period, the proportion of mixed precipitation (snow with rain) is estimated between 17 – 24% (Lahmeyer 2006 & Hydroproject Moscow 2009). Such proportion confirms that the majority of precipitation in the Vakhsh catchment is stored during winter time in the snow cover. Conversely during the summer season, precipitations are generally rare, mean values recorded range from 8 to 16 mm (Obigarm and Garm met. stations) in July, and range from 4 to 7 mm in August at the same stations. It is necessary to consider the orographic effect on precipitations, which means that even during the summer season; precipitations will be mixed between rain at low elevation and snow at higher elevation.

Figure 2-1: **Hydro meteorological network of the Vakhsh Basin, *source Lahmeyer 2006***



The Vakhsh River exhibits a typically snowmelt and glacier driven hydrological regime (Shults, 1958). It can be seen in Figure 2.2, which shows the annual pattern of runoff at the proposed Rogun dam site. The majority of the runoff flows during the thaw season (spring summer), up to 60% of the annual flow (Hydroproject Institute Moscow, 2009). Direct rainfall runoff represents approximately 5% of the annual flows and the groundwater component represents about 35%. The high flow season peak during July, and its average duration is 200 days. This is acknowledged to be characteristic of high altitude/glacier governed flows, compared to snowmelt dominated flows, with thaw season peaks earlier in the year. In addition, from Figure 2.2, it can be seen that the runoff is totally uncorrelated from the precipitation pattern, but is clearly linked to the temperature pattern.

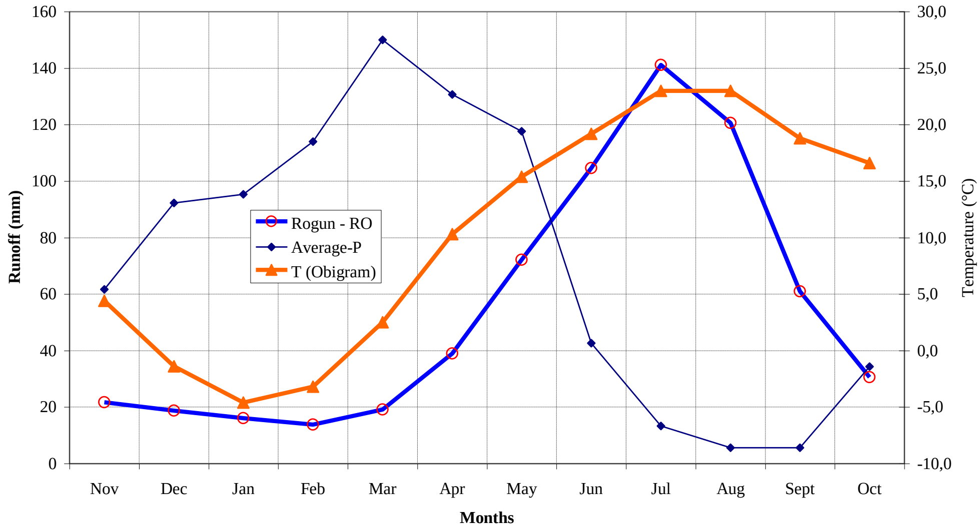
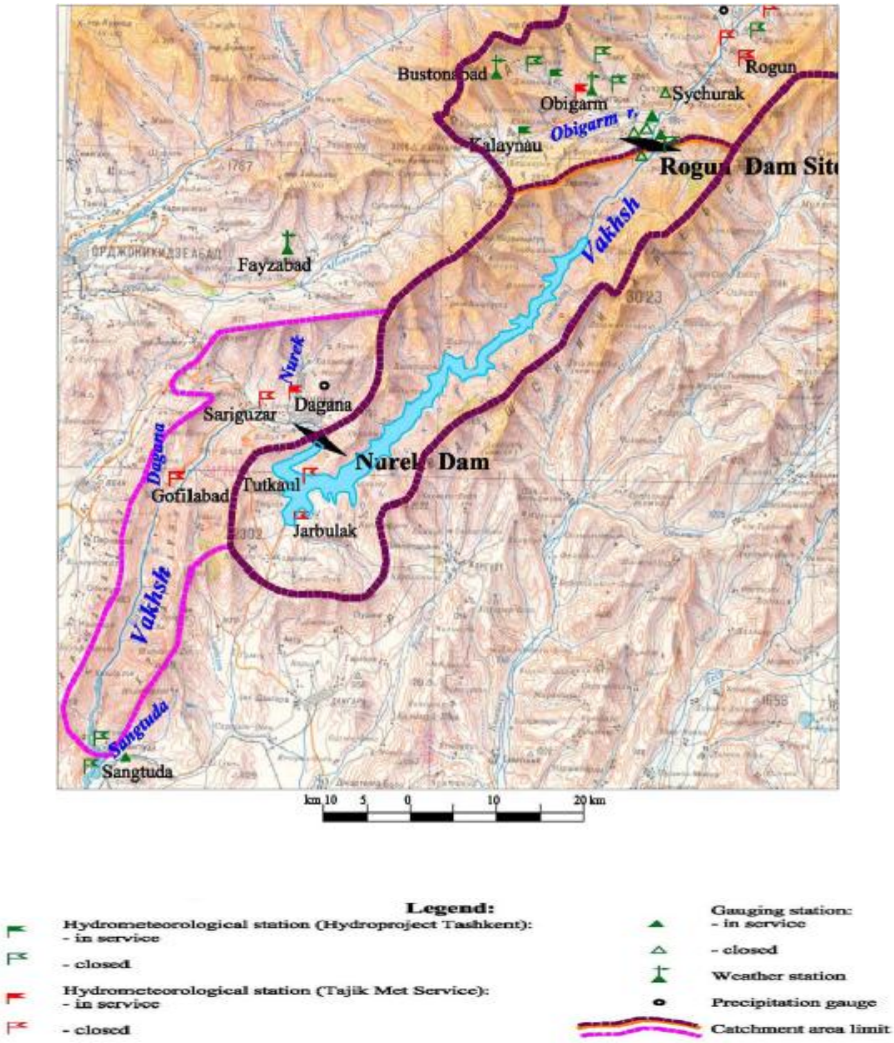


Figure 2-2 : **Annual pattern of runoff at Rogun, and average precipitations and temperatures recorded at Obigam**

2.3 Hydrometeorology data

Figure 2-3: **Hydrographic network and hydro meteorological coverage of the Vakhsh River basin at the stretch between the proposed Rogun Dam Site and Sangtuda,** ***source Lahmeyer 2006***



2.4 Climatic data

Climatic conditions in the area of the proposed Rogun HEP are controlled by the following meteorological stations: Garm (1316 m a.s.l.), Komsomolabad (1258 m a.s.l.), Obigarm (1387 m a.s.l.). They are completed by additional stations located in the Vakhsh catchment: Tavildara (1616 m a.s.l.),, Altyn Mazar (2782 m a.s.l.), Fedchenko Glacier (4169 m a.s.l.) and Abramov Glacier (3837 m a.s.l.). The station of Anzob pass (3737 m a.s.l.) is situated outside the catchment, approximately 60 km north of Dushanbe. Meteorological stations are placed in approximately equivalent natural environment, which allows using data without additional corrections. All climate parameters are accepted according to applied scientific Reference Book on Climate of the USSR (Hydrometheoizdat, L., 1988).

2.5 Hydrometric data

Observations at the gauging stations and discharge sites were carried out using standardized instruments and unified methods of the Tajik Met Service. Gauging stations used for the present hydrological study are summarised in Table 1. The gauging stations location can be appreciated in Figure 2-1 and Figure 2-2. Moreover, in design studies of the Rogun Dam Project, at different stages the Hydroproject of Tashkent has made verification of the recorded hydrological data. These verifications have confirmed the reliability and usability of direct discharge values from the gauging stations time series.

Table 1: Gauging stations in the Vakhsh River Basin

River	Station location	Catchment area (km²)	Observation Period
Surkhob	Garm	20 000	1932-1994
Surkob	Ustye	22 840	1973-present
Vakhsh	Komsomolabad	29 500	1942-1957 1975-present
Vakhsh	Rogun Dam Site	30 390	1973-1977
Vakhsh	Tutkaul kishlak	31 200	1930-1967
Obihingou	Tavildara kishlak	5 390	1953-present
Obihingou	Ustye	6 660	1941-1975

3. INFLOWS

3.1 Inflows assessment

Inflows at the proposed Rogun Dam site are issued from different sources:

- From 1932 to 1972, discharge recorded at Tutkaul gauging station are used,
- From 1973 to 1988, discharges at Tutkaul are reconstituted based on observations made at Komsomolabad. Correlations between the two stations are based on period of common recording (1949-1957 and 1963-1972),
- From 1988 to 2008: discharges are calculated based on Nurek HEP inflows issued from Nurek maintenance service.

There is no appreciable difference between measurements made at Tutkaul gauging station and the proposed Rogun Dam Site gauging station which was operated for 2-3 years. The greatest difference observed was about 16 m3/s, which was only 1% of the observed discharge. In addition Tutkaul station is situated just upstream of Nurek Dam. As it can be seen in Figure 2-3, the drained catchment area between the proposed Rogun Dam site and Nurek Dam is very limited in comparison of the rest of the Vakhsh catchment: less than 3%. Considering this, discharge measurements or reconstitutions at Nurek are considered valid for Rogun Dam Site.

3.2 Yearly and Seasonal Inflows

Next Table 2 details yearly and seasonal inflows (IV-IX = April to September, i.e. melt season – X-III = October to March, i.e. cold season) at Rogun damsite. Besides the inflow data, the Table below shows the frequency distribution of inflows at Rogun damsite.

Table 2:Data about Yearly and Seasonal Inflows at Rogun Damsite

A. Data about Observed Discharge

Year	Annual	IV-IX	X-III
1932 - 1933	621	1 052	187
1933 - 1934	609	1 008	208
1934 - 1935	696	1 163	227
1935 - 1936	562	919	204
1936 - 1937	647	1 101	190
1937 - 1938	640	1 057	222
1938 - 1939	561	919	200
1939 - 1940	588	973	200
1940 - 1941	527	845	208
1941 - 1942	721	1 171	268
1942 - 1943	737	1 188	282
1943 - 1944	615	977	252
1944 - 1945	621	1 018	223
1945 - 1946	680	1 117	240
1946 - 1947	612	986	235
1947 - 1948	516	850	182
1948 - 1949	703	1 153	251
1949 - 1950	785	1 268	299
1950 - 1951	597	979	214
1951 - 1952	559	880	239
1952 - 1953	730	1 207	250
1953 - 1954	689	1 101	274
1954 - 1955	733	1 200	264
1955 - 1956	575	923	226
1956 - 1957	704	1 184	222
1957 - 1958	493	765	220
1958 - 1959	718	1 197	237
1959 - 1960	705	1 158	252
1960 - 1961	632	1 039	223
1961 - 1962	580	945	213
1962 - 1963	522	839	204
1963 - 1964	582	956	209
1964 - 1965	652	1 083	220
1965 - 1966	514	816	211
1966 - 1967	652	1 101	202
1967 - 1968	569	917	220
1968 - 1969	654	1 052	254
1969 - 1970	867	1 438	293
1970 - 1971	667	1 092	239
1971 - 1972	591	973	209
1972 - 1973	513	814	210
1973 - 1974	765	1 290	237
1974 - 1975	495	798	191
1975 - 1976	577	939	215
1976 - 1977	578	933	221
1977 - 1978	624	1 017	228

Year			Annual	IV-IX	X-III
1978	-	1979	705	1 160	248
1979	-	1980	634	1 032	236
1980	-	1981	650	1 088	209
1981	-	1982	630	1 017	241
1982	-	1983	583	930	233
1983	-	1984	631	1 044	219
1984	-	1985	667	1 104	227
1985	-	1986	613	997	226
1986	-	1987	529	825	232
1987	-	1988	701	1 136	266
1988	-	1989	736	1 255	215
1989	-	1990	450	678	220
1990	-	1991	652	1 037	265
1991	-	1992	611	988	234
1992	-	1993	718	1 214	219
1993	-	1994	699	1 141	254
1994	-	1995	758	1 285	228
1995	-	1996	596	953	239
1996	-	1997	626	962	288
1997	-	1998	599	900	295
1998	-	1999	819	1 309	326
1999	-	2000	619	1 007	230
2000	-	2001	570	932	207
2001	-	2002	569	913	223
2002	-	2003	710	1 183	235
2003	-	2004	651	1 079	223
2004	-	2005	656	1 050	261
2005	-	2006	732	1 209	252
2006	-	2007	638	1 044	230
2007	-	2008	747	1 262	233
		N	76	76	76
		M	638	1 041	233
		S	80	145	28
		Cv	0,126	0,139	0,118
		Me	632	1 038	228
		Max	867	1 438	326
		Min	450	678	182

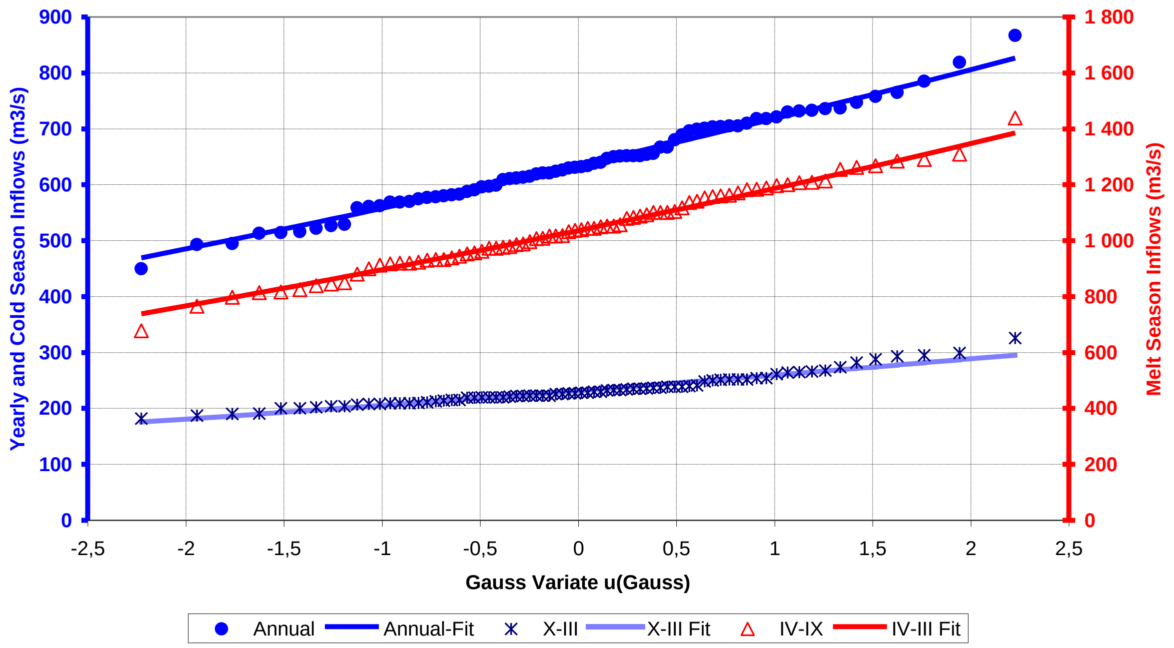
(m3/s)

B. Fit of Inflows to a Root-Gauss Distribution

	T	F	u(Gauss)	Annual-Fit	IV-III Fit	X-III Fit
	(years)			(m3/s)	(m3/s)	(m3/s)
	200	0,005	-2,5758	446	696	168
	100	0,01	-2,3263	463	726	173
Dry Years	50	0,02	-2,0537	481	760	180
	20	0,05	-1,6449	510	811	190
	10	0,1	-1,2816	537	859	199
	5	0,2	-0,8416	570	918	210
Median	2	0,5	0,0000	635	1 036	232
	5	0,8	0,8416	705	1 162	255
	10	0,9	1,2816	742	1 231	268
	20	0,95	1,6449	774	1 289	278
Wet Years	50	0,98	2,0537	811	1 356	291
	100	0,99	2,3263	836	1 401	299
	200	0,995	2,5758	859	1 444	307

Note: In a Root-Gauss distribution, the square root of the variable of interest is normally distributed.

Vakhsh River at Rogun - Inflows vs. Gauss Variate



Note: A Gauss Variate is a standard normal variable. If x is the variable of interest belonging to a sample with mean M and standard deviation S, the associated Gauss variate u(x)=(x-M)/S.

3.3 Monthly Inflows

Tables of monthly, yearly and seasonal inflows are presented as supporting documents. The following Table 3 details basic statistical information about the monthly inflows.

Table 3: Statistical parameters of monthly, yearly and seasonal inflows series 1932/2008:

Month	Mean	S	Cv	Min	Me	Max	M-2S	M-S	M	M+S	M+2S
April	469	135	0,287	292	437	839	200	334	469	604	738
May	831	203	0,244	512	793	1768	426	628	831	1 034	1 236
June	1 248	275	0,220	526	1 229	1892	698	973	1 248	1 523	1 798
July	1 594	292	0,183	995	1 580	2211	1 010	1 302	1 594	1 886	2 178
August	1 363	200	0,147	839	1 352	1814	963	1 163	1 363	1 563	1 763
September	721	139	0,193	479	711	1409	443	582	721	860	999
October	342	55	0,161	157	334	526	232	287	342	397	452
November	254	35	0,137	191	249	354	184	219	254	289	324
December	212	31	0,146	151	206	331	150	181	212	243	274
January	184	28	0,155	136	178	300	127	156	184	212	241
February	175	26	0,151	114	169	259	122	149	175	201	228
March	225	47	0,210	164	220	383	131	178	225	272	319
Year	638	79	0,124	450	632	867	480	559	638	717	796
April/September	1 041	145	0,139	678	1 038	1438	751	896	1 041	1 186	1 331
October/March	233	28	0,118	182	228	326	178	205	233	261	288

4. FLOODS

Flood studies were approached in two stages. The first approach was a frequency analysis of instantaneous and daily peaks. The second approach was an estimation of Probable Maximum Flood (PMF). Simultaneously, the Consultant determined the flood hydrograph by analysing three outstanding floods.

The flood study conducted for Rogun Hydroelectric construction project follows two main points:

- First, a statistical analysis of Vakhsh discharge data, completed by a regional analysis, using the station-year method,
- Second, a PMF assessment using the degree-day factor method.

4.1 Data for Flood Study

Data for flood study is presented either in the main text or in the supporting documents. These data have been gathered from previous reports, from data provided by the Client or data found in the literature (see references).

The set of data for flood study is mainly composed of:

- Daily and instantaneous peaks.
- Daily discharges and daily temperatures.
- Monthly and Seasonal Precipitations.

4.2 Regional flood samples – General Approach

Records obtained for the Vakhsh River at Tutkaul, and transposed to Rogun dam site are too short in order to conduct a statistical analysis and to assess flood estimate for large return period (10000 years). The station-year approach has been used as a pooling methodology in order to extend flood discharge sample (Garros-Berthet, Station-Year Approach: A Tool for Estimation of Design Floods, 1994). Samples from different gauging stations are standardised and pooled together. The method is built on the hypothesis of hydrological homogeneity.

The standardisation is made by using Francou-Rodier Index (Kfr), which is defined by:

Francou-Rodier formula:

$$\frac{Q}{10^6} = \left[\frac{A}{10^8}\right]^{1-0.1K}$$

Francou-Rodier 's Index:

$$K = 10 \times \left[1 - \frac{\ln(Q/10^6)}{\ln(A/10^8)}\right]$$

With Q the flood discharge (m3/s), and A the catchment area (km²).

The Francou-Rodier Index is used to assess the flood severity independently from the catchment area of the considered River (Francou & Rodier, 1967). It is used to determine equivalent severity flood to a catchment of interest (Garros-Berthet, Station-year and Lombardi's approach: tools for estimation of design floods, 1998). In the case of Rogun study the Francou-Rodier approach is used to transpose floods from regional sample to the Vakhsh at the proposed Rogun dam site.

The Consultant performed the frequency analysis using a regional approach in three steps. After considering the results of former studies, the Consultant defined regional flood samples transposed to Rogun conditions. The three steps were:

- First step. Regional sample based on Vakhsh gauging stations.
- Second step. First regional sample and transposed floods from Indus (Attock) and Chenab (Benzwar) rivers.
- Third step. Second regional sample and transposed floods from Syr Darya (Tyumen Aryk).

The statistical analysis was carried out on three different flood samples of rivers with similar hydrological regime and close climate condition of mountain range. The analysis favoured first time series within the catchment of interest and second, records from reference gauging stations in close climatic and geographic conditions with long time series.

4.3 Regional Approach

As discussed above, the regional approach was carried out in three steps based on three sets of data:

- A first sample is built using records from the Vakhsh River Basin. Records from gauging stations on the Surkhob at Garm, Surkhob at Ustye, Obihingou at Tavildara Kishlak and extended records from the Vakhsh at Tutkaul Kishlak are used. These stations have close hydrological characteristics as they belong to the same river basin.

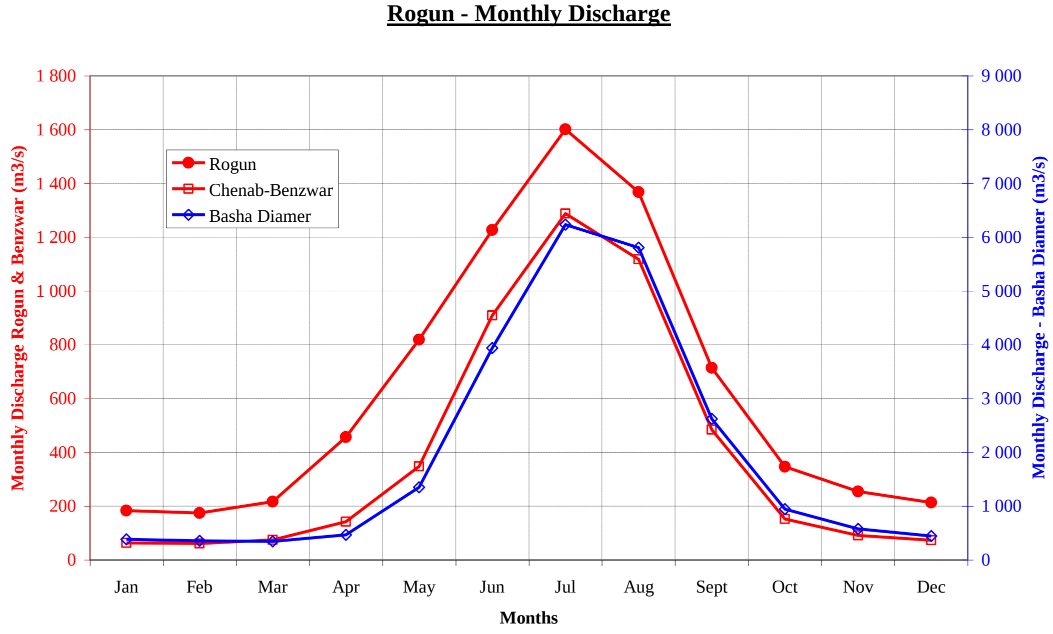
- A second sample is built by adding records from gauging station on the Indus River at Attock (catchment area of 264000 km²) and Chenab River at Benzwar (catchment area of 10500 km²). A comparison of the mean monthly discharge of the Vakhsh, the Indus[1] and the Chenab Rivers, is presented in Table 4, showing a very good agreement between the three hydrological regimes. Thus time series issued from the measurement of the Indus and the Chenab are well documented and exploited in the literature (Rodier & Roche, 1984). In particular the time series for the Indus is more than 100 years long (1868-1978). Such time series are worth using considering the fact that both the Indus and the Chenab Rivers flow from the Greater Himalaya region, which has many similarities with the Pamir Catchments, located 500 km upper north.

- A third sample is built by adding records from Syr-Darya River at Tyumen'Aryk (Kazakhstan) (catchment area of 219000 km²). This River flows from the Pamir-Alai Mountains. The hydrological regime is governed by snow and ice melt, under a very similar climate as the Vakhsh catchment.

The following Table discloses the analogy between Vakhsh, Indus, Chenab and Syr Darya river basins.

Table 4: Analogies between Regional River Basins

1 *Mean monthly discharge values presented in Table 2 are recorded at Basha Diamer located on the Indus River upstream Attock. Maximum discharge values were only available at Attock.*


Rogun - Monthly Discharge
Monthly Discharge Rogun & Benzwar (m3/s)
Monthly Discharge - Basha Diamer (m3/s)
Rogun
Chenab-Benzwar
Basha Diamer
0
200
400
600
800
1 000
1 200
1 400
1 600
1 800
1 000
2 000
3 000
4 000
5 000
6 000
7 000
8 000
9 000
Jan
Feb
Mar
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May
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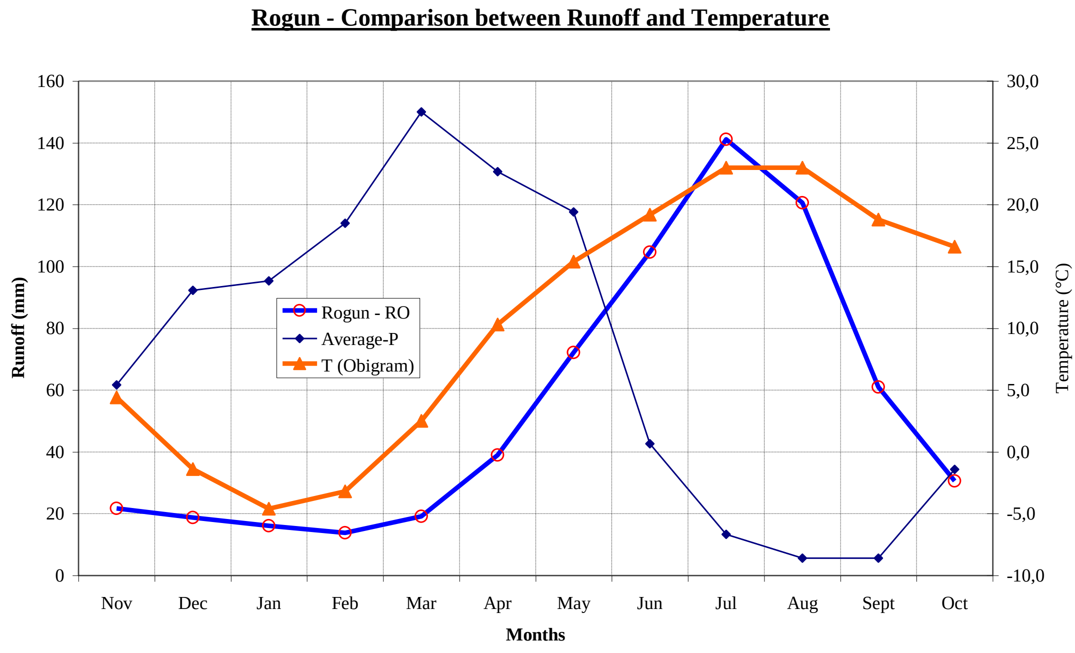
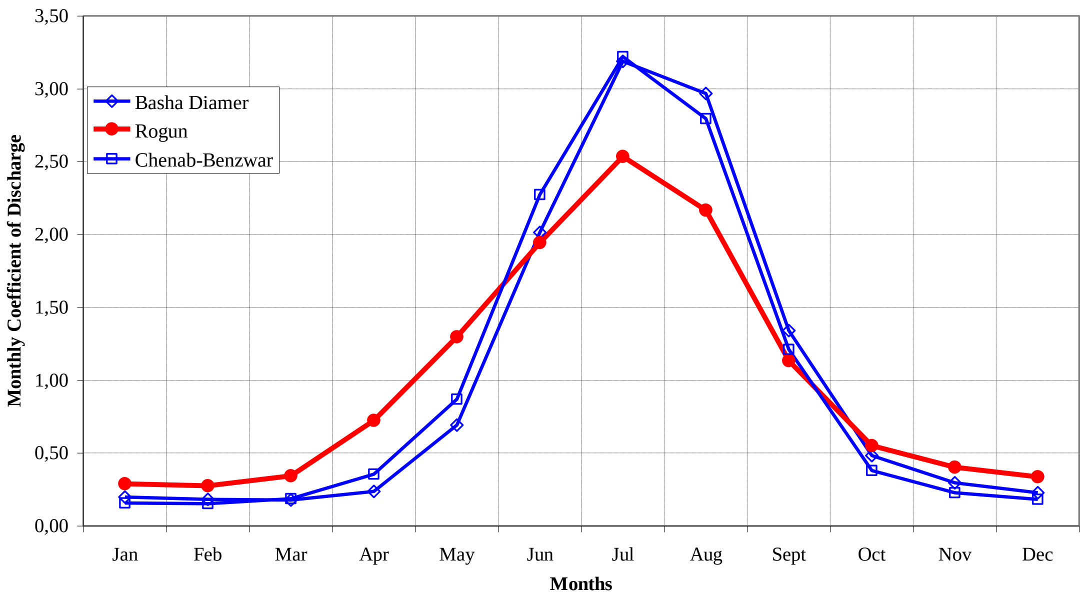
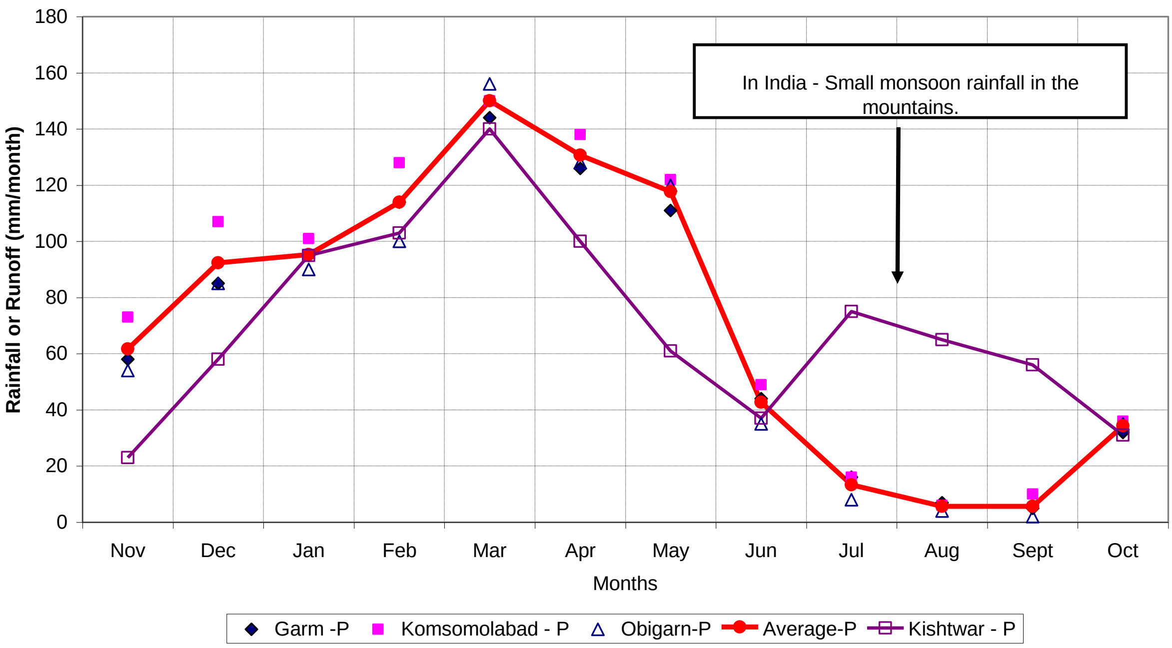
Months

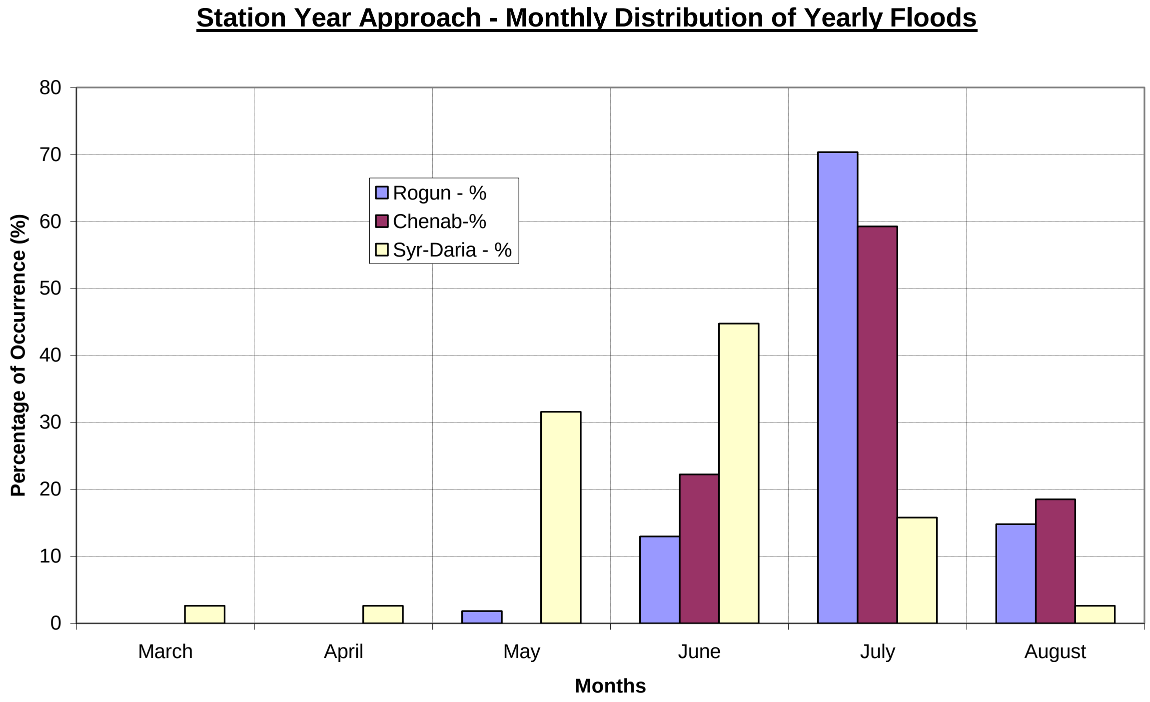

Rogun - Comparison between Runoff and Temperature
Runoff (mm)
Temperature (°C)
Rogun - RO
Average-P
T (Obigram)
0
20
40
60
80
100
120
140
160
30,0
25,0
20,0
15,0
10,0
5,0
0,0
-5,0
-10,0
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Months

Rogun - Monthly Coefficient of Discharge - Comparison with India and Pakistan



Monthly Rainfall - Comparison with India and Pakistan





The Consultant has selected Tiumen Aryk (Syr Darya), Attock (Indus) and Benzwar (Chenab) flood data in addition for the following reasons:

- Their flood data were readily available. Indus and Syr Darya data were abstracted from Rodier & Roche (1984). Chenab data came from Coyne et Bellier reports about Dul Hasti HPP.
- Their hydrologic regime is influenced mainly by snow melt and ice melt. Syr Darya regime is influenced by Tadjik and Kyrghiz mountain ranges. Indus upstream of Attock is under mountainous and semi-arid conditions with several glaciers. For Chenab, about 10 000 km² of its total area in India are largely above snow line.
- They had relatively long periods of records.

Chenab at Benzwar has a drainage area similar to drainage areas of Vakhsh subcatchments whereas Syr Darya and Indus catchments are about seven to nine times the Tutkaul catchment area.

The following table presents relevant statistics concerning the regional flood data bank used in the study.

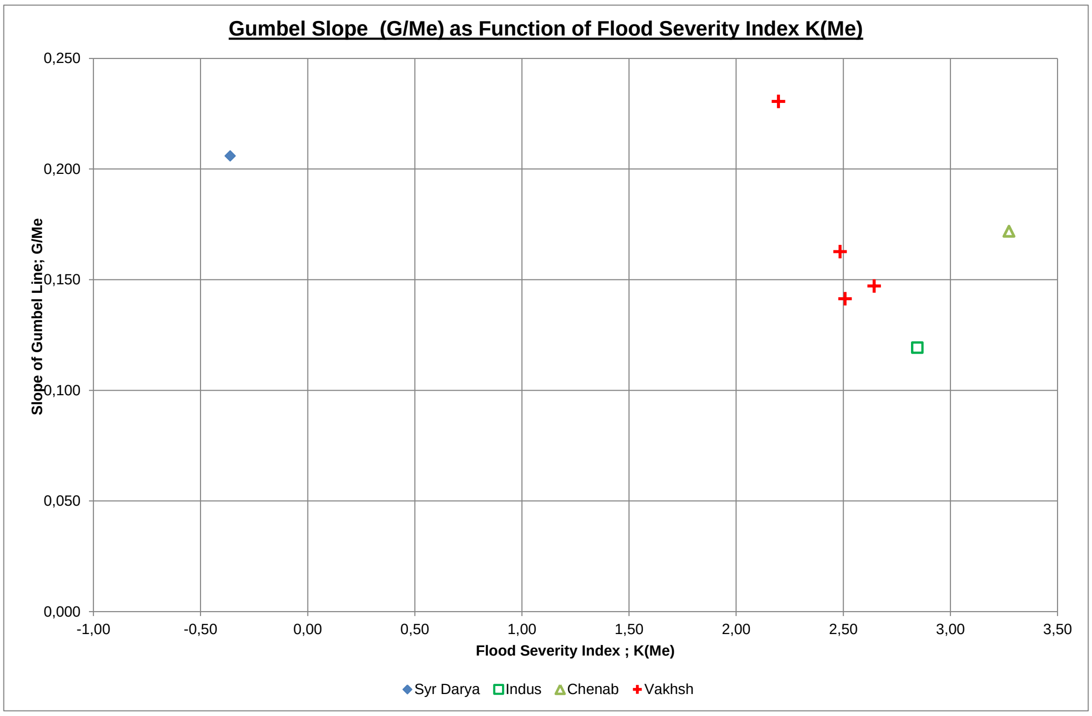
Table 5: Cluster analysis of considered series of data

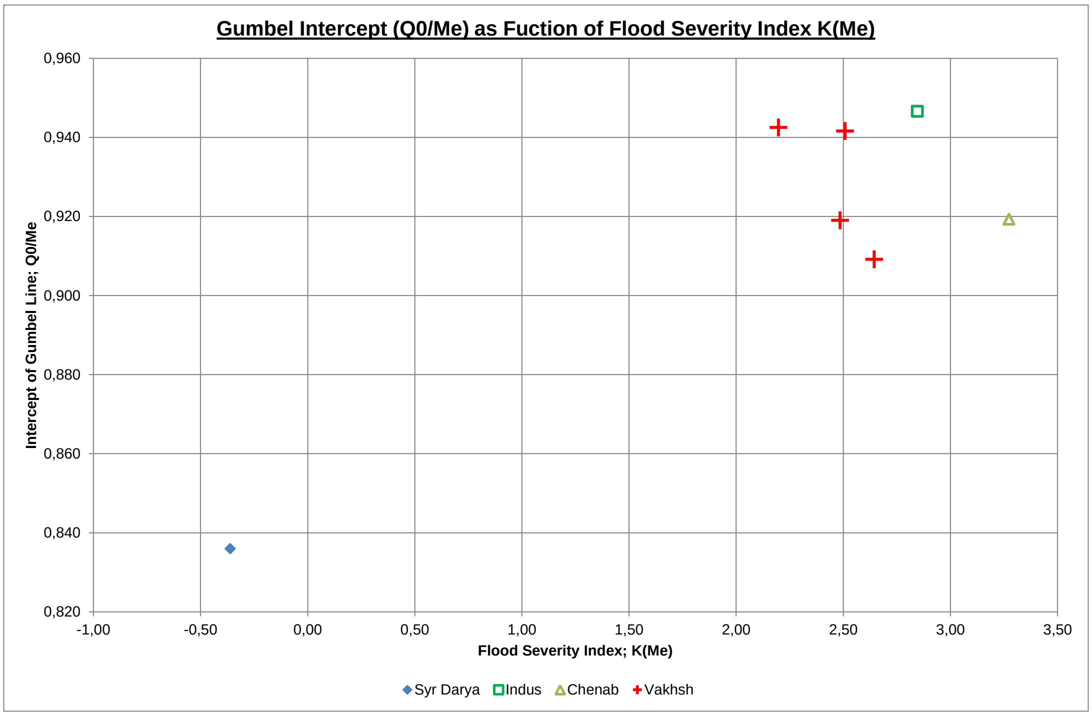
River	Station	A (km²)	n	M	S	Cv	Me	K(Me)	G	Q0	G/Me	Q0/Me
Syr Darya	Tiumen Aryk	219 000	38	1 676	465	0,277	1 755	-0,36	361	1 467	0,206	0,836
Surkhob	Garn	20 000	57	1 398	385	0,276	1 300	2,20	300	1 225	0,231	0,943
Vakhsh	Tutkaul	31 200	77	2 350	485	0,206	2 320	2,49	377	2 132	0,163	0,919
Obihingou	Tavildara	5 390	33	649	115	0,178	634	2,51	90	597	0,141	0,942
Obihingou	Ustye	6 660	35	842	160	0,190	847	2,64	125	770	0,147	0,909
Indus	Attock	264 000	111	14 521	2 193	0,151	14 300	2,85	1 706	13 537	0,119	0,947
Chenab	Benzwar	10 500	27	2 145	465	0,217	2 106	3,27	362	1 936	0,172	0,919

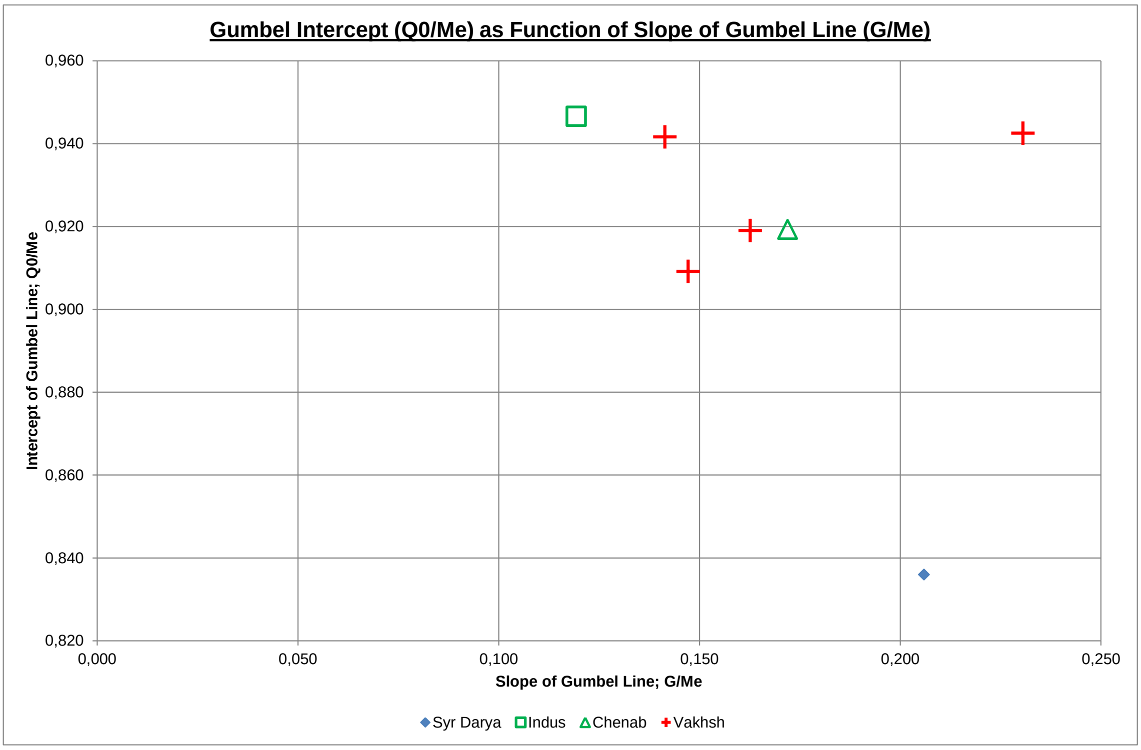
The graph of Gumbel slope (G/Me) against the median flood severity index K(Me) shows that Vakhsh data points are consistent with Attock and Benzwar data points. Tiumen Aryk has a very small K(Me) which is due to the lowland sub catchments under arid conditions. However the G/Me is within the range defined by the other stations.

Similarly, the graph of Gumbel intercept (Q0/Me) against the median flood severity index show a satisfying grouping of data points except the Tiumen Aryk data, for the same reason as given above.

A third graph is presented below which gives the plot of the Gumbel intercept (G/Me) as a function of the Gumbel slope (G/Me). It can be seen that Indus (Attock) and Chenab (Benzwar) data points are consistent with Vakhsh data points. Tiumen Aryk data point is apart from the other data points for the same reason as given above.


Gumbel Slope (G/Me) as Function of Flood Severity Index K(Me)
Slope of Gumbel Line; G/Me
0,250
0,200
0,150
0,100
0,050
0,000
-1,00
-0,50
0,00
0,50
1,00
1,50
2,00
2,50
3,00
3,50
Flood Severity Index ; K(Me)
Syr Darya
Indus
Chenab
Vakhsh


Gumbel Intercept (Q0/Me) as Fuction of Flood Severity Index K(Me)
Intercept of Gumbel Line; Q0/Me
0,960
0,940
0,920
0,900
0,880
0,860
0,840
0,820
-1,00
-0,50
0,00
0,50
1,00
1,50
2,00
2,50
3,00
3,50
Flood Severity Index; K(Me)
Syr Darya
Indus
Chenab
Vakhsh



This analysis allowed for selecting a proper approach:

- For transposition of data to Rogun conditions, each flood sample was transformed into a sample of Francou-Rodier's flood indexes. In second step; the flood indexes were standardized using sample mean and sample standard deviation of K values. In a third step; the mean and standard deviation of Tutkaul are used to obtain K values and Qp values at Rogun.
- Since the regional sample is a mix of data from several stations, it was decided to process the data in a progressive manner: Vakhsh data only (step 1) then adding Attock and Benzwar data (step 2) and finally adding Tiumen Aryk data (step 3).

4.3.1. First Step – Vakhsh River Basin

The Consultant adopted a station-year method which consisted in transposing to Rogun the flood data of Tutkaul (Vakhsh), Garm (Surkhob), Ustiye and Tavildara (Obihingou). The Consultant used Francou-Rodier's flood index (see notations) to perform the transposition to Rogun. After excluding the simultaneous events of lesser importance, the Consultant obtained a final sample of 111 station-years.

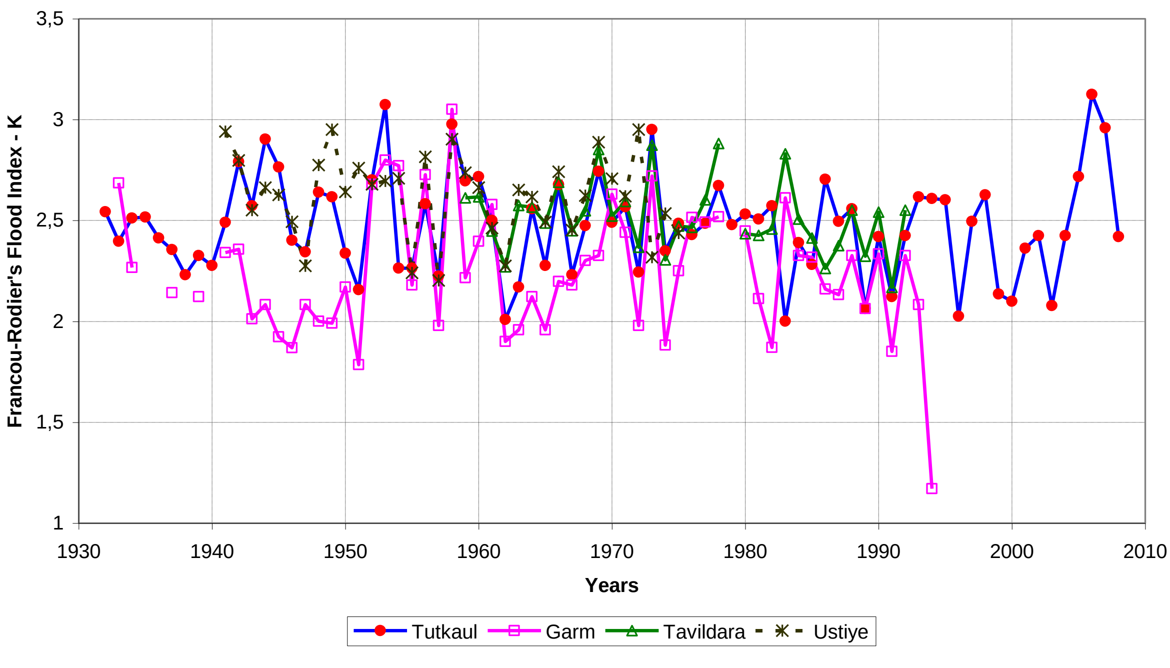
The following Table 6 details the data processing. It gives:

- The time series of Francou-Rodier's index. It can be seen that Francou-Rodier's indexes for Tutkaul, Garm, Tavildara and Ustiye have the same order of magnitude.
- The first step regional sample (sample size n = 111 station-years).
- The fit to a Gumbel distribution which is fully satisfying. Note that the Consultant gave floods estimates for return periods ranging from 2 years to 10 000 years. In addition the Consultant detailed, in italics, estimates for 100 000 and 1 000 000 years. These estimates are representative of the PMF domain. For this first step, the PMF domain is 6 920 / 7 870 m^3/s.
- The time series of flood peaks at Rogun which discloses a very weak decreasing trend of -2 $m^3/s/year$. This trend might be linked to the decrease of glacier feeding.

Table 6: First Step Regional Analysis

A. Francou-Rodier's Flood Index at Selected Stations

Vakhsh River Basin - Francou-Rodier's Flood Index at Selected Locations



B. First Step Regional Sample

Year	Date	Station	u(K)	K	Qp (Rogun)
1932	20/07/1932	Tutkaul	0,27	2,55	2 400
1933	16/07/1933	Garm	1,39	2,83	3 010
1934	24/06/1934	Tutkaul	0,14	2,52	2 340
1935	10/08/1935	Tutkaul	0,16	2,52	2 350

1936	06/07/1936	Tutkaul	-0,25	2,42	2 160
1937	27/07/1937	Garm	-0,31	2,40	2 130
1938	24/07/1938	Tutkaul	-1,00	2,23	1 860
1939	26/06/1939	Garm	-0,37	2,39	2 110
1939	26/07/1939	Tutkaul	-0,61	2,33	2 010
1940	28/06/1940	Tutkaul	-0,81	2,28	1 930
1941	28/04/1941	Ustiye	1,54	2,87	3 100
1941	02/07/1941	Garm	0,32	2,56	2 420
1942	10/07/1942	Tutkaul	1,28	2,80	2 940
1943	12/07/1943	Tutkaul	0,39	2,58	2 460
1943	05/08/1943	Garm	-0,72	2,30	1 960
1944	01/08/1944	Tutkaul	1,73	2,91	3 220
1945	28/07/1945	Tutkaul	1,18	2,77	2 880
Year	**Date**	**Station**	**u(K)**	**K**	**Qp (Rogun)**
1945	14/08/1945	Garm	-0,99	2,23	1 860
1946	02/08/1946	Tutkaul	-0,30	2,40	2 140
1947	22/07/1947	Garm	-0,49	2,36	2 050
1948	26/07/1948	Tutkaul	0,67	2,65	2 600
1948	05/08/1948	Ustiye	0,73	2,66	2 630
1949	22/05/1949	Ustiye	1,59	2,88	3 130
1949	09/07/1949	Tutkaul	0,57	2,62	2 550
1949	07/08/1949	Garm	-0,78	2,28	1 940
1950	01/08/1950	Tutkaul	-0,56	2,34	2 030
1950	11/08/1950	Ustiye	0,07	2,50	2 300
1951	30/05/1951	Ustiye	0,66	2,64	2 590
1951	03/08/1951	Garm	-1,43	2,12	1 700
1952	21/07/1952	Garm	1,38	2,82	3 000
1952	22/08/2011	Tutkaul	0,91	2,71	2 730
1953	10/07/1953	Tutkaul	2,43	3,09	3 710
1954	04/06/1954	Garm	1,67	2,90	3 180
1954	02/08/1954	Tutkaul	-0,87	2,26	1 910
1954	16/08/1954	Ustiye	0,41	2,58	2 470
1955	13/08/1955	Garm	-0,19	2,43	2 180
1956	24/07/1956	Garm	1,52	2,86	3 090
1957	19/07/1957	Garm	-0,82	2,28	1 920
1958	15/07/1958	Garm	2,54	3,12	3 790
1959	04/06/1959	Tutkaul	0,89	2,70	2 720
1959	03/07/1959	Tavildara	0,55	2,62	2 540
1960	11/07/1960	Tutkaul	0,98	2,73	2 770
1961	31/07/1961	Garm	1,06	2,75	2 810
1962	18/07/1962	Tavildara	-1,42	2,12	1 700
1962	06/08/1962	Garm	-1,07	2,21	1 830
1963	28/06/1963	Tutkaul	-1,24	2,17	1 770
1963	12/07/1963	Tavildara	0,34	2,56	2 430
1964	13/07/1964	Tutkaul	0,33	2,56	2 430
1964	27/07/1964	Garm	-0,37	2,39	2 110
1965	26/07/1965	Tavildara	-0,17	2,44	2 190
1966	26/06/1966	Tavildara	1,00	2,73	2 780
1966	08/08/1966	Garm	-0,14	2,45	2 210
1967	24/07/1967	Garm	-0,19	2,43	2 180
1968	08/07/1968	Garm	0,19	2,53	2 360
1969	25/07/1969	Tavildara	1,94	2,97	3 360

1970	02/07/1970	Ustiye	0,40	2,58	2 460
1970	19/07/1970	Garm	1,22	2,79	2 910
1971	29/07/1971	Garm	0,63	2,64	2 580
1972	06/07/1972	Garm	-0,82	2,28	1 920
1972	05/08/1972	Ustiye	1,59	2,88	3 130
1973	17/07/1973	Tavildara	2,06	2,99	3 440
1974	16/07/1974	Ustiye	-0,44	2,37	2 080
1975	*14/07/1975*	Tutkaul	0,04	2,49	2 290
1975	15/08/1975	Garm	0,03	2,49	2 280
1976	22/07/1976	Garm	0,86	2,70	2 700
1977	22/07/1977	Garm	0,79	2,68	2 660
Year	**Date**	**Station**	**u(K)**	**K**	**Qp (Rogun)**
1978	24/06/1978	Garm	0,87	2,70	2 710
1978	08/07/1978	Tavildara	2,11	3,01	3 480
1979		Tutkaul	0,01	2,48	2 280
1980	05/07/1980	Garm	0,65	2,64	2 590
1980		Tutkaul	0,23	2,54	2 380
1981	24/06/1981	Tavildara	-0,52	2,35	2 040
1981	09/07/1981	Garm	-0,40	2,38	2 090
1981		Tutkaul	0,12	2,51	2 330
1982	15/07/1982	Tavildara	-0,33	2,40	2 120
1982		Tutkaul	0,39	2,58	2 460
1983	05/08/1983	Tavildara	1,82	2,93	3 280
1984	03/08/1984	Garm	0,27	2,55	2 400
1985	28/06/1985	Tavildara	-0,59	2,33	2 010
1985	18/08/1985	Garm	0,24	2,54	2 380
1986	17/07/1986	Tavildara	-1,47	2,11	1 690
1986	31/07/1986	Garm	-0,25	2,42	2 160
1986		Tutkaul	0,93	2,71	2 740
1987	25/07/1987	Tutkaul	0,08	2,50	2 310
1988	28/06/1988	Tavildara	0,20	2,53	2 360
1988	15/07/1988	Tutkaul	0,33	2,56	2 430
1989	30/07/1989	Garm	-0,56	2,34	2 030
1990	22/06/1990	Tavildara	0,14	2,52	2 340
1990	02/08/1990	Garm	0,29	2,55	2 410
1991	16/06/1991	Tutkaul	-1,44	2,12	1 700
1991	30/07/1991	Tavildara	-2,01	1,98	1 510
1991	20/08/1991	Garm	-1,22	2,17	1 770
1992	13/07/1992	Tavildara	0,20	2,53	2 360
1992	15/07/1992	Garm	0,27	2,55	2 400
1993	24/06/1993	Tutkaul	0,57	2,62	2 550
1993	27/08/1993	Garm	-0,49	2,36	2 050
1994		Tutkaul	0,54	2,62	2 530
1995		Tutkaul	0,51	2,61	2 520
1996		Tutkaul	-1,84	2,02	1 570
1997	21/07/1997	Tutkaul	0,08	2,50	2 310
1998		Tutkaul	0,61	2,63	2 570
1999		Tutkaul	-1,38	2,13	1 720
2000		Tutkaul	-1,53	2,10	1 670
2001	03/07/2001	Tutkaul	-0,47	2,36	2 070
2002	22/07/2002	Tutkaul	-0,21	2,43	2 180
2003	28/08/2003	Tutkaul	-1,62	2,08	1 640

2004	08/07/2004	Tutkaul	-0,21	2,43	2 180
2005		Tutkaul	0,98	2,73	2 770
2006	13/08/2006	Tutkaul	2,64	3,14	3 870
2007		Tutkaul	1,96	2,97	3 370
2008		Tutkaul	-0,23	2,42	2 170

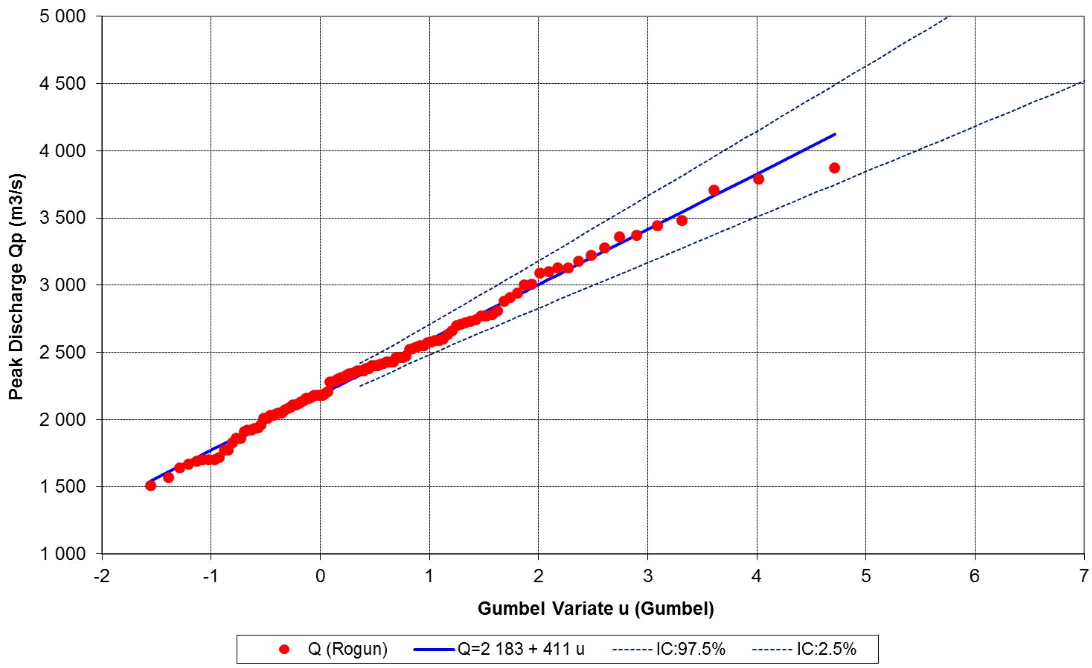
	u(K)	**K**	**Qp (Rogun)**
n	111	111	111
M	0,20	2,53	2 414
S	1,00	0,25	498
Cv		0,098	0,206
Me	0,20	2,53	2 360
Max	2,64	3,14	3 870
Min	-2,01	1,98	1 510

Regional samples transposed to Rogun dam site are adjusted to Gumbel distribution. The Gumbel variate U is defined as (with F the empirical frequency):

$$U = -ln\left(-ln(F)\right)$$

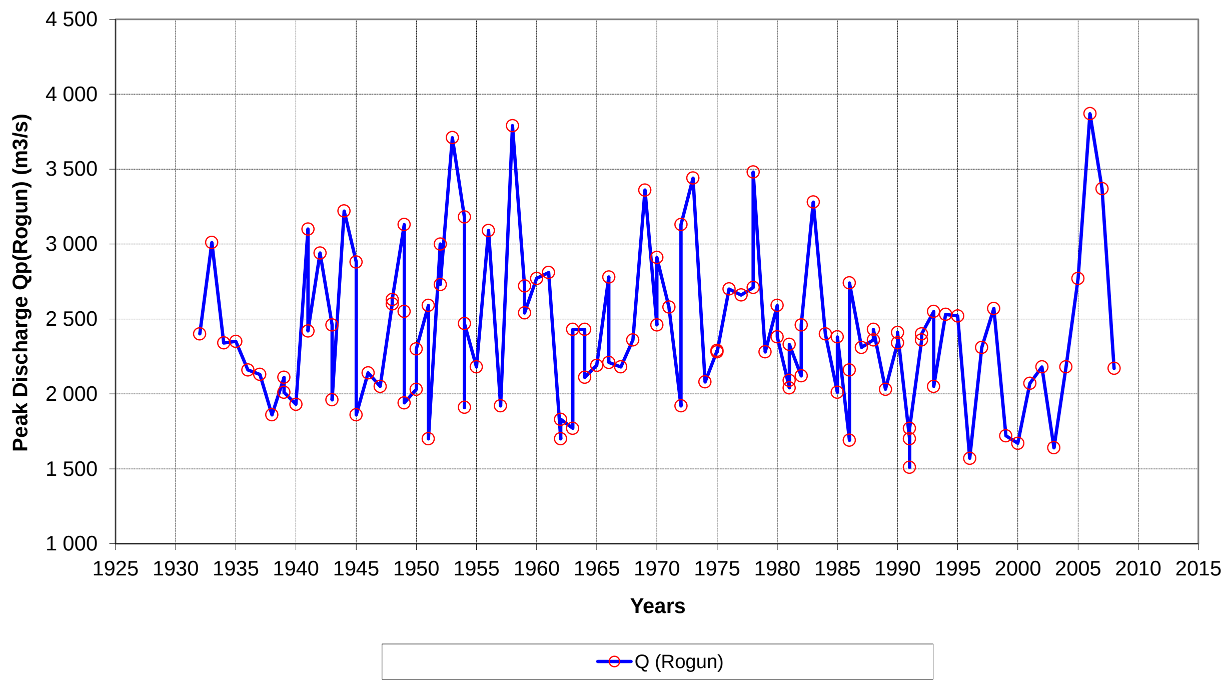
C. Fit to a Gumbel Distribution

T (years)	**Qp(T) - Rogun** (m^3/s)	**T** (years)	**Qp(T) - Rogun** (m^3/s)
2	2 340	200	4 360
5	2 800	500	4 740
10	3 110	1 000	5 030
20	3 410	2 000	5 310
50	3 790	5 000	5 690
100	4 080	10 000	5 970
		100 000	*6 920*
		1 000 000	*7 870*



D. Time Series of Qp

First Step - Regional Sample (111 Station-Years)



4.3.2. Second Step – Vakhsh River + Indus River + Chenab River

As discussed above as a second step, the Consultant adopted a station-year method which consisted in transposing to Rogun the flood data of Attock (Indus), Benzwar (Chenab) which were added to the first step sample (111 station-years). Thus a second step sample was obtained of 249 station-years.

The following Table details the data processing. It gives:

- The second step regional sample (sample size n = 249 station-years)
- The fit to a Gumbel distribution which is fully satisfying. For this second step, the PMF domain is 6 650 / 7 560 m^3/s.
- The time series of flood peaks at Rogun which does not show any significant trend. It is to be noted that Indus transposed data provided 4 floods greater than 3 000 m^3/s prior to 1930. The 1929 flood is the most important of the whole data set. More extreme floods are present and allow reducing the uncertainty for the high values range and in facto extrapolation of flood estimates for larger return periods. Outstanding Vakhsh floods are the ones observed in 1953, 1958 and 2006.

Table 7: Step 2 - Regional Sample of Flood Peaks at Rogun

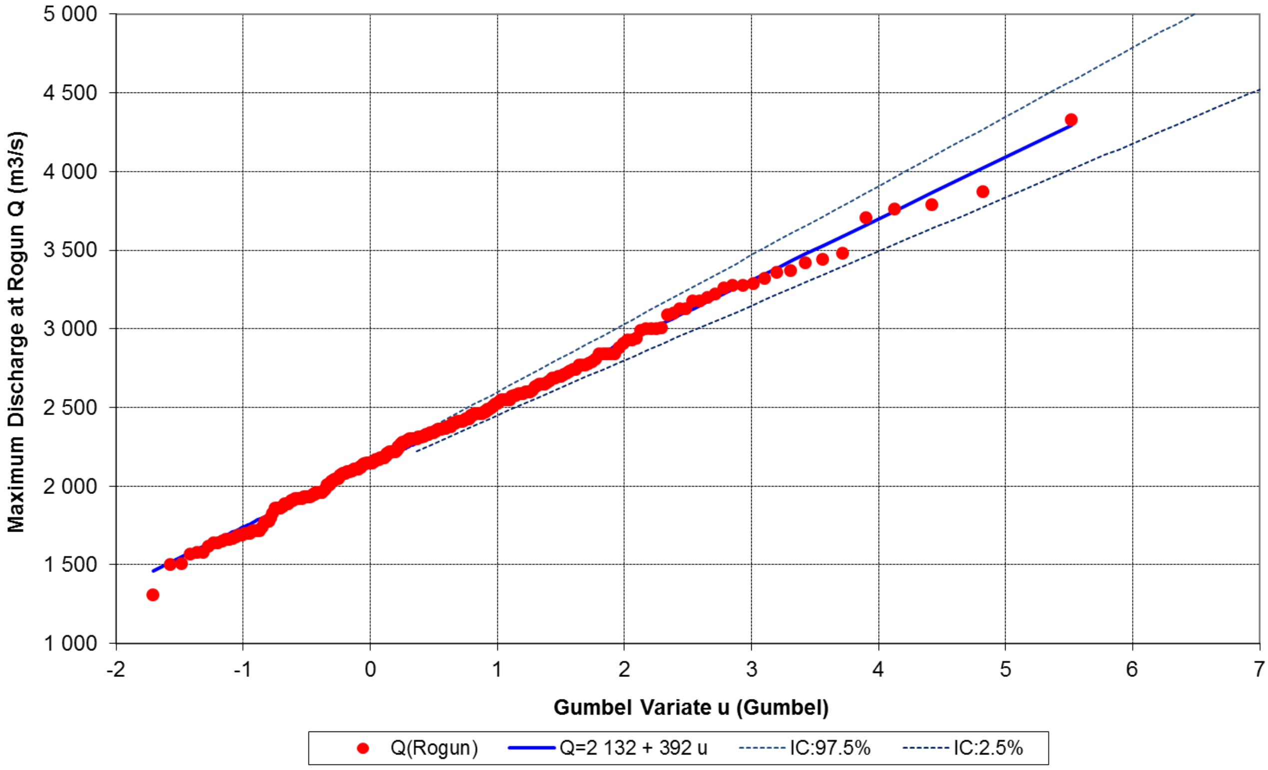
A. Regional Sample – (249 Station-Years)

Basin	Year	Q(Rogun)	Basin	Year	Q(Rogun)	Basin	Year	Q(Rogun)	Basin	Year	Q(Rogun)	Basin	Year	Q(Rogun)
Indus	1868	2 250	Indus	1918	1 650	Indus	1948	2 380	Vakhsh	1965	2 190	Chenab	1981	2 640
Indus	1869	1 930	Indus	1919	2 300	Vakhsh	1948	2 600	Indus	1966	3 180	Vakhsh	1981	2 040
Indus	1870	2 100	Indus	1920	2 330	Vakhsh	1948	2 630	Chenab	1966	2 170	Vakhsh	1981	2 090
Indus	1871	2 220	Indus	1921	2 450	Indus	1949	2 090	Vakhsh	1966	2 780	Vakhsh	1981	2 330
Indus	1872	2 790	Indus	1922	2 650	Vakhsh	1949	3 130	Vakhsh	1966	2 210	Chenab	1982	2 230
Indus	1873	2 300	Indus	1923	2 150	Vakhsh	1949	2 550	Indus	1967	2 740	Vakhsh	1982	2 120
Indus	1874	2 690	Indus	1924	3 420	Vakhsh	1949	1 940	Chenab	1967	2 220	Vakhsh	1982	2 460
Indus	1875	2 150	Indus	1925	2 220	Indus	1950	2 460	Vakhsh	1967	2 180	Chenab	1983	2 350
Indus	1876	2 410	Indus	1926	1 930	Vakhsh	1950	2 030	Indus	1968	2 510	Vakhsh	1983	3 280
Indus	1877	1 890	Indus	1927	2 080	Vakhsh	1950	2 300	Chenab	1968	2 670	Chenab	1984	1 780
Indus	1878	3 320	Indus	1928	2 300	Indus	1951	1 800	Vakhsh	1968	2 360	Vakhsh	1984	2 400
Indus	1879	1 960	Indus	1929	4 330	Vakhsh	1951	2 590	Indus	1969	1 960	Chenab	1985	1 980
Indus	1880	1 920	Indus	1930	2 840	Vakhsh	1951	1 700	Chenab	1969	2 070	Vakhsh	1985	2 010
Indus	1881	1 860	Indus	1931	1 930	Indus	1952	2 110	Vakhsh	1969	3 360	Vakhsh	1985	2 380
Indus	1882	3 760	Indus	1932	2 930	Vakhsh	1952	3 000	Indus	1970	1 500	Chenab	1986	2 320
Indus	1883	2 150	Vakhsh	1932	2 400	Vakhsh	1952	2 730	Chenab	1970	1 660	Vakhsh	1986	1 690
Indus	1884	2 490	Indus	1933	2 290	Indus	1953	2 840	Vakhsh	1970	2 460	Vakhsh	1986	2 160
Indus	1885	2 220	Vakhsh	1933	3 010	Vakhsh	1953	3 710	Vakhsh	1970	2 910	Vakhsh	1986	2 740

Indus	1886	2 450	Indus	1934	2 460	Indus	1954	1 620	Indus	1971	1 920	Chenab	1987	2 600
Indus	1887	2 150	Vakhsh	1934	2 340	Vakhsh	1954	3 180	Chenab	1971	1 970	Vakhsh	1987	2 310
Indus	1888	1 640	Indus	1935	2 340	Vakhsh	1954	1 910	Vakhsh	1971	2 580	Chenab	1988	2 700
Indus	1889	3 000	Vakhsh	1935	2 350	Vakhsh	1954	2 470	Indus	1972	1 720	Vakhsh	1988	2 360
Indus	1890	2 470	Indus	1936	1 720	Indus	1955	2 100	Chenab	1972	1 660	Vakhsh	1988	2 430
Indus	1891	1 950	Vakhsh	1936	2 160	Vakhsh	1955	2 180	Vakhsh	1972	1 920	Chenab	1989	3 260
Indus	1892	2 840	Indus	1937	1 950	Indus	1956	2 250	Vakhsh	1972	3 130	Vakhsh	1989	2 030
Indus	1893	2 650	Vakhsh	1937	2 130	Vakhsh	1956	3 090	Indus	1973	2 500	Vakhsh	1990	2 340
Indus	1894	3 000	Indus	1938	2 090	Indus	1957	2 120	Chenab	1973	2 410	Vakhsh	1990	2 410
Indus	1895	1 920	Vakhsh	1938	1 860	Vakhsh	1957	1 920	Vakhsh	1973	3 440	Vakhsh	1991	1 700
Indus	1896	2 210	Indus	1939	2 320	Indus	1958	3 290	Indus	1974	1 690	Vakhsh	1991	1 510
Indus	1897	2 590	Vakhsh	1939	2 110	Vakhsh	1958	3 790	Chenab	1974	1 680	Vakhsh	1991	1 770
Indus	1898	2 010	Vakhsh	1939	2 010	Indus	1959	2 610	Vakhsh	1974	2 080	Vakhsh	1992	2 360
Indus	1899	1 960	Indus	1940	1 960	Vakhsh	1959	2 720	Indus	1975	2 550	Vakhsh	1992	2 400
Basin	**Year**	**Q(Rogun)**	**Basin**	**Year**	**Q(Rogun)**	**Basin**	**Year**	**Q(Rogun)**	**Basin**	**Year**	**Q(Rogun)**	**Basin**	**Year**	**Q(Rogun)**
Indus	1900	2 220	Vakhsh	1940	1 930	Vakhsh	1959	2 540	Chenab	1975	3 280	Vakhsh	1993	2 550
Indus	1901	2 300	Indus	1941	1 910	Indus	1960	2 690	Vakhsh	1975	2 290	Vakhsh	1993	2 050
Indus	1902	1 310	Vakhsh	1941	3 100	Vakhsh	1960	2 770	Vakhsh	1975	2 280	Vakhsh	1994	2 530
Indus	1903	1 740	Vakhsh	1941	2 420	Indus	1961	1 890	Indus	1976	2 550	Vakhsh	1995	2 520
Indus	1904	2 080	Indus	1942	2 930	Vakhsh	1961	2 810	Chenab	1976	2 270	Vakhsh	1996	1 570
Indus	1905	2 150	Vakhsh	1942	2 940	Indus	1962	1 870	Vakhsh	1976	2 700	Vakhsh	1997	2 310
Indus	1906	2 770	Indus	1943	2 310	Vakhsh	1962	1 700	Indus	1977	2 170	Vakhsh	1998	2 570
Indus	1907	1 930	Vakhsh	1943	2 460	Vakhsh	1962	1 830	Chenab	1977	2 280	Vakhsh	1999	1 720
Indus	1908	2 840	Vakhsh	1943	1 960	Indus	1963	1 890	Vakhsh	1977	2 660	Vakhsh	2000	1 670
Indus	1909	2 040	Indus	1944	2 330	Chenab	1963	1 720	Indus	1978	2 840	Vakhsh	2001	2 070
Indus	1910	2 110	Vakhsh	1944	3 220	Vakhsh	1963	1 770	Chenab	1978	2 550	Vakhsh	2002	2 180
Indus	1911	2 370	Indus	1945	2 490	Vakhsh	1963	2 430	Vakhsh	1978	2 710	Vakhsh	2003	1 640
Indus	1912	2 370	Vakhsh	1945	2 880	Indus	1964	2 990	Vakhsh	1978	3 480	Vakhsh	2004	2 180
Indus	1913	2 300	Vakhsh	1945	1 860	Chenab	1964	2 580	Chenab	1979	2 140	Vakhsh	2005	2 770
Indus	1914	2 650	Indus	1946	1 860	Vakhsh	1964	2 430	Vakhsh	1979	2 280	Vakhsh	2006	3 870
Indus	1915	1 580	Vakhsh	1946	2 140	Vakhsh	1964	2 110	Chenab	1980	3 200	Vakhsh	2007	3 370
Indus	1916	2 370	Indus	1947	1 580	Indus	1965	2 600	Vakhsh	1980	2 590	Vakhsh	2008	2 170
Indus	1917	2 410	Vakhsh	1947	2 050	Chenab	1965	1 900	Vakhsh	1980	2 380			

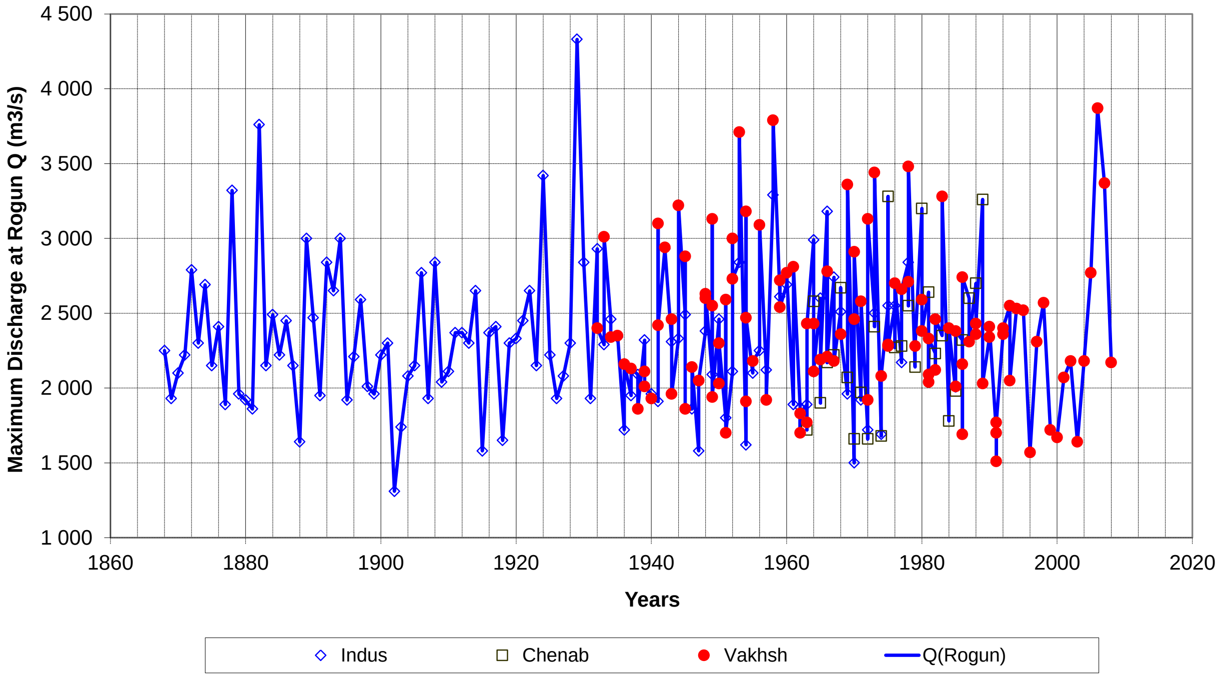
B. Fit to a Gumbel Distribution

T (years)	Qp(T) - Rogun (m^3/s)	T (years)	Qp(T) - Rogun (m^3/s)
2	2 280	200	4 210
5	2 730	500	4 570
10	3 020	1 000	4 850
20	3 300	2 000	5 120
50	3 670	5 000	5 480
100	3 940	10 000	5 750
		100 000	*6 650*
		1 000 000	*7 560*



C. Time Series of Qp

Regional Approach (Step 2) to Floods at Rogun - 249 Station-Years



4.3.3. Third Step – Second Step + Syr Darya River

The Consultant thereafter adopted a station-year method which consisted in transposing to Rogun the flood data of Tyumen Aryk (Syr Darya) which were added to the second step sample (249 station-years). Thus we obtained a third step sample of 287 station-years.

The following Table details the data processing. It gives:

- The transposition to Rogun of Tyumen Aryk data set (38 values). Thus, the third step regional sample has a sample size n = 287 station-years.
- The fit to a Gumbel distribution which is fully satisfying. For this third step, the PMF domain is 6 580 / 7 460 m^3/s.
- The time series of flood peaks at Rogun which does not show significant trend.

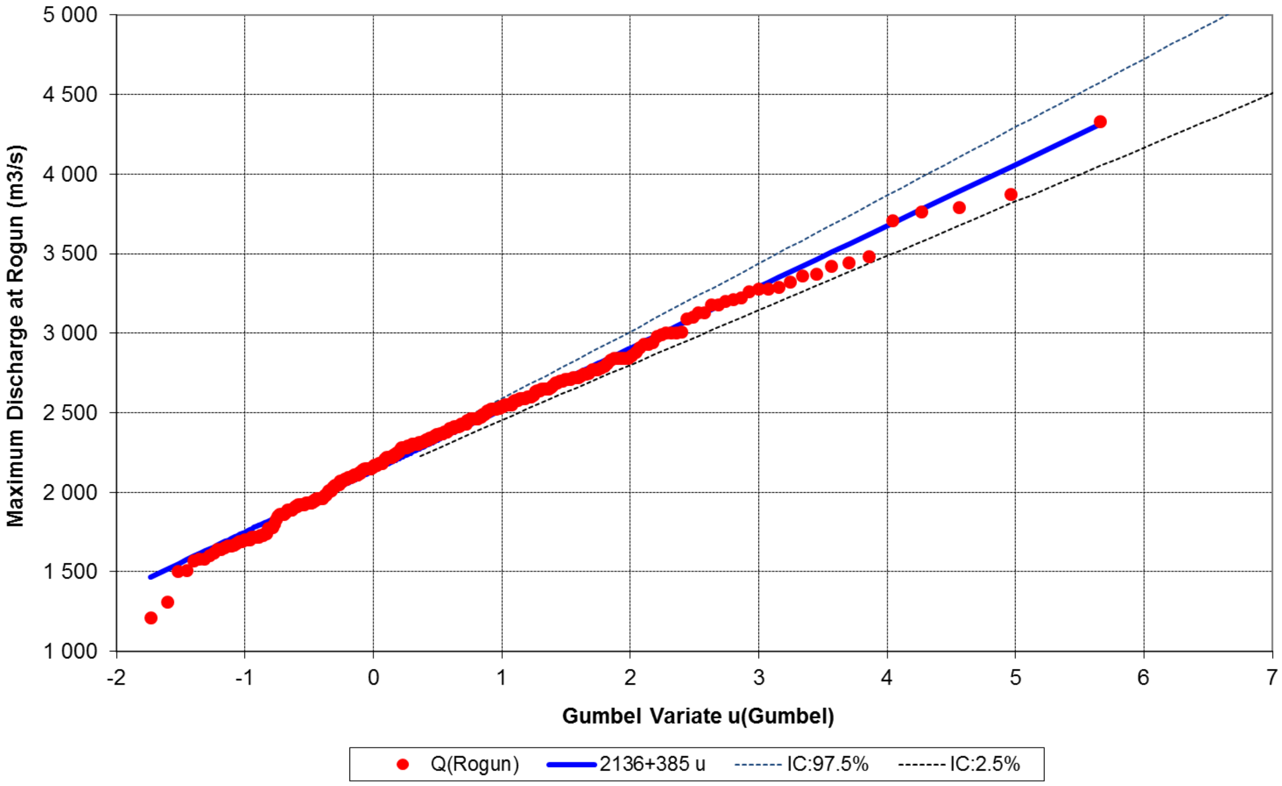
Table 8: Step 3 - Regional Flood Sample at Rogun (287 Station-Years)

A. Transposed data from Syr Darya

Year	Month	Day	Qdmx	Qp(Rogun)
1914	7	6	2 090	2 720
1915	5	17	1 250	1 980
1916	6	16	1 010	1 730
1917	8	16	567	1 210
1919	6	19	1 430	2 150
1920	7	18	1 520	2 230
1927	5	10	1 020	1 740
1928	6	17	2 260	2 860
1929	5	3	1 570	2 280
1930	6	26	1 770	2 460
1931	7	19	2 220	2 830
1932	5	31	1 580	2 290
1933	6	10	1 530	2 240
1934	6	30	2 730	3 210
1935	6	23	2 000	2 650
1936	6	9	2 420	2 980
1937	5	22	1 930	2 590
1938	5	21	1 160	1 890
1939	5	18	1 700	2 390
1940	6	9	1 570	2 280
1941	6	21	1 830	2 510
1942	7	3	2 070	2 710
1943	6	14	1 340	2 070
1944	7	14	1 010	1 730
1947	5	30	890	1 600
1948	5	3	1 270	2 000
1949	6	2	1 840	2 520
1950	5	25	1 740	2 430
1951	6	6	1 860	2 530
1952	5	19	2 130	2 750
1953	6	24	1 990	2 640
1954	5	8	1 850	2 520
1955	6	22	1 870	2 540
1956	6	12	1 530	2 240
1957	3	13	1 120	1 850
1958	7	24	1 840	2 520
1959	4	13	2 090	2 720
1960	6	1	2 080	2 710
		n	38	38
		M	1 676	2 350
		S	465	424
		Cv	0,277	0,180

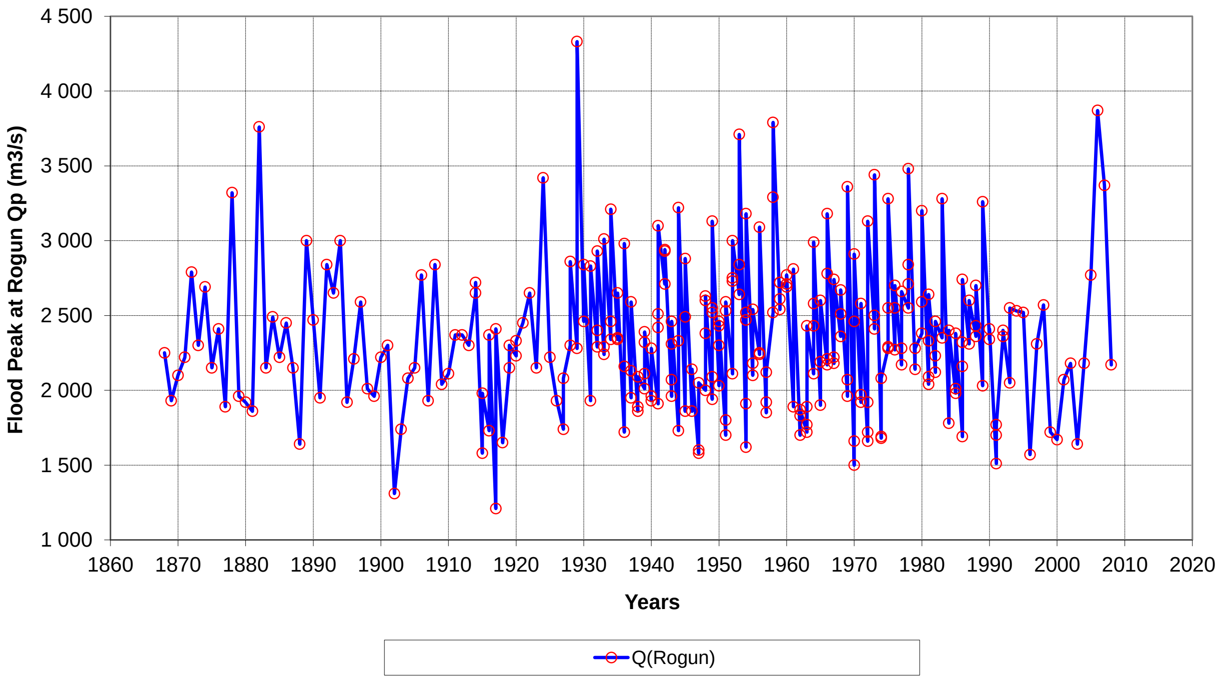
B. Fit to a Gumbel Distribution

T (years)	Qp(T) - Rogun (m^3/s)	T (years)	Qp(T) - Rogun (m^3/s)
2	2 280	200	4 180
5	2 720	500	4 530
10	3 010	1 000	4 800
20	3 280	2 000	5 070
50	3 640	5 000	5 420
100	3 910	10 000	5 690
		100 000	*6 580*
		1 000 000	*7 460*



C. Time Series of Qp

Regional Approach (Step 3) - Flood Peaks at Rogun (287 Station-Years)



4.3.4. Flood Frequency and Flood Hydrographs

The following Table 9 outlines the obtained results. Note that for the Vakhsh river, the following relation can be used: $Q_p = Q_{dmx} \times 1.05$. This relation is derived from observed data and has also been used in previous studies.

Results from sample 1, based on the Vakhsh discharge records are finally adopted in the study. It is to be noted that flood estimates are consistent with previous studies (Lahmeyer 2006 and HPI, 2009).

Table 9: Rogun – Flood Frequency and Flood Hydrographs

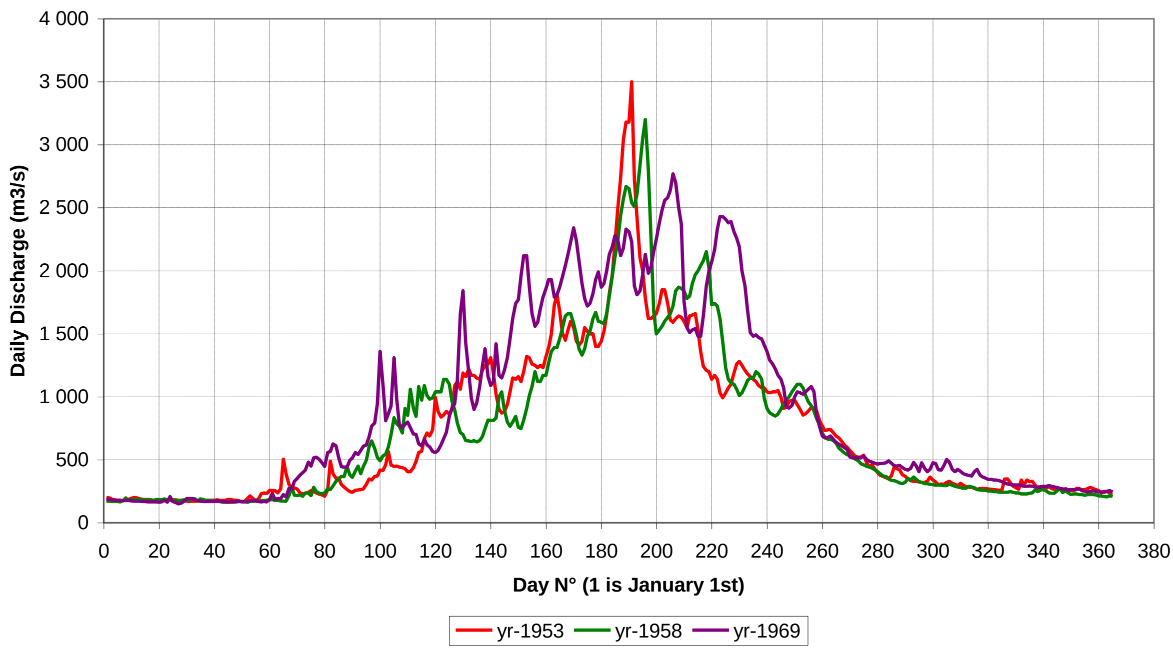
A. Conclusions on Flood Frequency

	Regional Approach			Former Studies		Synthesis of Results				
T	Step 1	Step 2	Step 3	2006	2009	M	S	M+2S/√5	Adopted	Daily
2	2 340	2 280	2 280	*2 370*	*2 210*	2 296	62	2 351	2 360	2 250
5	2 800	2 730	2 720	*2 740*	*2 660*	2 730	50	2 775	2 780	2 650
10	3 110	3 020	3 010	2 980	3 000	3 024	50	3 069	3 070	2 930
20	3 410	3 300	3 280	3 190	3 260	3 288	80	3 359	3 360	3 200
50	3 790	3 670	3 640	*3 520*	3 660	3 656	96	3 742	3 750	3 580
100	4 080	3 940	3 910	3 730	3 900	3 912	125	4 024	4 030	3 840
200	4 360	4 210	4 180	*3 970*	*4 170*	4 178	139	4 302	4 310	4 110
500	4 740	4 570	4 530	*4270*	4 370	4 496	182	4 659	4 660	4 440
1 000	5 030	4 850	4 800	4 550	4 700	4 786	178	4 945	4 950	4 720
2 000	5 310	5 120	5 070	*4 720*	*5 100*	5 064	214	5 255	5 260	5 010
5 000	5 690	5 480	5 420	*5 020*	*5 460*	5 414	244	5 632	5 640	5 380
10 000	5 970	5 750	5 690	5 200	5 880	5 698	299	5 966	5 970	5 690

T in years; Qdmx and Qp in m3/s.

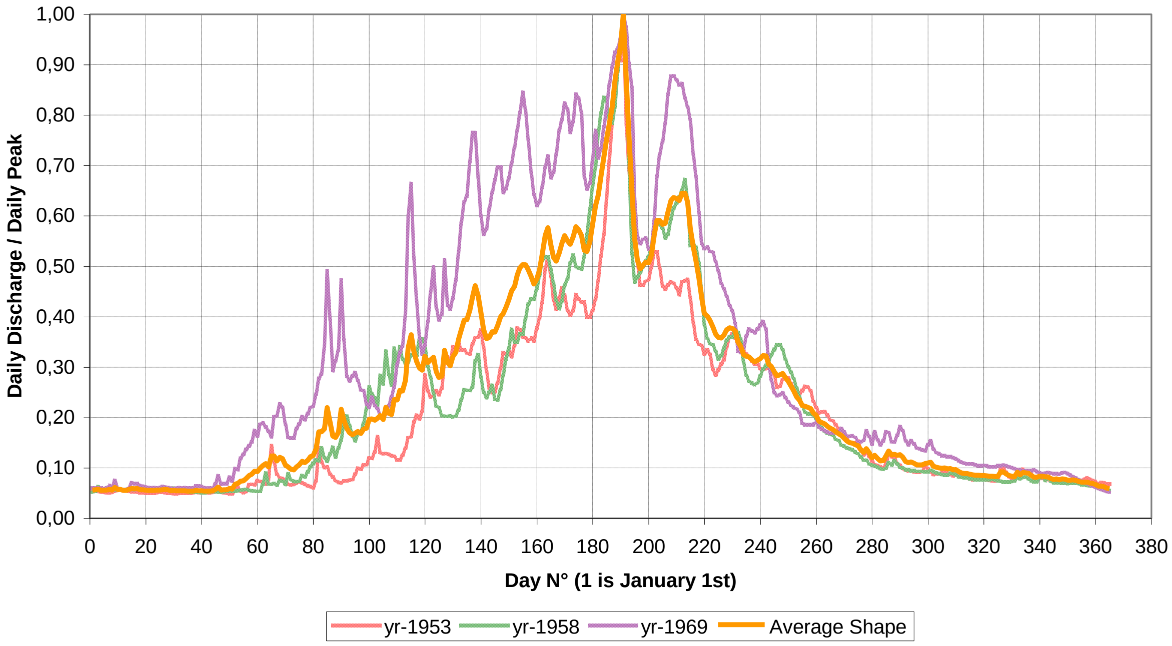
B. Oustanding Floods

Typical Hydrograph Shapes



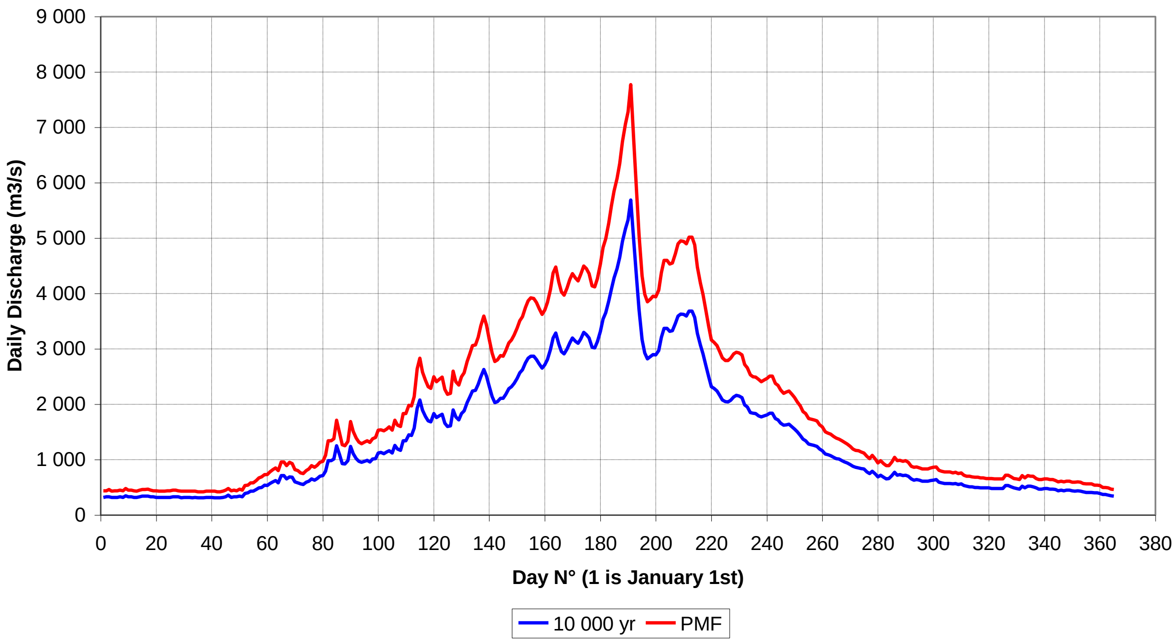
C. Typical Design Hydrograph

Adimensional Hydrograph Shape for Design



D. Hydrographs of Extreme Floods

Hydrographs for 10 000-yr Flood and Probable Maximum Flood



4.4 PMF Computation

4.4.1. Probable Maximum Flood (PMF) assessment

As presented above the Vakhsh is a snow and glaciers melt influenced river, high flows are related to the thaw season, which peaks principally in July/August. As previously mentioned the Vakhsh discharge is totally uncorrelated from the precipitations. Consequently as mentioned in this hydrology report and also mentioned in Lahmeyer 2006 and Hydroproject Moscow, 2009, the PMF cannot be assessed by the conventional method (World Meteorological Organisation, 2009), involving for example Probably Maximum Precipitation concept (PMP). It is therefore needed to study climate variables which control the flow regime.

The Consultant derived its own approach based on the basic observation of the two principal phenomena that are dominant in the Vakhsh basin:

- First the availability of snow and ice cover, which is determined by the quantity of the winter precipitations,
- Second the melting process in spring and summer, which is controlled by solar radiations (as described by Krenke, Mass exchange in glacier systems in the USSR territory, 1982).

This problem has been partially addressed in Lahmeyer study, which has highlighted the possibility of the existence of a certain physically validated limit of the maximum air temperature corresponding, in conjunction with other factors, to the most intensive snow and ice melting possible.

Practically, it may be taken that total heat supply onto the snow and ice surface and thus the ablation magnitude are proportional to mean daily temperatures (Tronov, 1966). Without consideration herein of complicated factors of radiation balance and air temperature relationship which are interacting and form the required conditions for snow and ice melting in mountain areas, temperature characteristics have been used for PMF estimation. Many publications give credit to the concept of prevailing air temperatures in the melting process (Krenke & Khodakov, 1966) (Palgov, 1947).

The degree-day method has been widely used to determine the quantity of snow or ice ablation in relation with the number of degrees above 0°C during 24 h. In this study this variable is correlated to the maximum discharge observed on the Vakhsh. Many studies showed that simple empirical approaches give comparable results than more complex methods or mass-balance modelling (Ohmura, 2001) (World Meteorological Organisation, 1986).

Considering the extent and the complexity of the Vakhsh catchment (30900 km²) and regarding the scarce meteorological network density, establishment of a physical based model would bring more uncertainty than direct established correlations between key climatic variables and observed discharges.

In this study the degree-day factor is calculated on the record of Anzob Pass (3737 m a.s.l.), using the average daily temperature derived from recorded series. This station is the most representative of the lower limit of glacier areas, with the longest and most reliable time series. Thus, it is also the station which best represents the Vakhsh catchment, with its mean elevation is 3250 m a.s.l., which corresponds approximately to Anzob pass.

The following calculation approach has been followed for derivation of PMF value:

a. The following input data were found relevant and representative: Daily discharges at Tutkaul / Sarygusar, daily temperatures at Anzob Pass, seasonal precipitation at Tavildara. Availability of data resulted in selecting a 40-year period from 1940 to 1980.

b. For each year of the 40-year periods, the degree-day factor was computed and a correlation was performed between maximum daily discharge and degree-day factor. Meaningful linear correlations with significant R^2 were obtained. The parameters of the linear relations varied from year to year but are related either to the seasonal precipitation or to the degree-day factor for the occurrence of flood peak.

c. Making use of these different features, the Consultant was able to perform several maximisations in line with accepted procedures about PMP and PMF (WMO and others). The final choice of PMF was based on all available information. It is to be reminded that this PMF estimate is basically an ice melt and a snow melt flood. No provisions were made in this value for GLOF and mud floods, which shall be addressed separately in the design criteria of the project.

4.4.2. PMF According to 2006 study

In 2006, the PMF has been computed using correlations between maximum temperatures and daily discharges. Three types of floods were considered: floods for wet years, floods for average years and floods for dry years. Exponential functions were fitted to each of these three subsets of data and provided the basis for PMF computation by extrapolation. Correlations are meaningful on a subset basis whereas the overall scatter of data is very important.

The Consultant retrieved the 2006 data for wet years and adjusted exponential functions to Altyn Mazar and Tavildara temperatures. Similarly the Consultant defined linear correlations which were also meaningful.

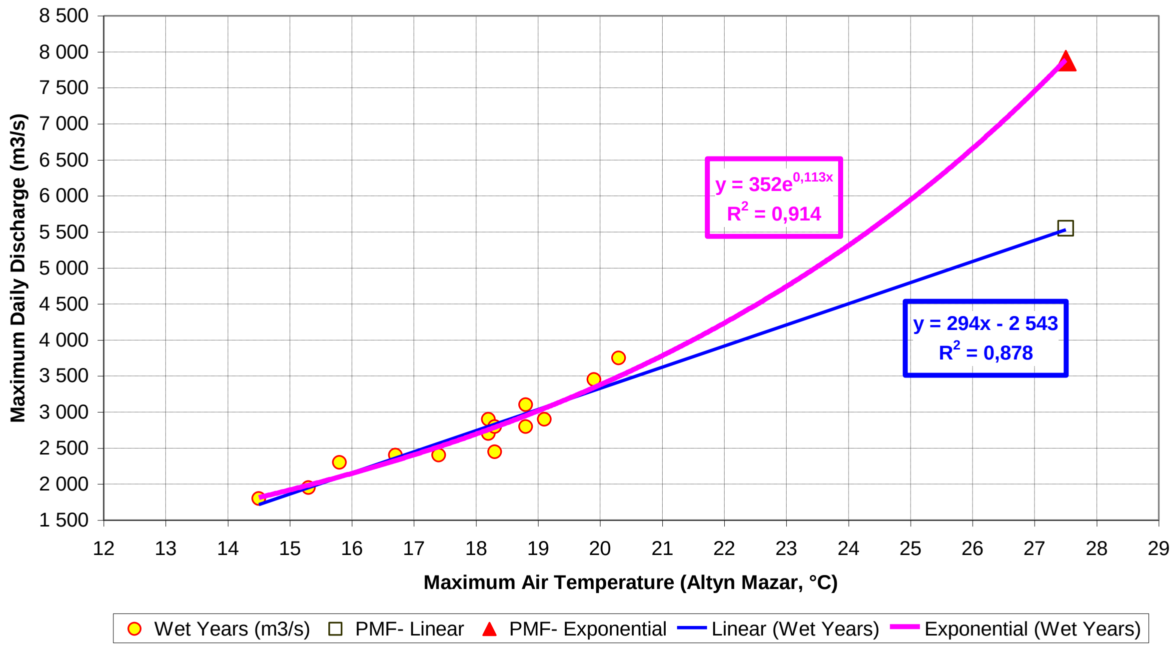
The extrapolation to the PMF was made for a temperature calculated with the formula $M_{(temp)} + 3.7\sigma_{(temp)}$, which correspond to a probability of exceedance of 1/10 000. As shown in the Table, the linear extrapolation gives PMF values which are comparable to the 10 000-year daily peak. The exponential extrapolation leads to much higher PMF estimate. The maximum temperature for which the PMF has been computed in 2006 corresponds to an occurrence of 1 / 10 000.

The selection of three types of year (dry, average, and wet) is a manner to overcome the problem of estimating the water available for melting. Extrapolating the PMF using the maximum temperature exceeded with a probability of 1 / 10 000 is acceptable, but neglecting the snow and ice reserves seems inaccurate. Thus, the main default of the 2006 approach is to neglect the impact of precipitation (stored as ice and snow) on the melt peak discharge. Our own approach relies heavily on the well-known degree-day approach.

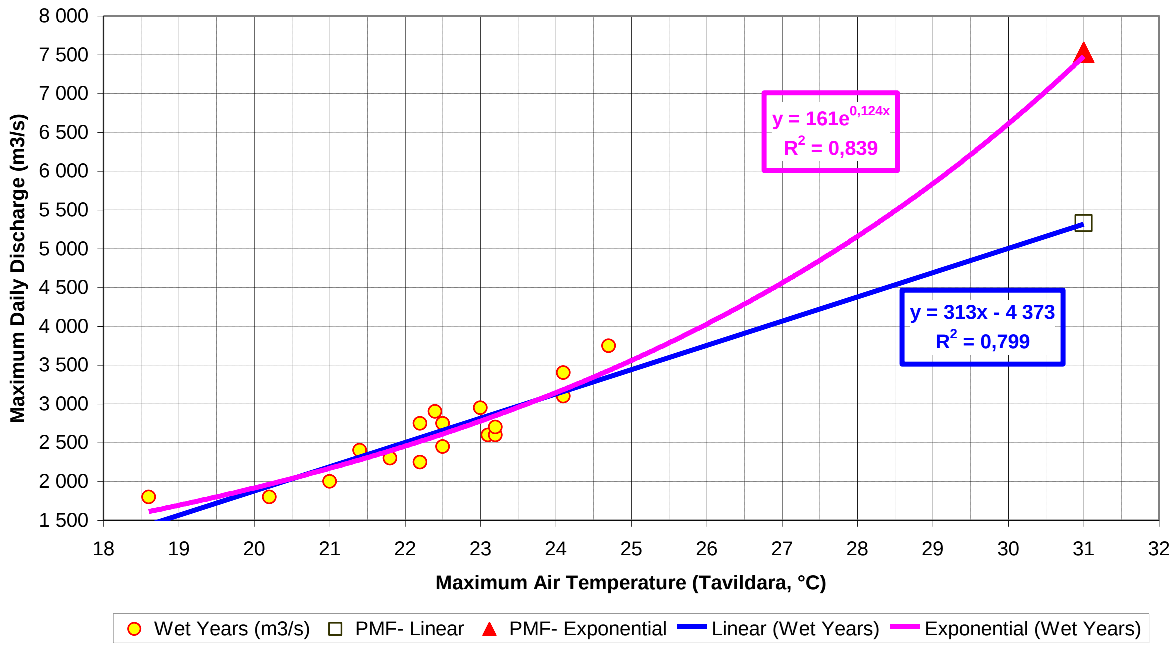
Table 10: PMF Computation According to 2006 Study

A. Daily Peaks vs. Air Temperature

Wet Years - Maximum Daily Discharge vs. Altyn Mazar Air Temperature



Wet Years - Maximum Daily Discharge vs. Tavildara Air Temperature



B. PMF computed by Extrapolation

Station	Tmax	PMF- Linear	PMF- Exponential
	(°C)	(m^3/s)	(m^3/s)
Altyn Mazar	27,5	5 550	7 880
Tavildara	31,0	5 330	7 530

4.4.3. Degree-Day Approach

In the degree-day approach, the Consultant defines a degree-day factor by adding up the daily average temperatures when they are positive. By doing so, some kind of measure of the heat available for melting the stock of snow and ice is quantified. For our analysis, Anzob Pass temperatures series were adopted, for which 40 years of data are available. In addition, the elevation of Anzob Pass (3 737 m) is representative of glacier elevation.

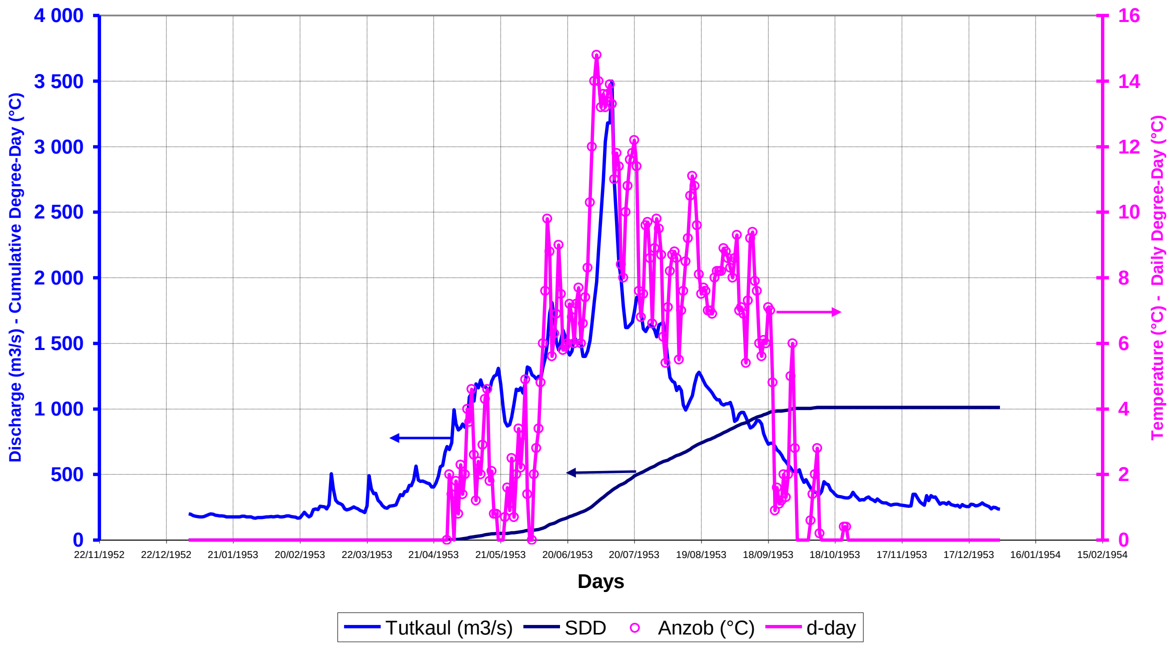
The following Table 9 shows the discharge and temperature features of typical years (one wet and one dry). The correlation between degree-days and discharge are obvious (see first graph for each typical year). Moreover, the correlation between the daily discharge and the degree-day factor (cumulative degree-day at a given date) is significant (see second graph for each typical day).

The last part of the Table presents a chart summarising the results of the investigation of the 40 available years. Related graphs are given in supporting documents. The table gives the degree-day factor for both the daily peak and the yearly discharge. It quotes also each yearly equation and each yearly R^2.

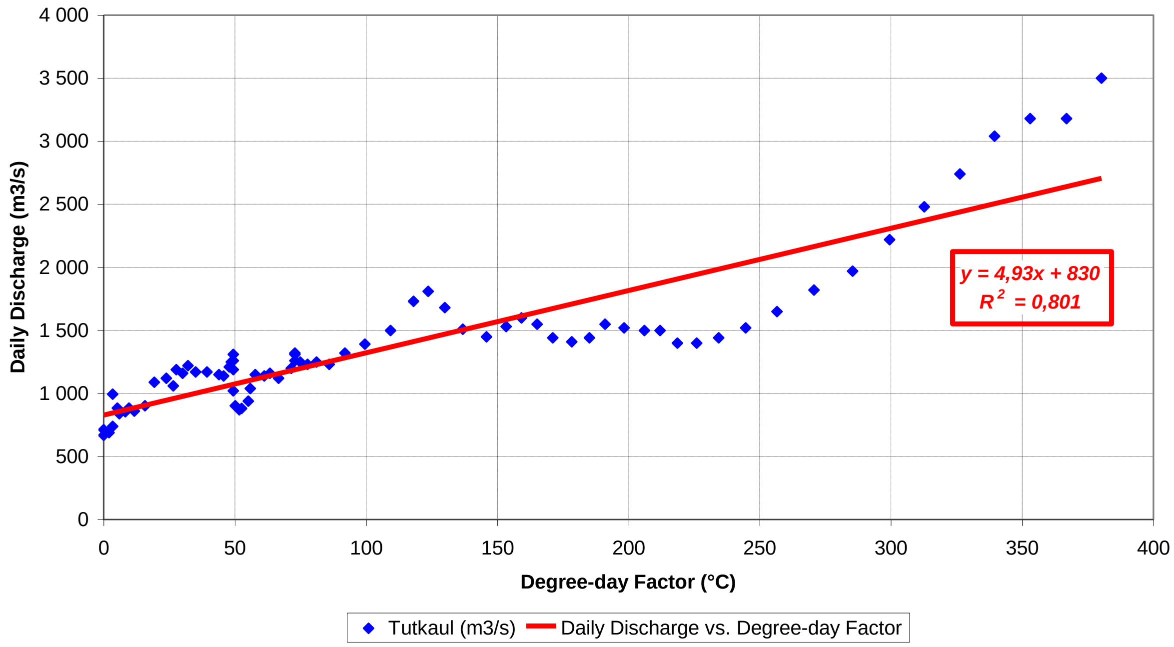
Table 9 - Presentation of Degree-Day Approch

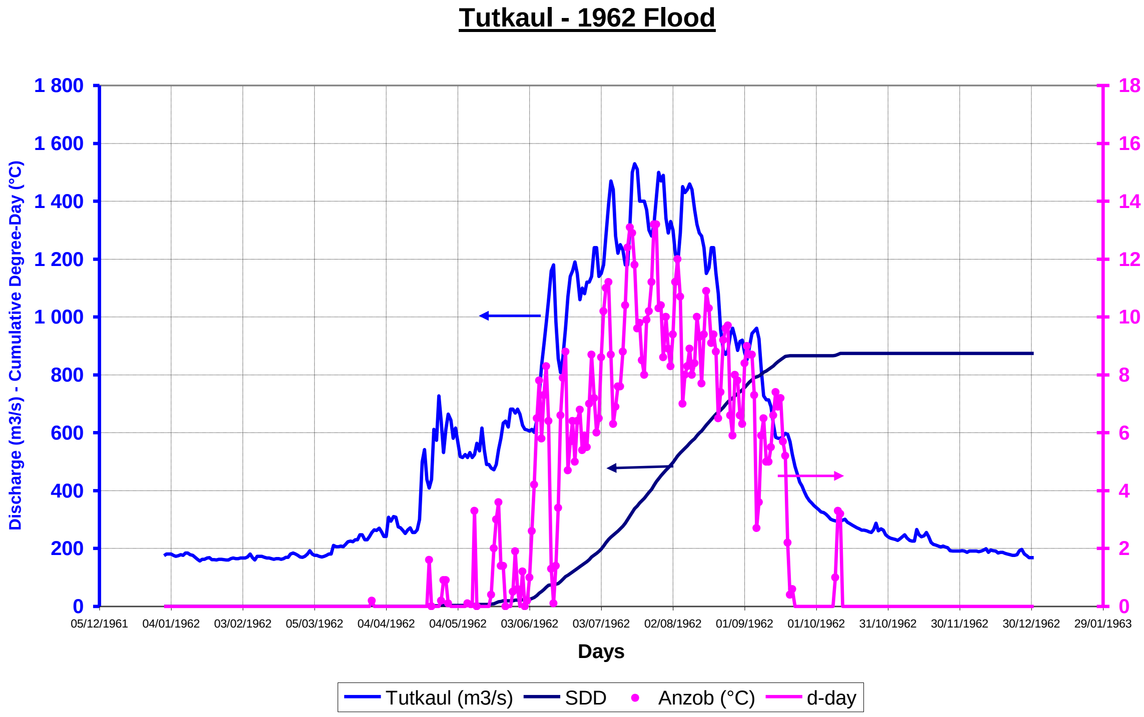
A. Temperature and Discharge Data for Typical Years

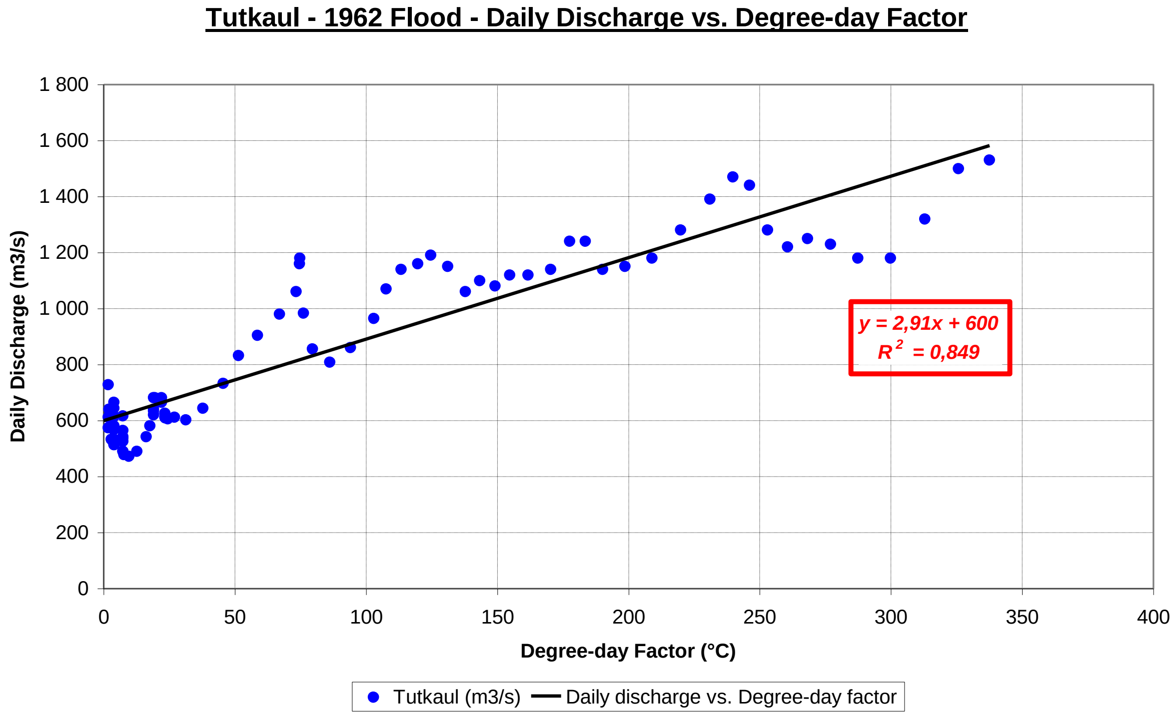
Tutkaul - 1953 Flood



Tutkaul - 1953 Flood - Daily Discharge vs. Degree-day Factor




Tutkaul - 1962 Flood
Discharge (m3/s) - Cumulative Degree-Day (°C)
Temperature (°C) - Daily Degree-Day (°C)
1 800
1 600
1 400
1 200
1 000
800
600
400
200
0
18
16
14
12
10
8
6
4
2
0
05/12/1961
04/01/1962
03/02/1962
05/03/1962
04/04/1962
04/05/1962
03/06/1962
03/07/1962
02/08/1962
01/09/1962
01/10/1962
31/10/1962
30/11/1962
30/12/1962
29/01/1963
Days
Tutkaul (m3/s)
SDD
Anzob (°C)
d-day


Tutkaul - 1962 Flood - Daily Discharge vs. Degree-day Factor
Daily Discharge (m3/s)
1 800
1 600
1 400
1 200
1 000
800
600
400
200
0
0
50
100
150
200
250
300
350
400
Degree-day Factor (°C)
y = 2,91x + 600
R 2 = 0,849
Tutkaul (m3/s)
Daily discharge vs. Degree-day factor

B. Synthesis of Data Processing

Year	Qdmx (m^3/s)	DDF (Max) (°C)	Qyr (m^3/s)	DDF (Year) (°C)	P(Oct/May) (mm)	Equation	R^2	Slope (°C/m^3/s)	Intercept (m^3/s)
1940	1 640	333	527	1 052	779	y=3,36x+513	0,845	3,36	513
1941	2 520	402	735	1 248	969	y=2,90x+911	0,627	2,90	911
1942	2 690	409	782	1 066	933	y=4,20x+652	0,849	4,20	652
1943	2 320	306	683	947	873	y=4,23x+744	0,850	4,23	744
1944	2 988	732	679	1 194	794	y=2,47x+577	0,887	2,47	577
1945	2 330	475	715	1 054	840	y=2,83x+940	0,814	2,83	940
1946	1 860	630	622	1 120	668	y=1,27x+759	0,797	1,27	759
1947	1 760	472	531	1 068	679	y=1,39x+650	0,684	1,39	650
1948	2 430	483	696	1 020	951	y=2,74x+807	0,882	2,74	807
1949	2 380	510	786	883	1 208	y=3,22x+968	0,762	3,22	968
1950	1 840	577	597	1 035	492	y=1,67x+773	0,843	1,67	773
1951	1 670	506	537	878	776	y=1,51x+756	0,432	1,51	756
1952	2 400	455	735	987	1 204	y=2,92x+930	0,833	2,92	930
1953	3 500	380	720	1 012	1 012	y=4,93x+830	0,801	4,93	830
1954	1 910	425	719	793	1 264	y=2,32x+904	0,637	2,32	904
1955	1 820	661	580	929	672	y=1,54x+756	0,677	1,54	756
1956	2 590	626	723	1 229	956	y=2,79x+752	0,854	2,79	752
1957	1 600	321	490	791	739	y=2,42x+678	0,693	2,42	678
1958	3 200	372	728	904	1 142	y=5,92x+727	0,927	5,92	727
1959	2 660	307	715	1 196	890	y=5,00x+577	0,819	5,00	577
1960	2 720	350	640	971	737	y=5,36x+585	0,943	5,36	585
1961	2 120	703	586	1 163	640	y=1,72x+573	0,735	1,72	573
1962	1 530	338	527	874	1 021	y=2,91x+600	0,849	2,91	600
1963	1 760	253	591	949	813	y=4,65x+505	0,925	4,65	505
1964	2 420	310	658	861	837	y=5,09x+809	0,908	5,09	809
1965	1 900	485	517	927	639	y=2,17x+619	0,785	2,17	619
1966	2 670	177	665	930	948	y=11,1x+630	0,899	11,10	630
1967	1 830	450		971	801	y=1,02x+968	0,190	1,02	968
1968	2 230	308	646	971	711	y=4,08x+671	0,778	4,08	671
1969	2 770	448	883	883	1 533	y=2,85x+1329	0,657	2,85	1 329
1970					765				
1971	2 300	685	608	1 126	619	y=1,74x+636	0,644	1,74	636
1972	1 630	433	506	755	838	y=1,47x+656	0,441	1,47	656
1973	2 810	525	763	1 197	994	y=3,05x+929	0,752	3,05	929
1974	1 760	475	475	869	536	y=2,84x+376	0,839	2,84	376
1975	2 100	395	553	1 081	744	y=2,65x+624	0,591	2,65	624
1976	1 480	521	462	1 102	777	y=0,42x+831	0,130	0,42	831
1977	1 860	488	600	1 156	680				
1978	2 530	384	695	1 202	869	y=7,05x+11	0,957	7,05	11
1979	1 770	445	612	1 071	768	y=2,77x+330	0,785	2,77	330
1980	1 930	579	671	1 150	917	y=1,26x+722	0,716	1,26	722

Item	Qdmx	DDF (Max)	Qyr	DDF (Year)	P(Oct/May)	R^2	Slope	Intercept
N	40	40	39	40	41	39	39	39
M	2 206	453	640	1 015	854	0,745	3,18	708

S	492	127	98	132	206	0,185	1,97	215
Cv	0,223	0,281	0,154	0,130	0,241	0,248	0,620	0,303
Me	2 175	449	646	1 016	813	0,797	2,83	722
Max	3 500	732	883	1 248	1 533	0,957	11,10	1 329
Min	1 480	177	462	755	492	0,130	0,42	11

4.4.4. Maximisation Procedures to Obtain PMF

The next Table 10 details the relationships needed to estimate the daily peak by equations of the following form:

- Qdmx = Slope x Degree-day factor at Peak + Intercept.
- Slope = f (Degree-day factor).
- Intercept = g (Seasonal Precipitation).

In such a model, the Consultant took into account both the precipitation (responsible for available water amount) and the temperature (responsible for melt intensity) during the melt season prior to the peak of discharge. The four graphs show that the relationships are significant and that the proposed model is apt to reproduce observed daily peaks with an underestimating bias of 11%.

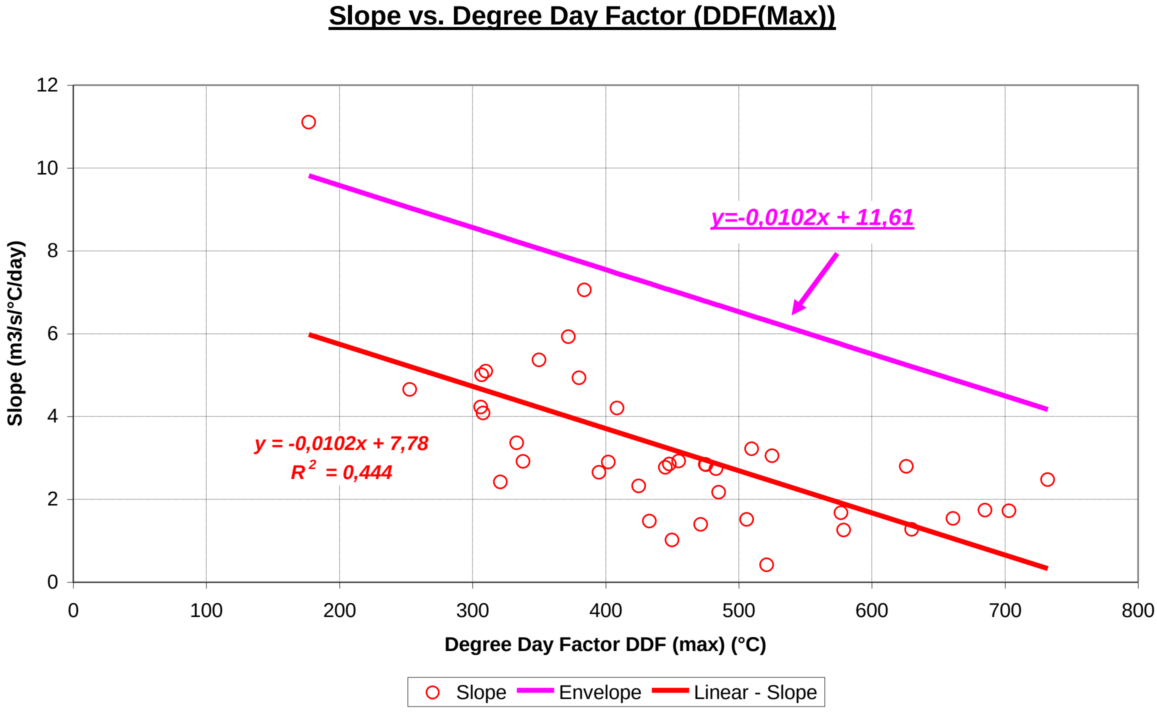
On the two first graphs, the linear correlations obtained were drawn by taking into account the set of 40 flood events. The R^2 values are about 0,42 / 0,44 which is significant although indicating a scatter of data. Lower values would have been encountered in the 2006 approach when considering the whole data set instead of three subsets. For the slope versus degree day factor, the trend is decreasing. Small degree day factor at yearly peak means early flood and a larger slope (i.e. a larger amount of m^3/s per °C/day). Large degree day at yearly peak means late flood and a smaller slope (i.e. a smaller amount of m3/s per °C/day).

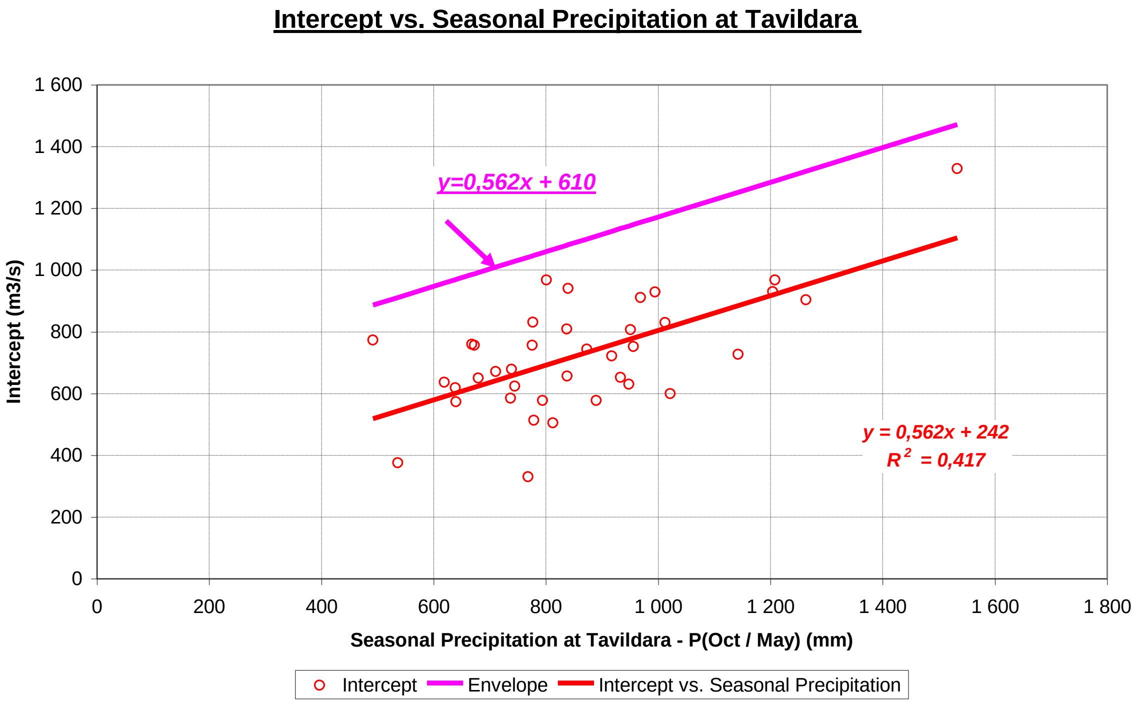
For the intercept versus seasonal precipitation, the trend is increasing. This means that bigger precipitation will provide bigger floods. In addition to the correlation lines, some envelopes were shown allowing for maximising observed events.

The third graph displays the independence between seasonal precipitation and degree day factor.

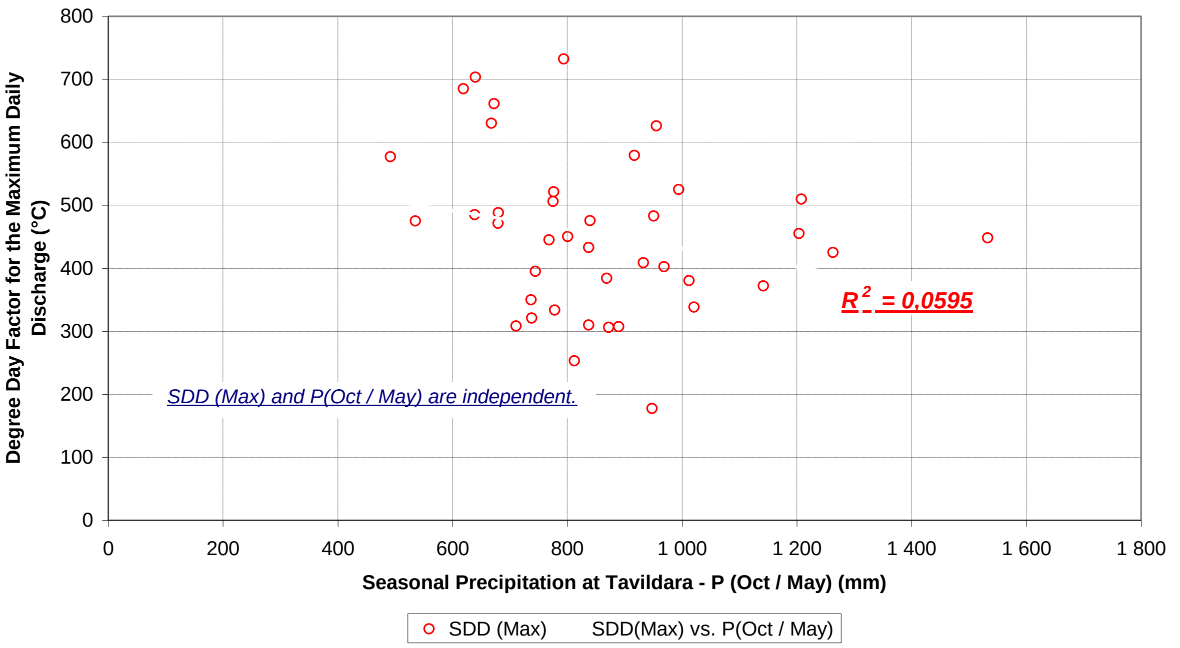
Finally, the fourth graph compares observed daily peak with computed peaks according to the 40 relations detailed in the recapitulative table. There is a good adequacy but a bias of 11% is noticeable.

Table 10 - Slope and Intercept vs. Degree-day Factor and Seasonal Precipitation

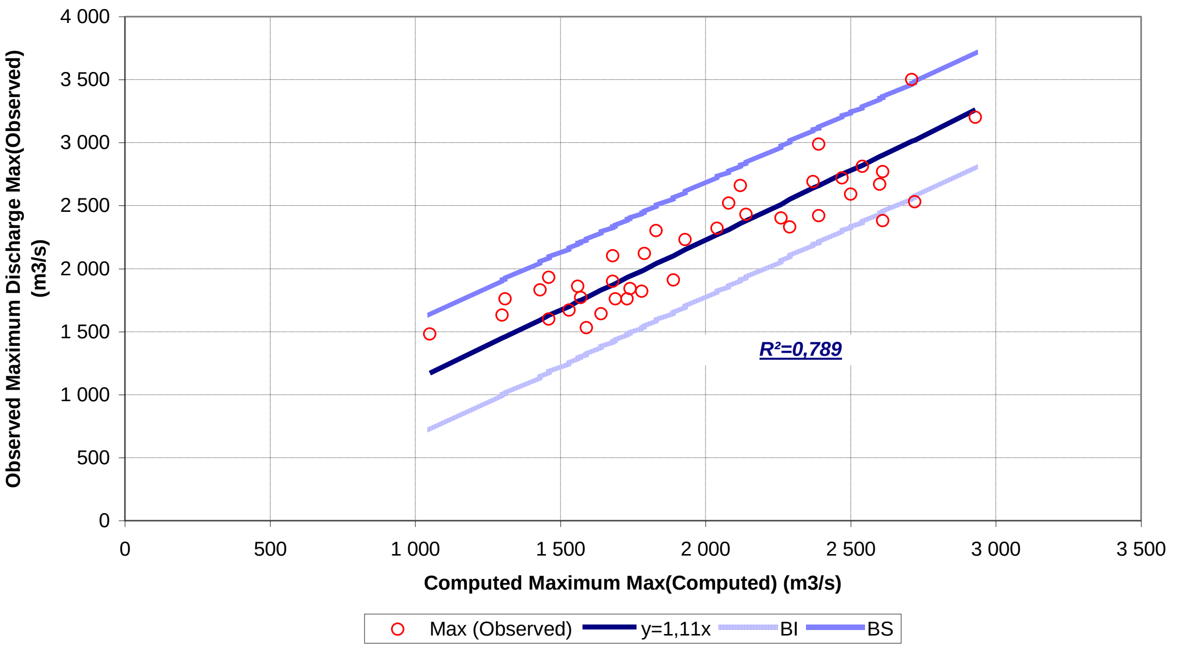




Degree Day Factor (SDD(Max)) vs. Seasonal Precipitation at Tavildara



Test of Model Adequacy



4.4.5. First Maximisation:

The Consultant proceeded to a ***first maximisation*** by considering the frequency distribution of seasonal rainfall and degree day-factor at peak. The next Table details this first maximisation.

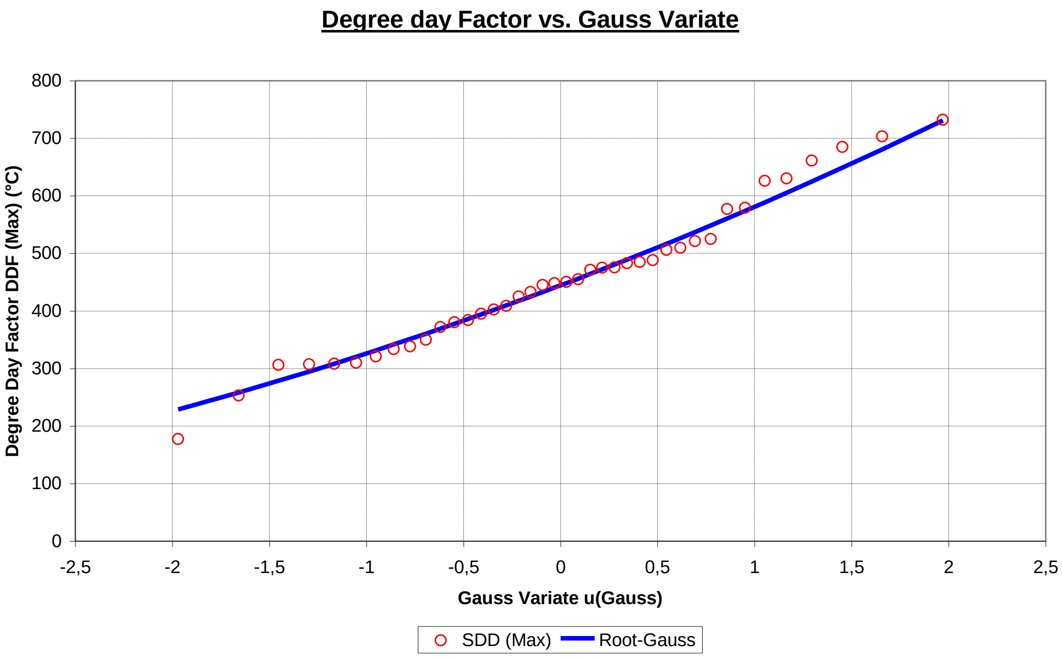
It was found that a Root-Gauss distribution was suitable for the two independent variables as shown by the two graphs. Thus it was possible to compute the slope and intersect parameters for extreme degree-day factors and extreme seasonal precipitation. This computation is summarised by part B in which the frequency domain varies from 0,90 to 0,9999. Such a scatter is consistent since it was shown that seasonal precipitation and degree day factors are independent.

From 10 realisations of intercept and 10 realisations of the product (slope x degree day factor), the Consultant deduced 100 flood peaks candidates for PMF. Part C details this first maximisation.

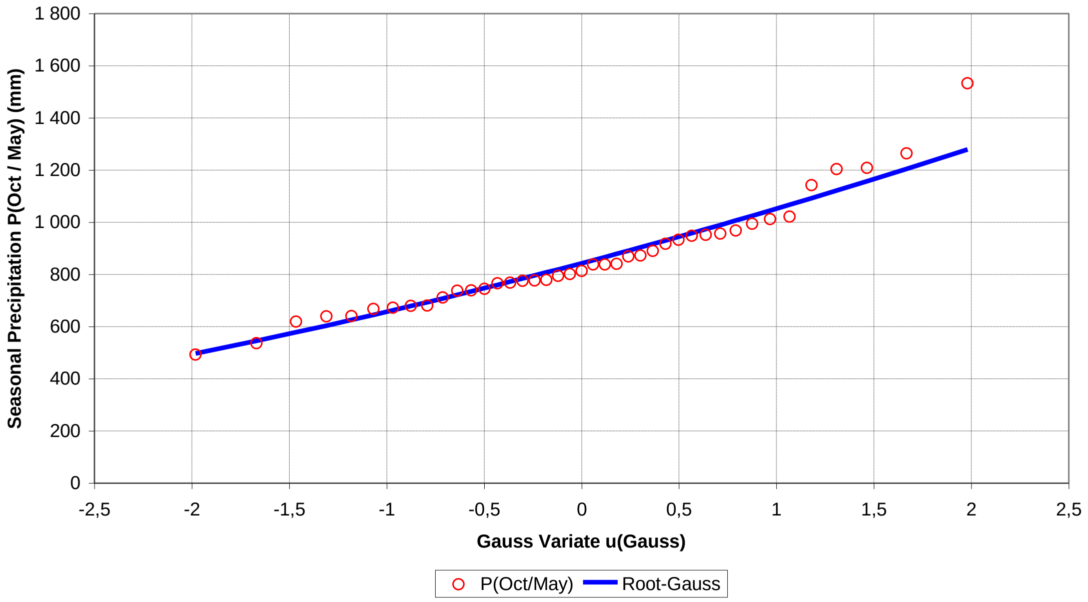
By this first approach, the PMF amounts to 6 710 m3/s that is 1,92 times the maximum observed daily peak of 3 500 m3/s.

Table 11 - First Maximisation - Using Frequency Distributions

A. Frequency Distribution for Degree-Day Factor and for Seasonal Precipitation



Seasonal Precipitation at Tavildara vs. Gauss Variate



B. Intercept and Slope vs. Frequency

Fr	u(Gauss)	P(Oct/May) (mm)	Intercept (m^3/s)	DDF(Max) (°C)	Slope (m^3/s)	Product (m^3/s)
0,9000	1,2816	1 115	1 237	623	5,26	3 274
0,9500	1,6449	1 199	1 284	679	4,69	3 181
0,9800	2,0537	1 298	1 339	745	4,01	2 989
0,9900	2,3263	1 365	1 377	790	3,55	2 804
0,9950	2,5758	1 429	1 413	833	3,55	2 957
0,9980	2,8782	1 508	1 457	887	3,55	3 147
0,9990	3,0902	1 564	1 489	926	3,55	3 284
0,9995	3,2905	1 619	1 520	963	3,55	3 416
0,9998	3,5401	1 688	1 558	1 010	3,55	3 584
0,9999	3,7190	1 738	1 587	1045	3,55	3707

C. First Maximisation

	Intercept									
Product	*1 237*	*1 284*	*1 339*	*1 377*	*1 413*	*1 457*	*1 489*	*1 520*	*1 558*	*1 587*
3 274	5 010	5 060	5 130	5 170	5 210	5 260	5 290	5 330	5 370	5 400
3 181	4 910	4 960	5 020	5 060	5 100	5 150	5 190	5 220	5 270	5 300
2 989	4 700	4 750	4 810	4 850	4 890	4 940	4 980	5 010	5 050	5 080
2 804	4 490	4 540	4 600	4 650	4 690	4 740	4 770	4 800	4 850	4 880
2 957	4 660	4 710	4 770	4 820	4 860	4 900	4 940	4 970	5 020	5 050
3 147	4 870	4 920	4 980	5 030	5 070	5 120	5 150	5 180	5 230	5 260
3 284	5 020	5 080	5 140	5 180	5 220	5 270	5 300	5 340	5 380	5 410
3 416	5 170	5 220	5 280	5 330	5 370	5 410	5 450	5 480	5 530	5 560
3 584	5 360	5 410	5 470	5 510	5 550	5 600	5 640	5 670	5 710	5 740
3 707	5 490	5 550	5 610	5 650	5 690	5 740	5 770	5 810	5 850	5 880

(m^3/s)

Item	Result	Result/ 3 500
n	100	
M	5 178	1,48
S	323	
Cv	0,062	
Me	5 170	1,48
Max	5 880	1,68
Min	4 490	1,28
PMF (daily)	*6 390*	*1,83*
PMF (peak)	*6 710*	*1,92*
	(m^3/s)	

4.4.6. Second Maximisation:

For the second maximisation, the Consultant made use of the envelope curves defined for slope and intercept parameters. The associated Table discloses that a daily PMF of 5 830 m^3/s is obtained whereas the upper bound for PMF is 7 130 m^3/s. Part A lists the 40 flood events considered. In this table the input data is recalled (DDF and P), the envelope parameters (slope and intercept) together with observed and maximised daily peaks. Part B gives the results of the second maximisation. On the basis of the mean maximised daily peak (4 433 m^3/s) and its standard deviation (374 m^3/s), it was found that a daily PMF of 5 830 m^3/s is acceptable. Making use of the ratio 5 830 / (Observed daily peak), a possible upper bound of 6 790 m^3/s for the daily peak was derived.

Table 11: Second Maximisation - Using 40 Flood Events

A. Table of Observed and Maximised Events

	Input Data		Envelope Parameters		Daily Peaks		Ratios	
Year	DDF(Max)	P(Oct/May)	Slope-max	Intercept-max	Observed	Maximised	Maxim./Obs	5830/Qdmx
	(°C)	(mm)	(m^3/s/°C)	(m^3/s)	(m^3/s)	(m^3/s)		
1953	380	1 012	7,73	1 179	3 500	4 450	1,27	1,67
1958	372	1 142	7,82	1 252	3 200	4 480	1,40	1,82
1944	732	794	4,14	1 056	2 988	4 430	1,48	1,95
1973	525	994	6,26	1 169	2 810	4 820	1,72	2,07
1969	448	1 533	7,04	1 471	2 770	4 980	1,80	2,10
1960	350	737	8,04	1 024	2 720	4 150	1,53	2,14
1942	409	933	7,44	1 134	2 690	4 520	1,68	2,17
1966	177	948	9,80	1 143	2 670	3 070	1,15	2,18
1959	307	890	8,48	1 110	2 660	4 000	1,50	2,19
1956	626	956	5,22	1 147	2 590	4 780	1,85	2,25
1978	384	869	7,69	1 098	2 530	4 380	1,73	2,30
1941	402	969	7,51	1 154	2 520	4 510	1,79	2,31

1948	483	951	6,68	1 144	2 430	4 730	1,95	2,40
1964	310	837	8,45	1 081	2 420	3 990	1,65	2,41
1952	455	1 204	6,97	1 287	2 400	4 810	2,00	2,43
1949	510	1 208	6,41	1 289	2 380	4 920	2,07	2,45
1945	475	840	6,76	1 082	2 330	4 650	2,00	2,50
1943	306	873	8,49	1 100	2 320	3 990	1,72	2,51
1971	685	619	4,62	958	2 300	4 480	1,95	2,53
1968	308	711	8,47	1 009	2 230	3 910	1,75	2,61
1961	703	640	4,44	970	2 120	4 440	2,09	2,75
1975	395	744	7,58	1 028	2 100	4 360	2,08	2,78
1980	579	917	5,70	1 125	1 930	4 800	2,49	3,02
1954	425	1 264	7,28	1 320	1 910	4 760	2,49	3,05
1965	485	639	6,66	969	1 900	4 560	2,40	3,07
1946	630	668	5,18	985	1 860	4 620	2,48	3,13
1977	488	680	6,63	992	1 860	4 590	2,47	3,13
1950	577	492	5,72	886	1 840	4 560	2,48	3,17
1967	450	801	7,02	1 060	1 830	4 570	2,50	3,19
1955	661	672	4,87	988	1 820	4 560	2,51	3,20
1979	445	768	7,07	1 042	1 770	4 540	2,56	3,29
1947	472	679	6,80	992	1 760	4 560	2,59	3,31
1963	253	813	9,03	1 067	1 760	3 610	2,05	3,31
1974	475	536	6,77	911	1 760	4 480	2,55	3,31
1951	506	776	6,45	1 046	1 670	4 670	2,80	3,49
1940	333	779	8,21	1 048	1 640	4 090	2,49	3,55
1972	433	838	7,19	1 081	1 630	4 540	2,79	3,58
1957	321	739	8,34	1 025	1 600	4 000	2,50	3,64
1962	338	1 021	8,16	1 184	1 530	4 250	2,78	3,81
1976	521	777	6,30	1 047	1 480	4 690	3,17	3,94

	Input Data		Envelope Parameters		Daily Peaks		Ratios	
Year	**DDF(Max)**	**P(Oct/May)**	**Slope-max**	**Intercept-max**	**Observed**	**Maximised**	**Maxim./Obs**	**5830/Qdmx**
	(°C)	(mm)	($m^3/s/°C$)	(m^3/s)	(m^3/s)	(m^3/s)		
N	40	40	40	40	40	40	40	40
M	453	857	6,99	1 091	2 206	4 433	2,11	2,77
S	127	208	1,30	117	492	374	0,48	0,59
Cv	0,281	0,243	0,186	0,107	0,223	0,084	0,229	0,214
Me	449	825	7,03	1 074	2 175	4 530	2,06	2,68
Max	732	1 533	9,80	1 471	3 500	4 980	3,17	3,94
Min	177	492	4,14	886	1 480	3 070	1,15	1,67

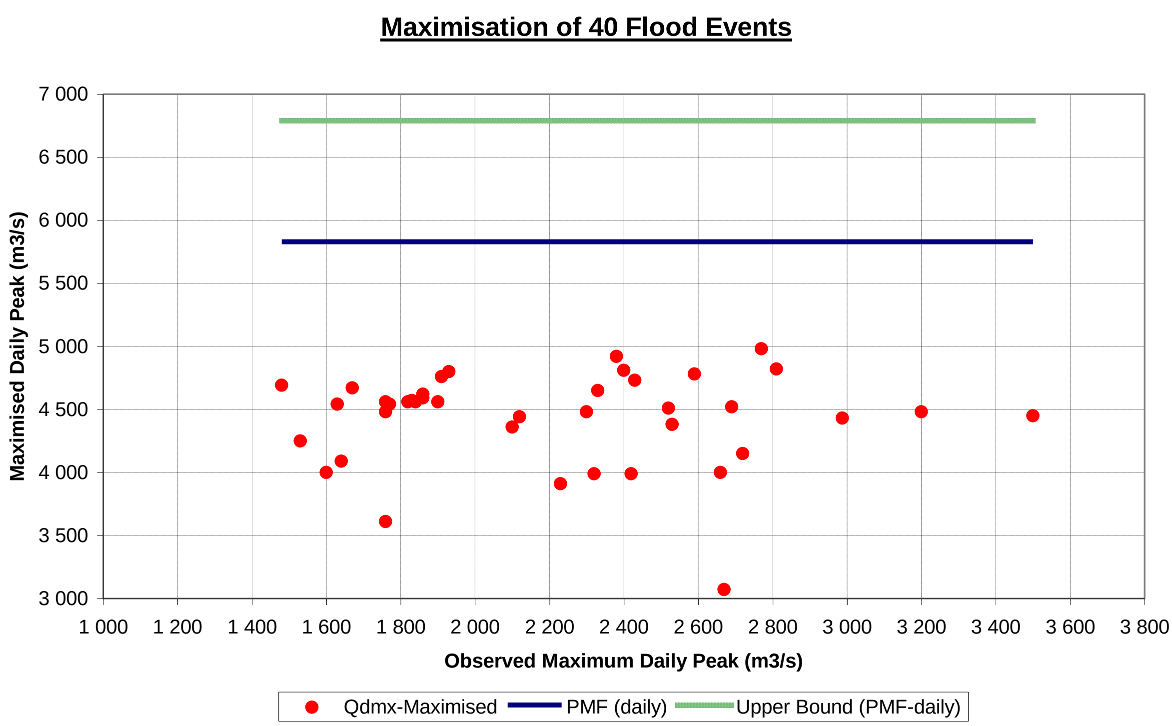
B. Results of Second Maximisation

1. Using 40 maximised events
PMF (daily) 5 830 m3/s
Defined by PMF= 4433 + 3,72 x 374
PMF (peak) 6 130 m3/s

2. Upper bound on PMF
PMF (daily) 6 790 m3/s
Defined by PMF = 2,77 x 1,11 x 2 206 (1)
PMF (peak) 7 130 m3/s

(1) – 2.77 is the mean 5830/Qdmx ratio, 2 206 is the mean daily peak observed and 1.11 is the bias (see § 31)

C. Illustration of Second Maximisation



4.4.7. *Third Maximisation:*

The third maximisation corresponds to a hypothetical case for which degree day and seasonal precipitation are linked. For this, the Consultant adopted a rank correlation approach.

In this approach, the Consultant defined a multiple correlation between daily peak discharge as a dependent variable and degree day factor together with seasonal rainfall as independent variables, but after having ranked separately the three samples (DDF, Qdmx and P(Oct/May)) in ascending order.

The following equation was obtained:

Qdmx = 1,165 x P(Oct/May) + 1,903 x DDF + 345. (R^2=0;956).

This formula was applied for several values o DDF and P(Oct / May) providing estimates of maximised daily discharges. Next Table details the third maximisation. It shows successively the graphical description of the initial samples, the table of maximised daily peaks and the final results.

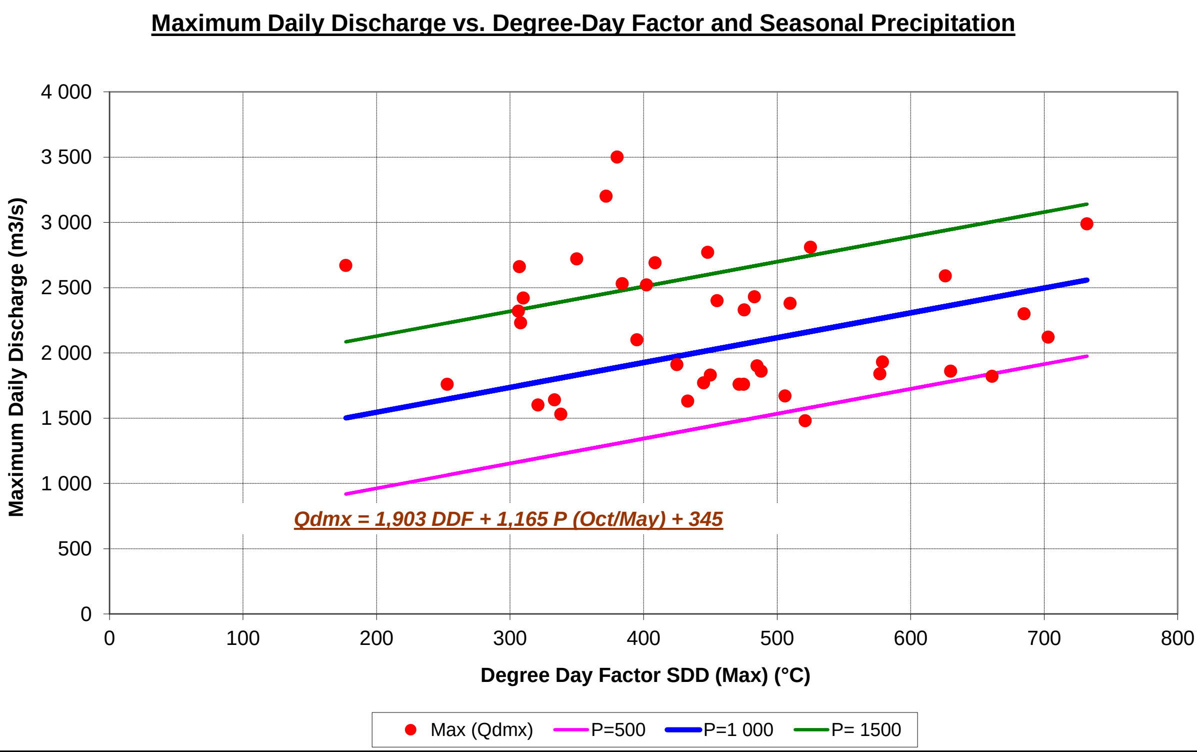
The first graph displays the relationship (presented for P = 500, 1 000 and 1 500 mm) together with the real set of data (DDF and Qdmx values).

The second graph shows the ranked values allowing for finding the model equation. Table B gives 5 PMF candidates based on extreme events.

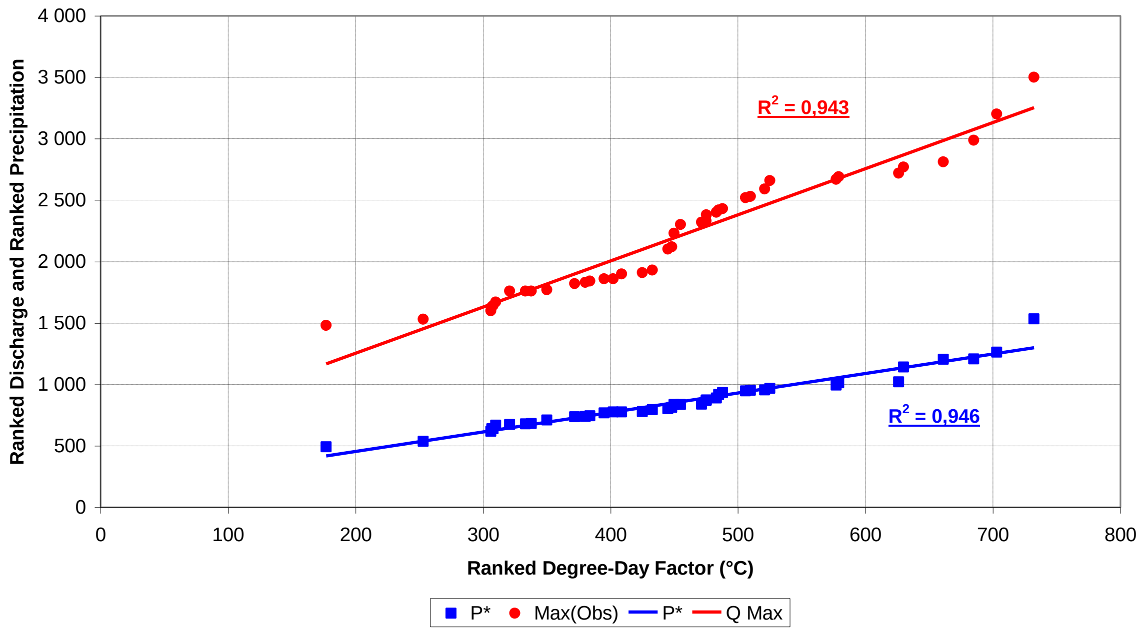
Table B gives also our estimate of PMF (daily PMF = 5 600 m^3/s and instantaneous PMF = 5 880 m^3/s).

Table 12:Third Maximisation - Station Year Approach

A. Graphical Display of multiple correlation on Ranked values (2 graphs)



Data for Ranked Correlation



TB. Table of Maximised DailyFloods (m3/s)

T (years)	Pseas (mm)	SDD (°C)	Qdmax (m3/s)
10 000	1 738	1 045	4 360
20 000	1 787	1 079	4 480
50 000	1 850	1 122	4 640
100 000	1 896	1 154	4 760
200 000	1 942	1 186	4 870
500 000	2 000	1 226	5 010
1 000 000	2 044	1 257	5 120

N	5
M	4 880
S	191
Cv	0,039
Me	4 870
Max	5 120
Min	4 640
PMF (daily)	5 600
PMF (peak)	*5 880*

4.4.8. PMF Choice and PMF Hydrograph

Computation of flood hydrographs is based on three major observed floods at Tutkaul. These floods are:

- July 1953 the largest flood recorded on the Vakhsh, with daily discharge of 3500 m3/s and a peak discharge of 3730 m3/s. Note that first estimation of peak discharge was 4290 m3/s but was recalculated in 1978 for Rogun Project Report by Hydroproject (1978),
- July 1958, with a daily discharge of 3250 m3/s,
- July 1969, with a daily discharge of 2800 m3/s, but this flood is the major event in terms of volume recorded on the Vakhsh.

The choice of an a-dimensional hydrograph shape was made in order to combine the aspect of flood peaking issued from July 1953 and July 1958, and flood volume from July 1969. The peak coefficient was derived from observed discharge made in July 1953, and equals 1.05.

The following Table summarises the obtained results and the choice of PMF together with a plot of the PMF hydrograph. In part A the various PMF estimates were ranked in ascending order. The rank correlation (third maximisation) is the smallest estimate (5 600 m^3/s) followed by the maximisation of 40 floods (second maximisation, 5 830 m^3/s). The frequency approach (first maximisation) arrives at the third place with a daily peak of 6 390 m^3/s. As shown in the observation column, these three estimates are within the domain of the 10 000 year flood. Thus, they are discarded for the choice of PMF.

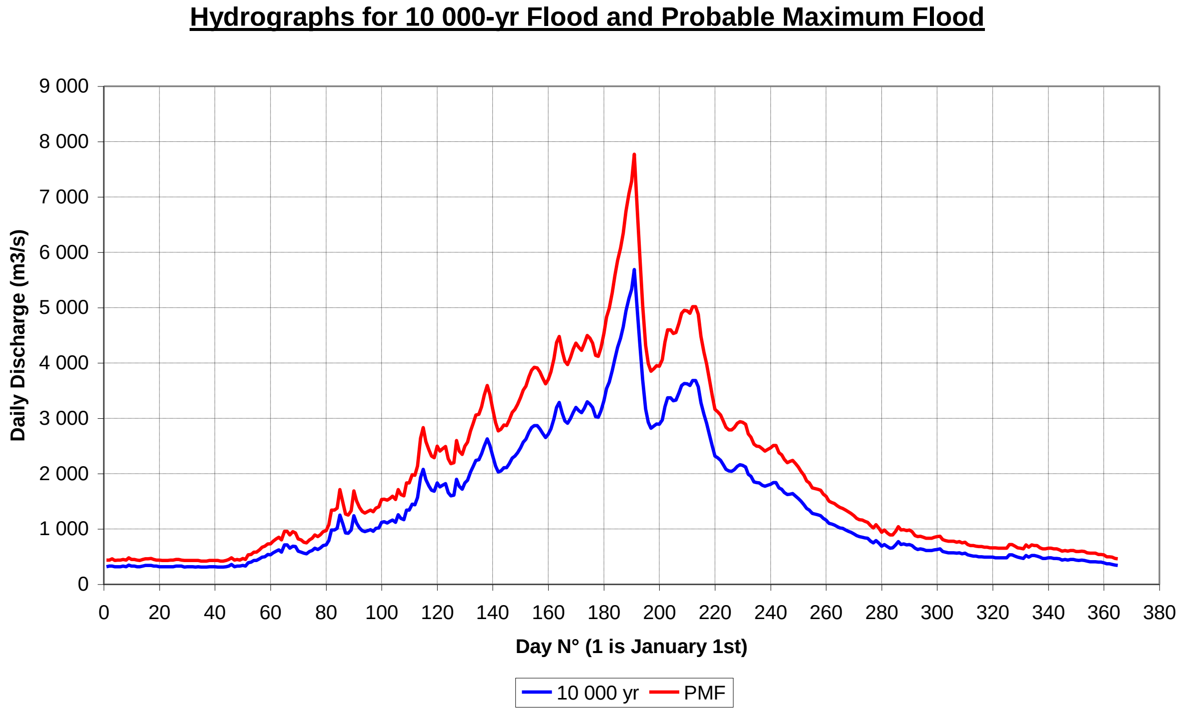
The upper bound of the maximisation of 40 floods together with the PMF estimate of 2006 are retained. They provide a mean value of 6 950 m^3/s associated to a standard deviation of 220 m^3/s. These results lead to recommend a daily PMF of 7 770 m^3/s associated to an instantaneous peak of 8 160 m^3/s.

Table 13: PMF Choice and PMF Hydrograph

A. PMF Choice

Approach	PMF (daily) (m^3/s)	PMF (peak) (m^3/s)	Peak / 5 970	Observations
Ranked Correlation (3rd maxim.)	5 600	5 880	0,98	Domain
Maximisation of 40 floods (2nd maxim.)	5 830	6 130	1,03	of the
Frequency approach (1st maxim)	6 390	6 710	1,12	10 000 yr flood
2nd maxim.- Upper Bound	6 790	7 130	1,19	Retained
2006 – approach (Lahmeyer)	7 100	7 460	1,25	Retained
M	6 950			Of retained values
S	220			Of retained values
Proposed PMF: M+3,72S	**7 770**	**8 160**	**1,42**	

B. PMF Hydrograph



5. CLIMATE CHANGE

The Consultant tried to develop its own approach based on trend analysis of historical data as well as available literature on Climate Change in Central Asia and Tajikistan. Even if downscaling of climate models to local conditions is still subject to lot of uncertainties, this approach of confronting deducted trends to global models results was found useful in order to define potential scenarios.

The study was therefore conducted in the following steps:

- Firstly an analysis of the observed trends concerning the period 1930 / 2010 for precipitation, discharge, and temperatures. The correlations found are not fully convincing, but some trend for increased precipitation and discharges could be assumed. Concerning temperatures at Anzob Pass and Tavildara, there is no significant trend. For Gorbunov (Fedchenko Glacier), an increase of 0,5°C per 100 years is noticeable but linked to a weak R^2 (0,190). It is however in the same order of magnitude as existing models.

- Thereafter, a review of the literature quoted in the reference list was made to obtain a general understanding of the current status of Climate Change predictions in Central Asia and Tajikistan. It became obvious from the extensive records that glacier melt was an important issue, and a recorded fact based on a close monitoring of Glaciers in Central Asia. Data enclosed in Aral Sea depletion studies indicate that as per projections, in 2080 / 2100, the glaciers feeding Aral Sea could disappear. Studies carried out by Tajik institutes clearly show that the glaciers are receding.

- It was therefore found of interest to carry out a specific analysis about glacier vanishing and try to evaluate its impact on Vakhsh river regime. After this specific study about the vanishing of glacier, the Consultant tried to make an assessment of the evolution of Vakhsh discharges under the assumption of a discharge increasing trend (at same level as the historical trend) associated to an ice feeding reduction due to temperature increase as suggested by the Climate Models.

5.1 Data for Climate Change Analysis

Data for climate change study is either included in the main text or in the supporting documents. These data have been taken from previous reports, from data provided by the Client or data found in the existing literature (see references).

The main inputs for this climate change study are:

- For Trend Analysis: Yearly and seasonal discharges; yearly temperatures; yearly precipitations (1932/2010)
- For Climate Forecasts: Increase / Decrease of temperature as given by several climate models. Percentage change of precipitation as given by several climate models. Forecast about glacier melts as given by several researchers about Central Asia and Aral Sea Basin (see reference list).

5.2 Trend Analysis of Precipitation, Temperature and Discharge

5.2.1 Trend Analysis of Precipitation

The following Table 4 presents the results of our trend analysis for precipitation. It consists of three tables and five graphs. Part A details the available data concerning five rain gauges: Racht, Altynmazar, Komsomolabad and Tavildara. Part B illustrates the graphs of precipitation time series. The trends were computed using the 5-year moving averages. The R^2 values are often rather weak, but trends can be assessed from the observed data. Part C presents the results and gives a forecast of average precipitation and yearly discharge until 2100. If precipitation trends are not modified, the rainfall and runoff could increase by about **15% by 2100.** Such increase is in line with a temperature increase resulting in a more humid atmospheric column. As it will be detailed in the general review of existing climate change models, precipitation trends are difficult to determine and still subject to a large uncertainty. Consequently, a no change option is still the most prudent scenario to be considered for precipitation trend forecast.

Table 14: Trend Analysis of Precipitation Data

A. Yearly Precipitation Data

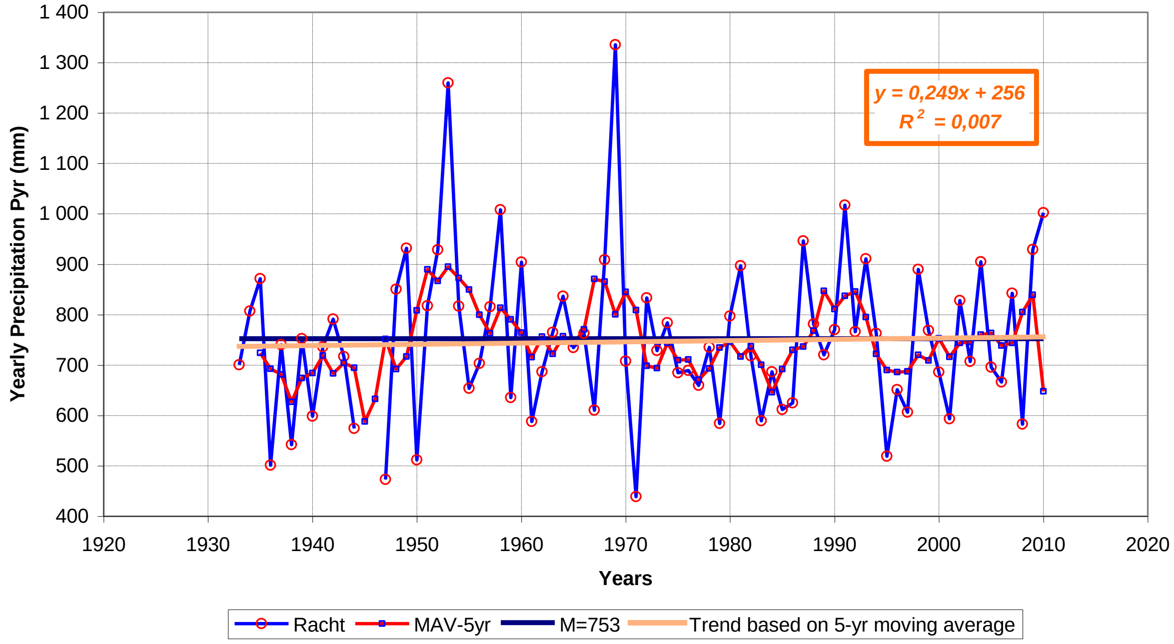
Year	Racht	Altynmazar	Komsomolabad	Anzob	Tavildara
1933	700	***157***			620
1934	807	91			1 035
1935	872	155			***1 047***
1936	501	128			***642***
1937	741	185			***944***
1938	***542***	106			***661***
1939	***753***	119			***946***
1940	599	120		***268***	790
1941	736	157		248	910
1942	791	155		349	1 045
1943	717	145		285	1 012
1944	***574***	117		230	724
1945		195		263	921
1946		154		259	***630***
1947	***473***	94		271	***654***
1948	851	180	***1 008***	313	***1 150***
1949	932	247	***1 136***	318	1 179
1950	512	84	***675***	270	568
1951	***817***	233	***941***	595	1 001
1952	929	139	***1 176***	528	1 065
1953	1 260	331	***1 376***	572	1 480
1954	817	213	919	***457***	978
1955	654	115	***865***	266	855
1956	703	133	***864***	216	806
1957	816	177	***1 028***	511	1 050
1958	1 008	223	***1 129***	498	1 186
1959	635	***109***	***709***	***514***	839
1960	904	172	869	510	842
1961	588	123	***758***	384	714
1962	686	131	887	511	***1 056***
1963	765	144	887	739	781
1964	837	194	758	482	918
1965	735	168	872	382	848
1966	763	212	964	470	1 088
1967	611	119	811	354	809
1968	909	167	1 038	451	943
1969	1 336	240	1 539	590	1 525
1970	708	150	838	491	771
1971	439	88	590	230	580
1972	833	171	973	529	959
1973	729	177	868	443	***893***
1974	784	167	814	***500***	825
1975	685	111	751	505	791
1976	690	179	901	518	842
Year	**Racht**	**Altynmazar**	**Komsomolabad**	**Anzob**	**Tavildara**
1977	660	174	797	520	914

1978	736	143	891	534	817
1979	584	153	***767***	456	718
1980	797	159	***937***	468	***1 048***
1981	897	187	***1 116***	527	1 120
1982	718	168	870	542	843
1983	589	122	680	470	***765***
1984	687	142	999	464	***1 102***
1985	612	165	805	438	943
1986	625	157	***786***	411	855
1987	946	261	1 081	548	1 357
1988	781	224	870	466	1 031
1989	720	145	***758***	478	948
1990	770	138	970	509	922
1991	1 018	257	***1 266***	728	1 336
1992	***766***	150		571	1 107
1993	***911***	269		847	1 358
1994	763	87		591	***1 012***
1995	519	***248***		***306***	656
1996	***651***			382	***807***
1997	***607***			460	***834***
1998	890			***537***	***1 482***
1999	769			462	
2000	***686***			249	
2001	593			129	
2002	828			237	
2003	707			395	
2004	905			722	
2005	696			474	
2006	667			***542***	
2007	843			***492***	
2008	583			272	
2009	929			541	
2010	1 002			***349***	
N	76	63	44	71	66
M	753	164	921	443	938
S	159	50	185	138	216
Cv	0,211	0,307	0,201	0,312	0,231
Me	736	157	879	468	919
Max	1 336	331	1 539	847	1 525
Min	439	84	590	129	568

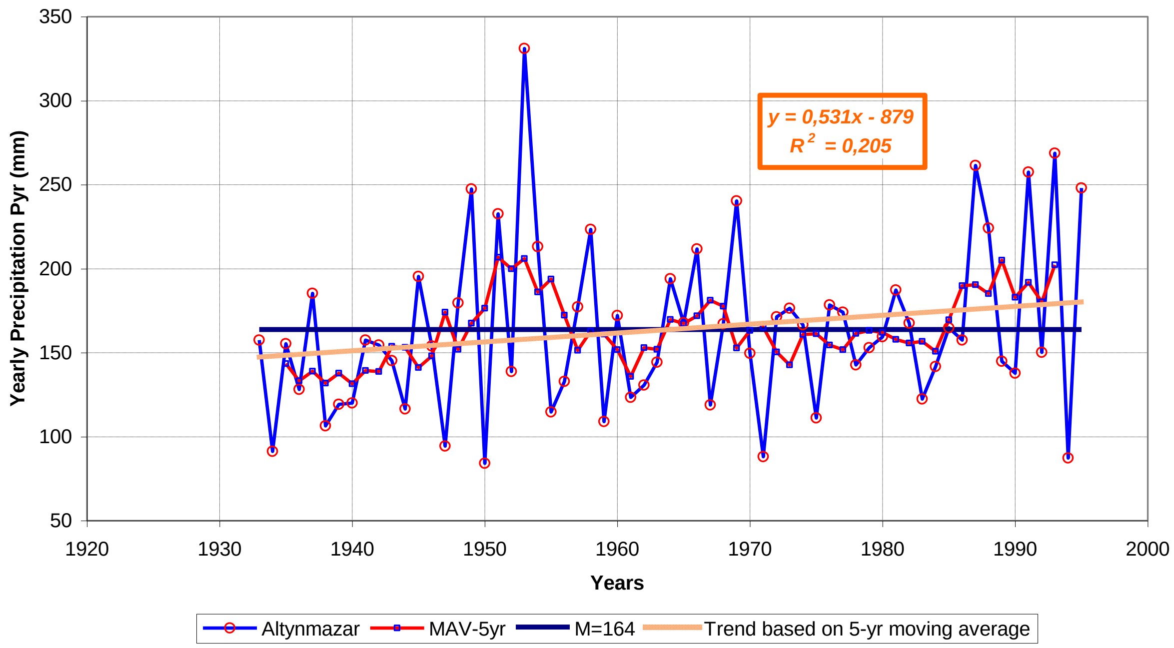
(mm/year)

B. Graphs about Precipitation Trend

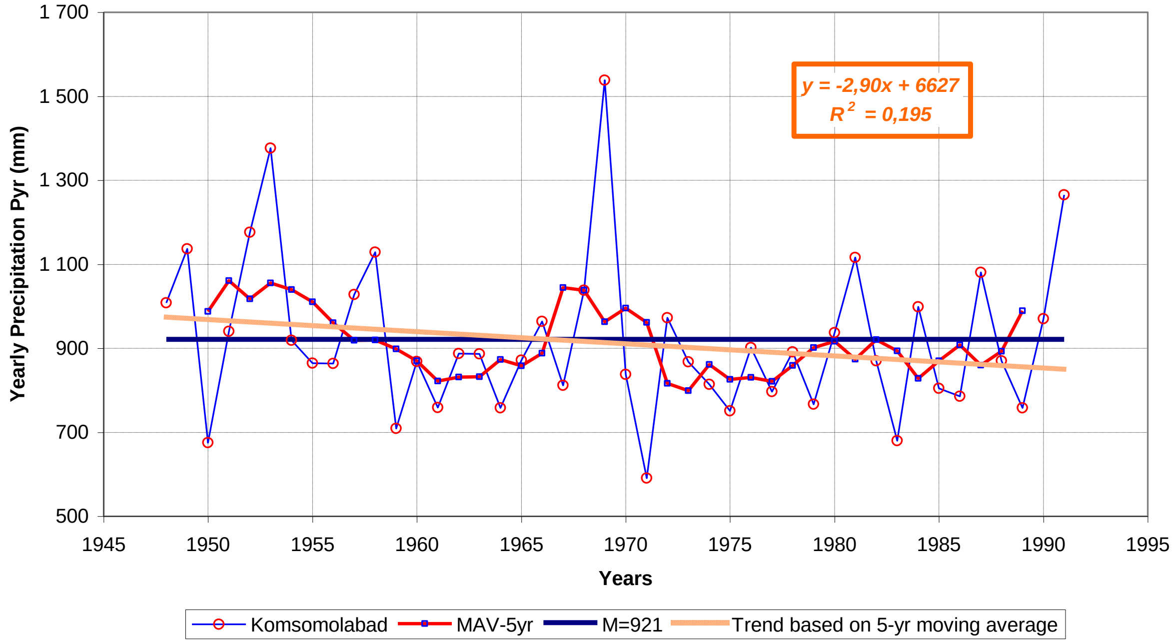
Racht - Yearly Precipitation



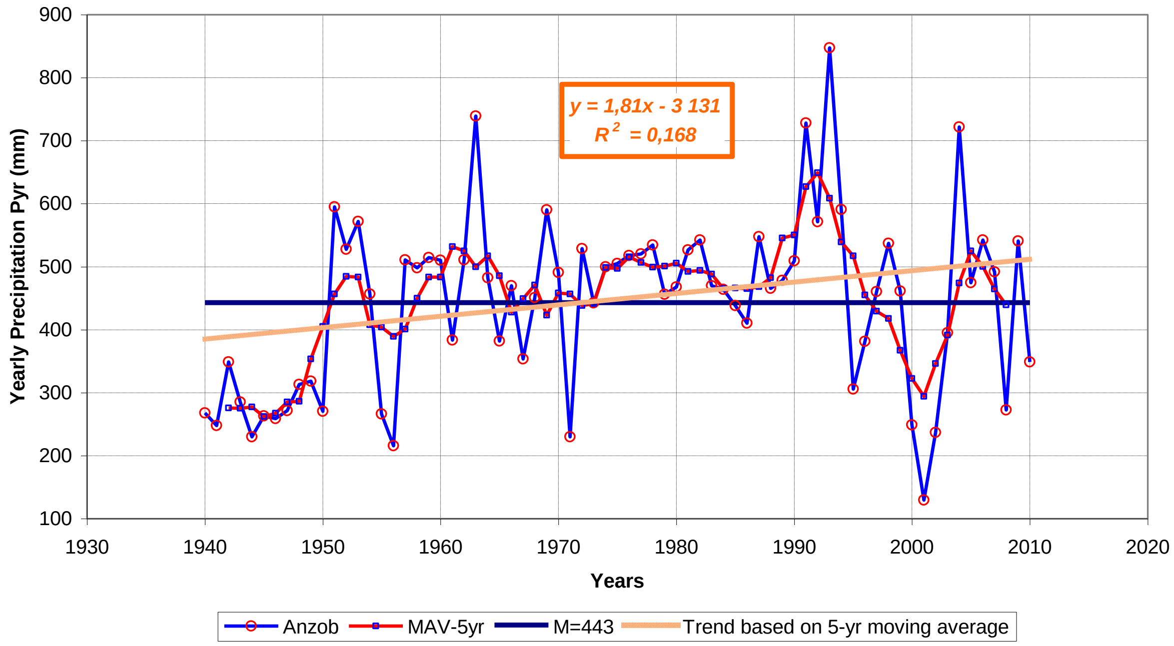
Altynmazar - Yearly Precipitation



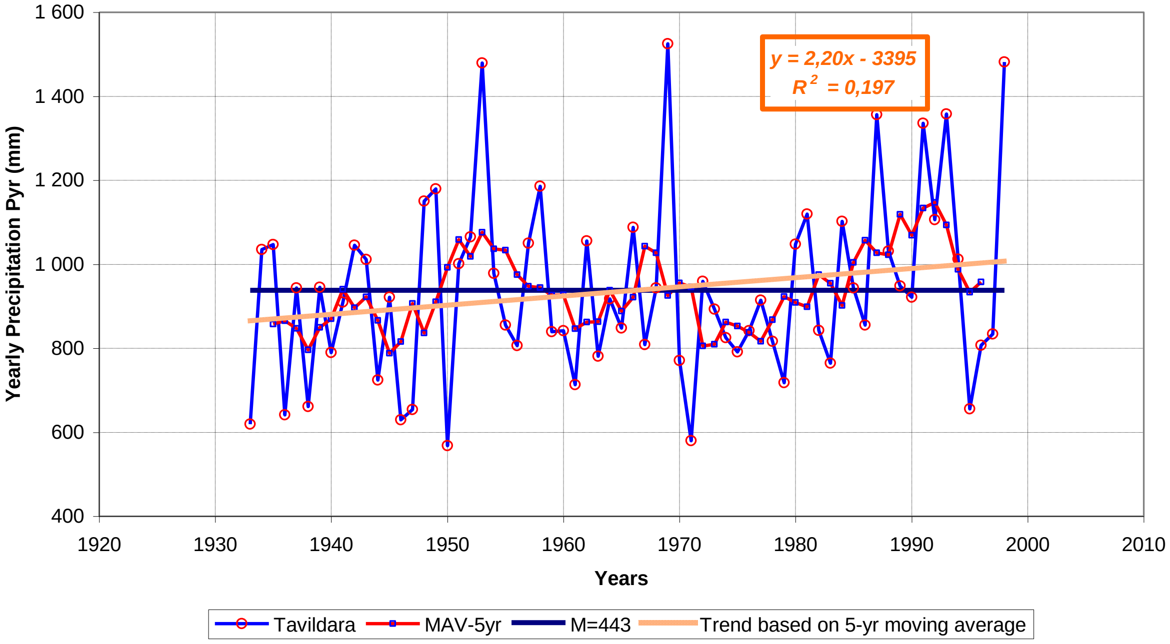
Komsomolabad - Yearly Rainfall



Anzob - Yearly Precipitation



Tavildara - Yearly Precipitation



C. Results concerning Precipitation Trend

Observed Trend

Station	Period	n	M(Pyr)	Trend (mm/yr)	Trend (%)	R²	Trend(%) x R²
Altynmazar	1933-1995	63	164	0,53	0,32	0,205	0,066
Anzob	1940-2010	71	443	1,81	0,41	0,168	0,069
Racht	1933-2010	76	753	0,25	0,03	0,007	0,000
Komsomolabad	1948-1991	44	921	-2,90	-0,31	0,195	-0,061
Tavildara	1933-1998	66	938	2,20	0,23	0,197	0,046
				Average	0,14	%	
				Regional trend	0,16	%	

Precipitation Forecast

Year	Pyr	%	Change %	Tavildara Seasonal	Qyr	%	Change
	(mm)			(mm)	(m3/s)		
2010	1 090	100,0	0,0	866	638	100,0	0,0
2015	1 099	100,8	0,8	873	643	100,8	0,8
2020	1 108	101,6	1,6	880	648	101,6	1,6
2025	1 116	102,4	2,4	887	653	102,4	2,4
2030	1 125	103,2	3,2	894	658	103,2	3,2
2035	1 134	104,1	4,1	901	663	104,0	4,0
2040	1 144	104,9	4,9	908	669	104,8	4,8
2050	1 162	106,6	6,6	923	679	106,5	6,5
2055	1 171	107,5	7,5	930	684	107,3	7,3
2060	1 181	108,3	8,3	938	690	108,1	8,1
2065	1 190	109,2	9,2	945	695	109,0	9,0
2070	1 200	110,1	10,1	953	701	109,8	9,8
2075	1 209	111,0	11,0	961	706	110,7	10,7
2080	1 219	111,8	11,8	968	712	111,6	11,6
2085	1 229	112,7	12,7	976	717	112,4	12,4
2090	1 239	113,6	13,6	984	723	113,3	13,3
2095	1 249	114,6	14,6	992	729	114,2	14,2
2100	1 259	115,5	15,5	1 000	734	115,1	15,1

5.2.2 Trend Analysis of Temperature

The analysis of temperature trend was based on three stations: Fedchenko (Gorbunov), Anzob Pass and Tavildara. These stations are in a mountainous context. Part A details the available data concerning these three stations. Part B illustrates the graphs of precipitation time series. Trends were computed using the 5-year moving averages. The R^2 values are often rather weak, but trends can be assessed for Tavildara and Fedchenko (Gorbunov). For Tavildara, the observed trend is about **0,8°C per century** and for Fedchenko (Gorbunov) it is **0,5°C per century**. These trends are much smaller than those given by the climate change models, but in a rather similar range of magnitude.

Table 15: Trend Analysis of Temperature Data

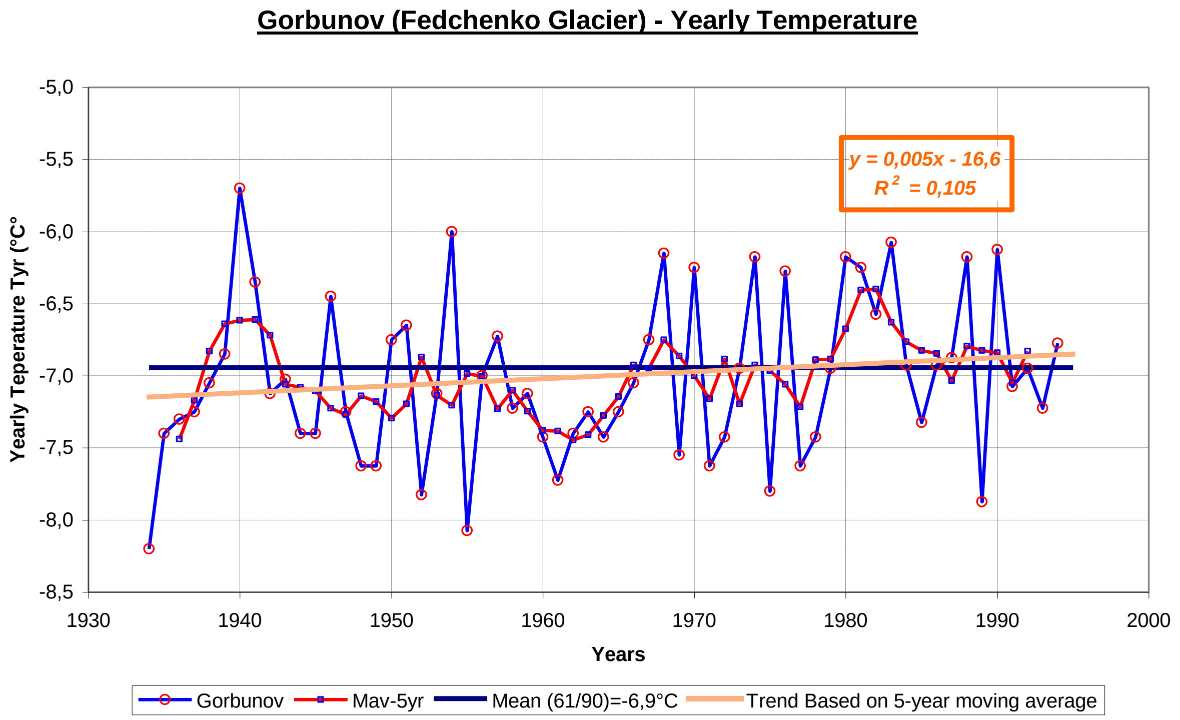
A. Yearly Temperature Data

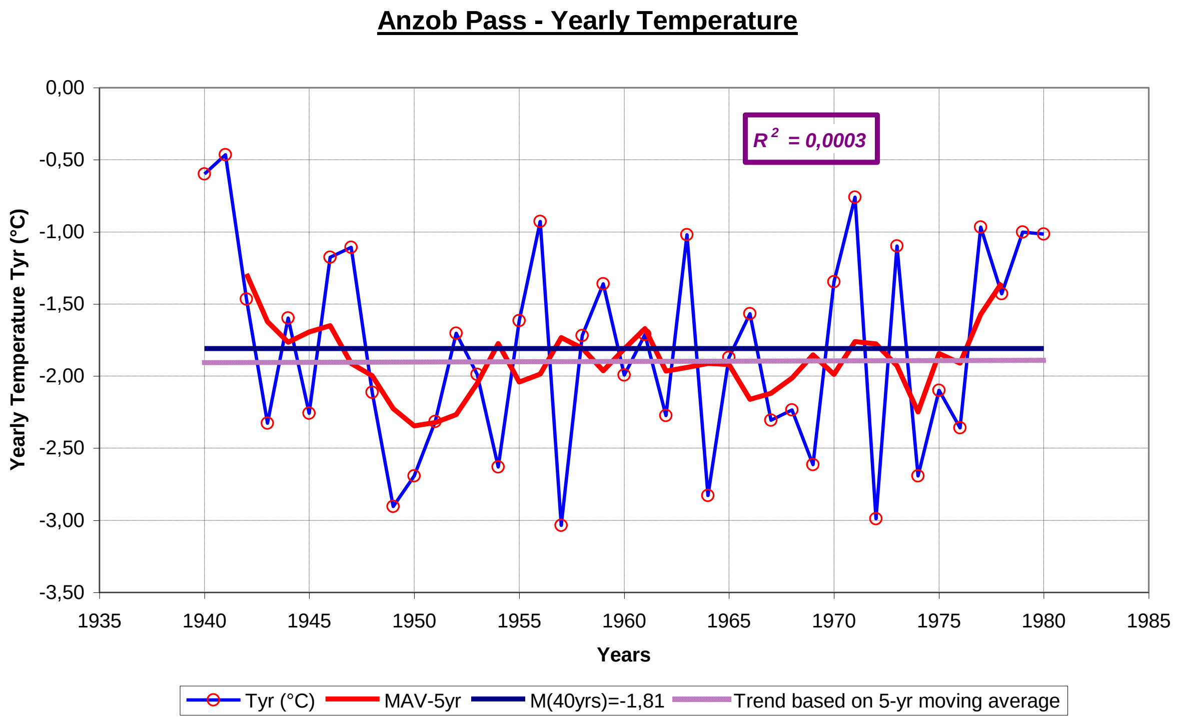
Year	Gorbunov	Anzob Pass	Tavildara
1934	-8,2		
1935	-7,4		
1936	-7,3		
1937	-7,3		
1938	-7,1		
1939	-6,9		
1940	-5,7	-0,60	
1941	-6,4	-0,46	
1942	-7,1	-1,47	
1943	-7,0	-2,33	
1944	-7,4	-1,60	
1945	-7,4	-2,26	
1946	-6,5	-1,18	
1947	-7,3	-1,11	
1948	-7,6	-2,11	
1949	-7,6	-2,90	
1950	-6,8	-2,69	
1951	-6,7	-2,31	
1952	-7,8	-1,70	
1953	-7,1	-1,99	
1954	-6,0	-2,63	
1955	-8,1	-1,62	
1956	-7,0	-0,93	
1957	-6,7	-3,04	
1958	-7,2	-1,72	
1959	-7,1	-1,36	
1960	-7,4	-1,99	
1961	-7,7	-1,71	9,1
1962	-7,4	-2,27	8,6
1963	-7,3	-1,02	9,6
1964	-7,4	-2,83	7,6
1965	-7,3	-1,87	8,8
1966	-7,1	-1,57	9,5
1967	-6,8	-2,30	8,6
1968	-6,2	-2,23	8,6
1969	-7,6	-2,61	8,0
1970	-6,3	-1,35	9,7
1971	-7,6	-0,76	10,0
1972	-7,4	-2,99	7,7
1973	-7,0	-1,10	9,6
1974	-6,2	-2,69	8,2
1975	-7,8	-2,10	8,2
1976	-6,3	-2,36	8,9
1977	-7,6	-0,97	10,5
Year	Gorbunov	Anzob Pass	Tavildara
1978	-7,4	-1,43	9,2

1979	-7,0	-1,00	9,8
1980	-6,2	-1,01	9,9
1981	-6,3		9,0
1982	-6,6		8,1
1983	-6,1		9,0
1984	-6,9		8,5
1985	-7,3		9,1
1986	-6,9		8,7
1987	-6,9		8,9
1988	-6,2		9,6
1989	-7,9		7,9
1990	-6,1		9,7
1991	-7,1		
1992	-7,0		
1993	-7,2		
1994	-6,8		
1995			
N	61	41	30
M	-7,0	-1,8	9,0
S	0,6	0,7	0,7
Cv	-0,080	-0,390	0,083
Me	-7,1	-1,7	9,0
Max	-5,7	-0,5	10,5
Min	-8,2	-3,0	7,6

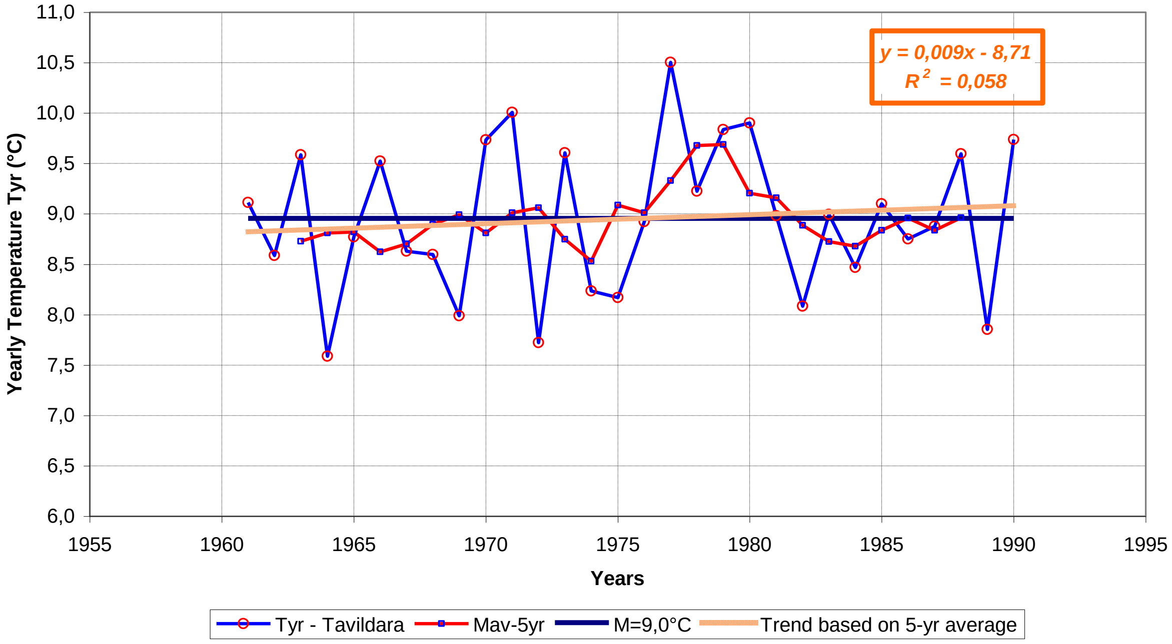
(°C)

B. Graphs about Temperature Trend





Tavildara - Yearly Temperature



5.2.3 Trend Analysis of Discharges

The following Table 16 details our trend analysis for discharges. The coefficients of correlation R^2 are rather weak. The best R^2 is obtained for the cold season discharge (base flow). An increase of discharge of about **0,26 / 0,30 m3/s/year** could be assumed. The Table presents forecast until 2100 according to these trends.

Table 16: Trend Analysis of Discharges

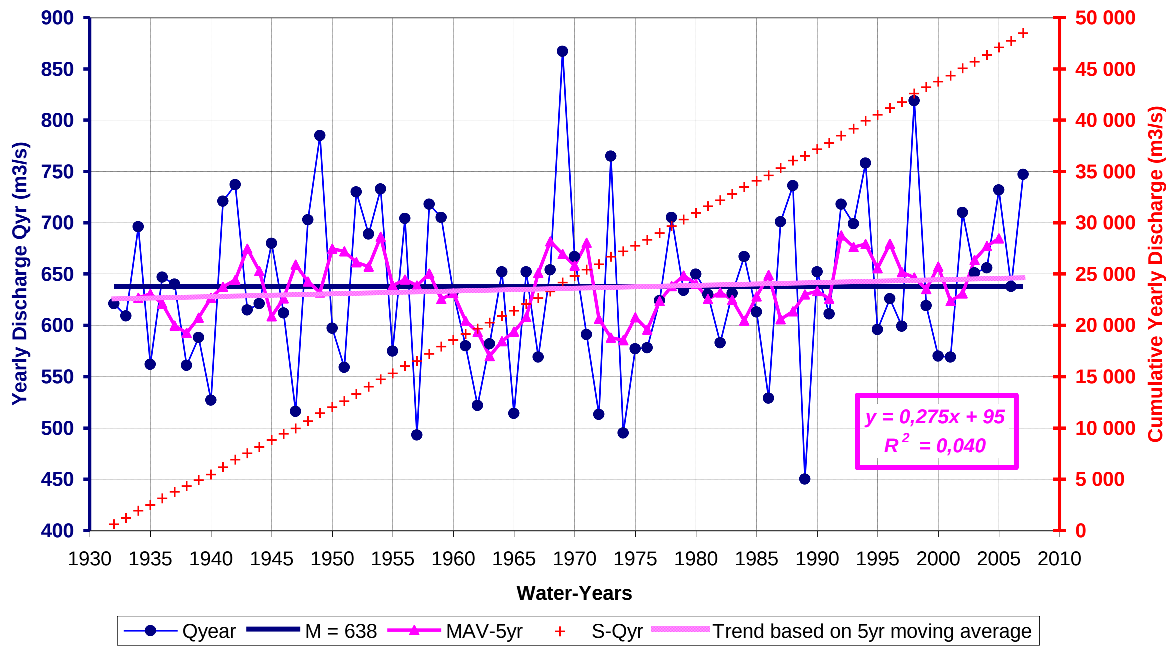
A. Data about Observed Discharge

Year	Annual	IV-IX	X-III
1932 - 1933	621	1 052	187
1933 - 1934	609	1 008	208
1934 - 1935	696	1 163	227
1935 - 1936	562	919	204
1936 - 1937	647	1 101	190
1937 - 1938	640	1 057	222
1938 - 1939	561	919	200
1939 - 1940	588	973	200
1940 - 1941	527	845	208
1941 - 1942	721	1 171	268
1942 - 1943	737	1 188	282
1943 - 1944	615	977	252
1944 - 1945	621	1 018	223
1945 - 1946	680	1 117	240
1946 - 1947	612	986	235
1947 - 1948	516	850	182
1948 - 1949	703	1 153	251
1949 - 1950	785	1 268	299
1950 - 1951	597	979	214
1951 - 1952	559	880	239
1952 - 1953	730	1 207	250
1953 - 1954	689	1 101	274
1954 - 1955	733	1 200	264
1955 - 1956	575	923	226
1956 - 1957	704	1 184	222
1957 - 1958	493	765	220
1958 - 1959	718	1 197	237
1959 - 1960	705	1 158	252
1960 - 1961	632	1 039	223
1961 - 1962	580	945	213
1962 - 1963	522	839	204
1963 - 1964	582	956	209
1964 - 1965	652	1 083	220
1965 - 1966	514	816	211
1966 - 1967	652	1 101	202
1967 - 1968	569	917	220
1968 - 1969	654	1 052	254
1969 - 1970	867	1 438	293
1970 - 1971	667	1 092	239
1971 - 1972	591	973	209
1972 - 1973	513	814	210
1973 - 1974	765	1 290	237
1974 - 1975	495	798	191
1975 - 1976	577	939	215
1976 - 1977	578	933	221
Year	**Annual**	**IV-IX**	**X-III**
1977 - 1978	624	1 017	228

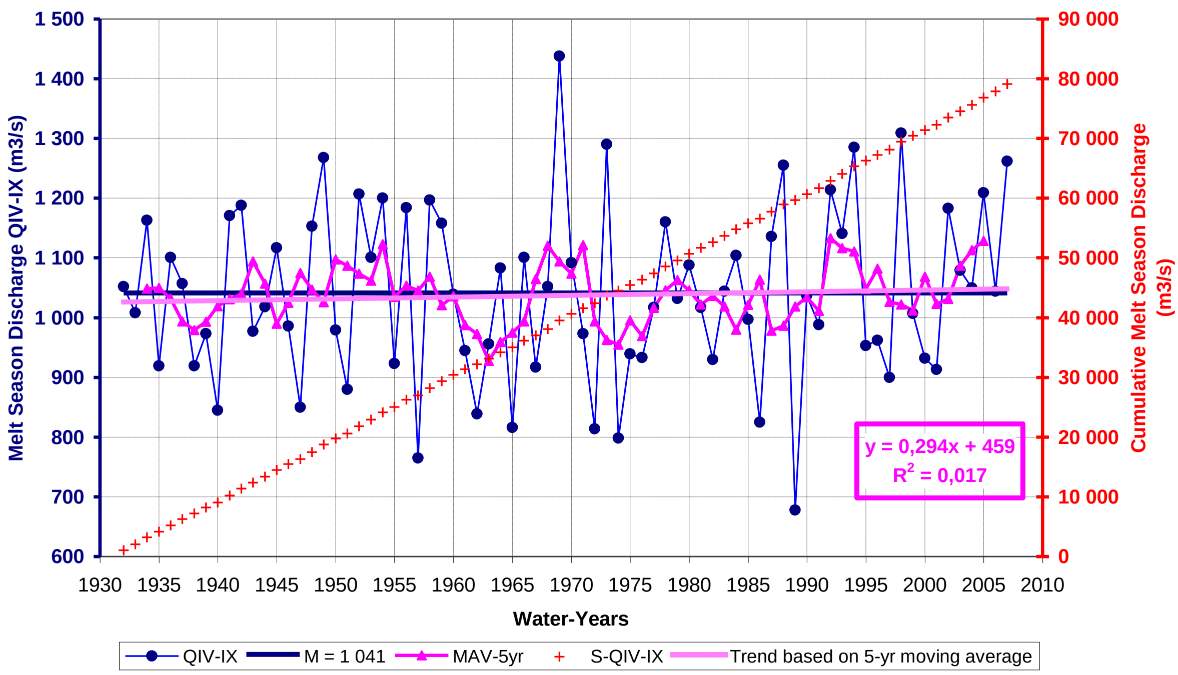
1978	-	1979	705	1 160	248
1979	-	1980	634	1 032	236
1980	-	1981	650	1 088	209
1981	-	1982	630	1 017	241
1982	-	1983	583	930	233
1983	-	1984	631	1 044	219
1984	-	1985	667	1 104	227
1985	-	1986	613	997	226
1986	-	1987	529	825	232
1987	-	1988	701	1 136	266
1988	-	1989	736	1 255	215
1989	-	1990	450	678	220
1990	-	1991	652	1 037	265
1991	-	1992	611	988	234
1992	-	1993	718	1 214	219
1993	-	1994	699	1 141	254
1994	-	1995	758	1 285	228
1995	-	1996	596	953	239
1996	-	1997	626	962	288
1997	-	1998	599	900	295
1998	-	1999	819	1 309	326
1999	-	2000	619	1 007	230
2000	-	2001	570	932	207
2001	-	2002	569	913	223
2002	-	2003	710	1 183	235
2003	-	2004	651	1 079	223
2004	-	2005	656	1 050	261
2005	-	2006	732	1 209	252
2006	-	2007	638	1 044	230
2007	-	2008	747	1 262	233
		n	76	76	76
		M	638	1 041	233
		S	80	145	28
		Cv	0,126	0,139	0,118
		Me	632	1 038	228
		Max	867	1 438	326
		Min	450	678	182

B. Discharge Time Series

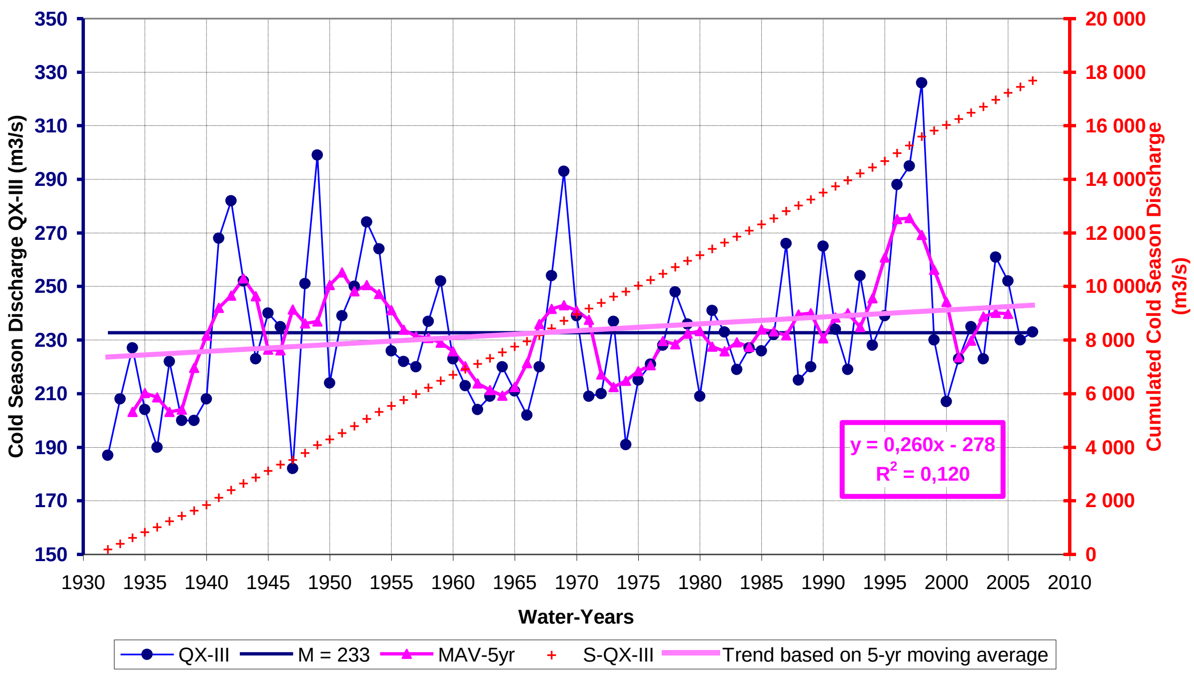
Vakhsh River at Rogun Damsite - Yearly Discharges - 1932/33 to 2007/08



Vakhsh River at Rogun Damsite - Melt Season Discharges - 1932/33 to 2007/08



Vakhsh River at Rogun Damsite - Cold Season Discharge - 1932/33 to 2007/08



C. Results concerning Discharge Trend

Observed Trend

Period	Mean (m3/s)	Trend (m3/s/yr)	Trend (%)
Year	638	0,275	0,043
Melt Season	1 041	0,294	0,028
Cold Season	233	0,260	0,112

Discharge Forecast

Year	Mean (m3/s)	Melt Season (m3/s)	Cold Season (m3/s)	Mean (%)	Melt Season (%)	Cold Season (%)
2010	638	1 041	233	100,0	100,0	100,0
2015	639	1 042	234	100,2	100,1	100,6
2020	641	1 044	236	100,4	100,3	101,1
2025	642	1 045	237	100,6	100,4	101,7
2030	644	1 047	238	100,9	100,6	102,2
2035	645	1 048	240	101,1	100,7	102,8
2040	646	1 050	241	101,3	100,8	103,3
2045	648	1 051	242	101,5	101,0	103,9
2050	649	1 053	243	101,7	101,1	104,5
2055	650	1 054	245	101,9	101,3	105,0
2060	652	1 056	246	102,2	101,4	105,6
2065	653	1 057	247	102,4	101,6	106,1
2070	654	1 059	249	102,6	101,7	106,7
2075	656	1 060	250	102,8	101,8	107,3
Year	Mean	Melt Season	Cold Season	Mean	Melt Season	Cold Season
2080	657	1 062	251	103,0	102,0	107,8

2085	659	1 063	252	103,2	102,1	108,4
2090	660	1 065	254	103,4	102,3	108,9
2095	661	1 066	255	103,7	102,4	109,5
2100	663	1 067	256	103,9	102,5	110,0

5.2.4 Existing models in Central Asia – Temperature and Precipitation Projections

This section presents the temperature and precipitation forecasts which are quoted in the report of René Roy about Tajikistan and Kyrgyz Republic. Next Table details the values of interest for Rogun project.

From René Roy report, the distribution of climate change given by several models for the years 2020, 2050 and 2080 was extracted and extrapolated until 2100:

- For temperature the models are rather consistent since they all imply an increase of temperature.
- For precipitation, as quoted by Roy and several other authors, the dispersion of the results is of the same order of magnitude as the percentage change. Thus some models forecast decrease of precipitation whereas some forecast increase of precipitation, leading to opposite conclusions.

In part A, the anticipated temperature increase given by the climate models is presented. The historical trend that could be assumed from trend analysis has also been added to the graph. It is to be noted that the historic trend corresponds to an increase which is about one third of the minimum increase given by climate models.

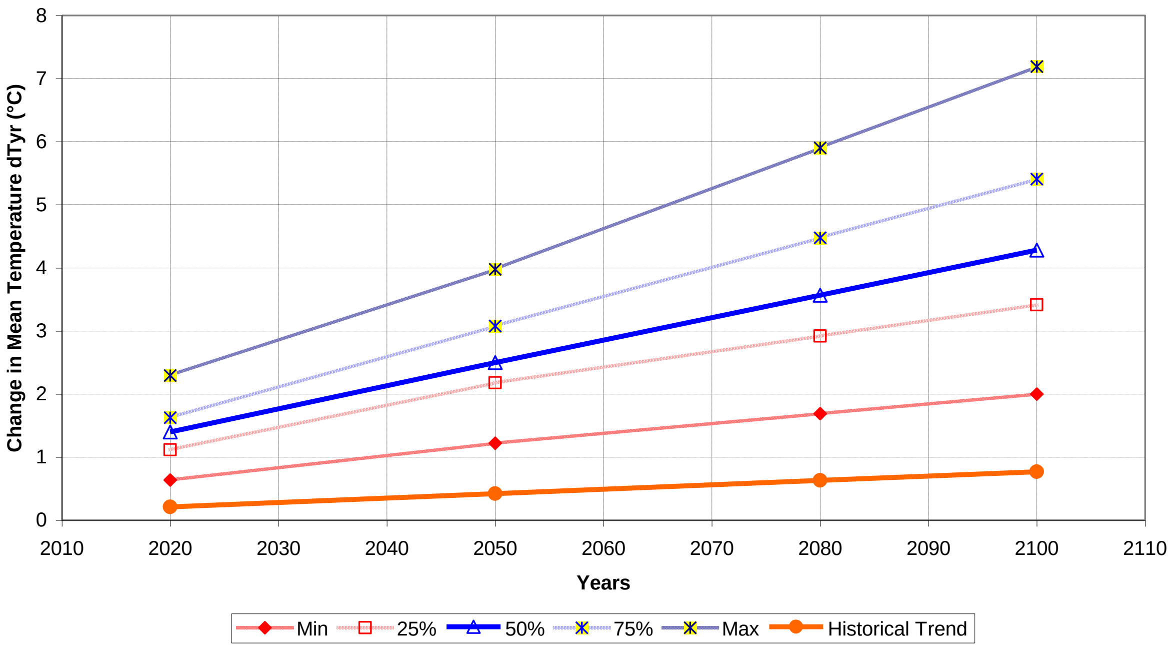
Part B concerns the change in precipitation. The wide scatter given by the climate models is evident. The no change option corresponds more or less to the median results. The historical trend, based on five rain gauges would lead to an increase of about 16% in 2100. The historical trend is within the range provided by the climate models, but a no change option would be a safe approach given the uncertainties carried by the models.

Table 17: Climate Change in Central Asia - Temperature and Precipitation

A. Temperature Change (°C)

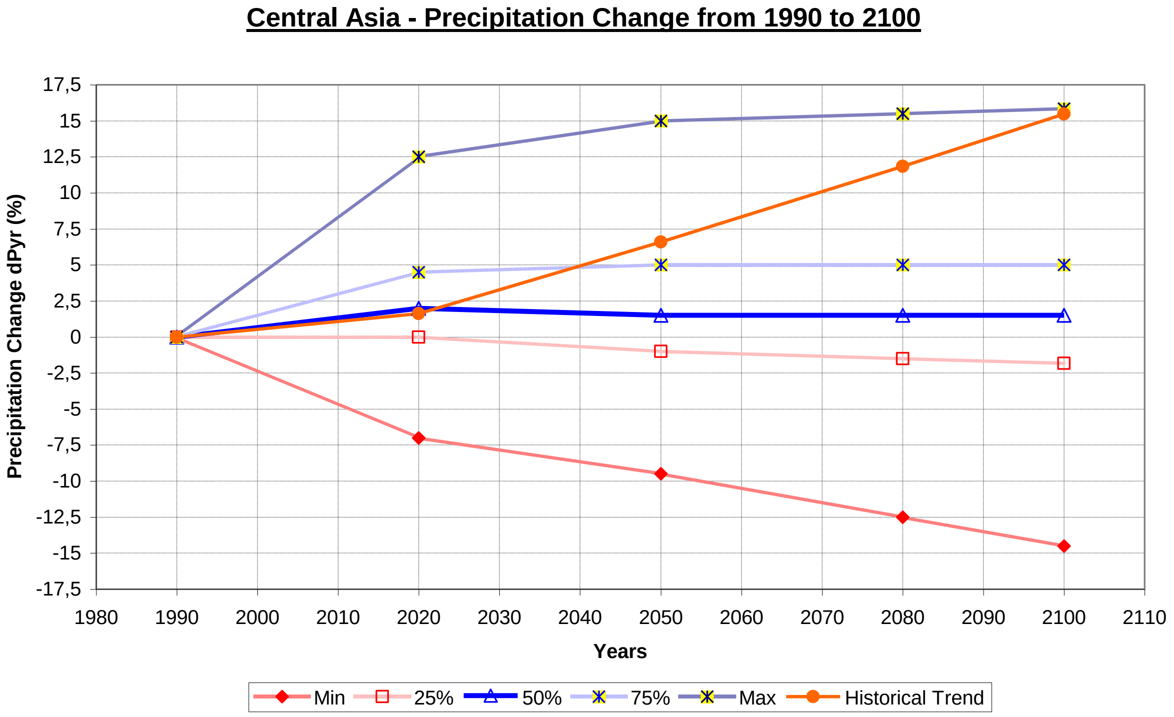
Year	Min	25%	50%	75%	Max	Historical Trend
2020	0,6	1,1	1,4	1,6	2,3	0,2
2050	1,2	2,2	2,5	3,1	4,0	0,4
2080	1,7	2,9	3,6	4,5	5,9	0,6
2100	2,0	3,4	4,3	5,4	7,2	0,8

Central Asia - Temperature Changes with respect to 1980-1999 Conditions



B. Precipitaton Change (%)

Year	Min	25%	50%	75%	Max	Historical Trend
1990	0,0	0,0	0,0	0,0	0,0	0,0
2020	-7,0	0,0	2,0	4,5	12,5	1,6
2050	-9,5	-1,0	1,5	5,0	15,0	6,6
2080	-12,5	-1,5	1,5	5,0	15,5	11,8
2100	-14,5	-1,8	1,5	5,0	15,8	15,5



5.3 Snow Accumulation and Glacier Melt

5.3.1. Analysis of Regional Information

Homidov (2006) and Makmadaliev, Novikov and al. (2002, 2003 and 2008) show that the glacier are receding in Tajikistan. Analysis of present climate discloses that temperature can either increase or decrease or remain stable according to the location. Roy (2009) and Siegfried (2010) have reviewed data and results of climate change model for Central Asia. Tajik experts forecast a disappearance of small glaciers and a decrease of about 50% of glaciers in low elevations. At higher elevations and according to them the reduction could be between 20 and 50% or smaller than 20%.

Next Table illustrates findings quoted by Tajik experts, Roy and Siegfried together with extrapolations until 2100. Part A presents a broad picture of conditions in Tajikistan and Kyrgyz Republic as presented by Roy. Roy evokes disappearance of glaciers. That might be right for low and medium elevations. But, high altitude glaciers will still exist. Similarly, the 30% decrease of Amu Darya flows might be debatable. Such a value might be inapplicable to Vakhsh case. Roy quotes also a runoff decrease of 100 mm for Tajikistan. Transposed to Vakhsh case, this would mean a reduction of 96 m3/s compared to the present average of 638 m3/s (a 15% reduction).

Part B details the decrease of Ice Reserve within Aral Sea Basin which, under the assumption of linear correlation, might lead to a total disappearance before 2100. The Consultant believes that such a strong linear assumption is not realistic. With an exponential extrapolation, in 2100, Ice reserve could be 22% of 1957 value.

Part C concerns the Tien Shan glaciers for which Siegfried and others studied Ice reserves for two climate scenarios. The lower one leads to an ice reserve of 87% of 1990 ice reserve, whereas the higher one leads to an ice reserve of 44% of 1990 ice reserve.

As a conclusion part D compares Aral Sea and Tien Shan ice reserves. From this comparison the Consultant has derived an average trend that could represent a realistic assumption for Tajik glaciers. According to this average trend, in 2100, 36% of ice reserves will remain in 2100.

Table 18: Regional Information About Climate Change and Melt

A. Climate Evolution for Tajikistan and Kyrgyz Republic

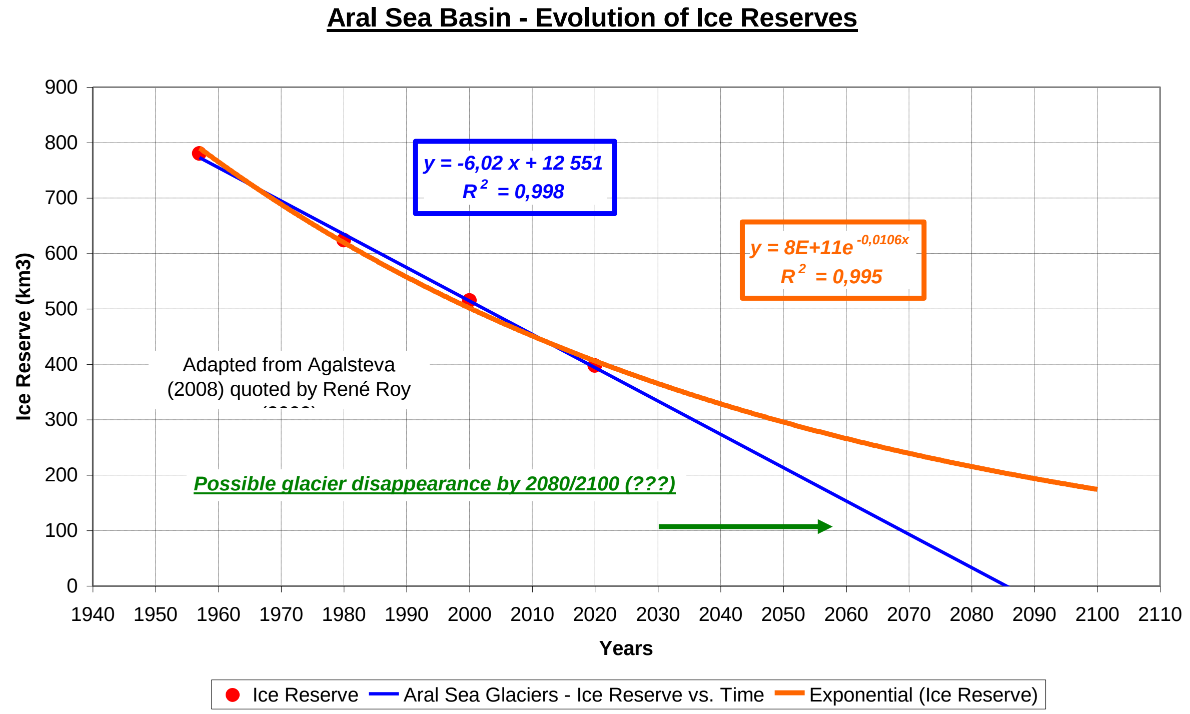
Time Step	Recent Past (1950-2000)	2050	2080
		Temperature	
Annual	Increase by 0,6 to 1,2°C	Increase of about 2,5°C	Increase of about 3,6°C
Seasonal	Same as annual	Summer, increase of about 2,8°C	Summer, increase of about 3,9°C
Monthly		August, +2,9°C	August, +4,2°C
		Precipitation	
Annual	No trend	Slight increase (3%) but dispersion	Slight increase (3%) but dispersion
Seasonal	Increase in spring precipitation	-10% in summer and +10% in winter	-12% in summer and +12% in winter
Monthly	March with most important increase	-15% in August and +15% in December	-22% in August and +23% in December
		Glacier Melt	
	Glacier retreat in the Aral Sea Basin of About -35% of the 1957 volume.	Expected glacier retreat: Between -0,2% and -1%/year.	Expected glacier retreat: >-1% Until disappearance.
	River Discharge	**Runoff**	
Annual	Increase annual runoff (glacier melt)	Decrease in Tajikistan: -5%. Increase in Kyrgyz Republic: +4%. Important regional variations	Runoff may decrease upt to 25 mm (Kyr) and 100 mm (Tjk) -30% decrease of Amu Darya flows.
Seasonal	Earlier (1week) and decreased summer flood peak and increased winter flows.	Changes in hydrograph shape: increased spring and summer runoff (glacier melt)	Changes in hydrograph shape: increased spring runoff decreased summer runoff
Monthly	Good match between irrigation demand and natural flow pattern.	Maximum positive differences in: May, June, July	Maximum negative differences in: July and August

Adapted from René Roy (2009).

B. Evolution of Ice Reserve – Aral Sea Basin

	Ice Reserve (km3)			Ice Reserve (%)		
Year	**1957/2020**	**Linear**	**Exponential**	**1957/2020**	**Linear**	**Exponential**
1957	780			100		
1980	624			80		
2000	515			66		
2020	398			51		
2040		274	325		35	42
2060		153	263		20	34
2080		33	213		4	27
2085		3	202		0,36	26
2090			191			25
2095			181			23
2100			172			22

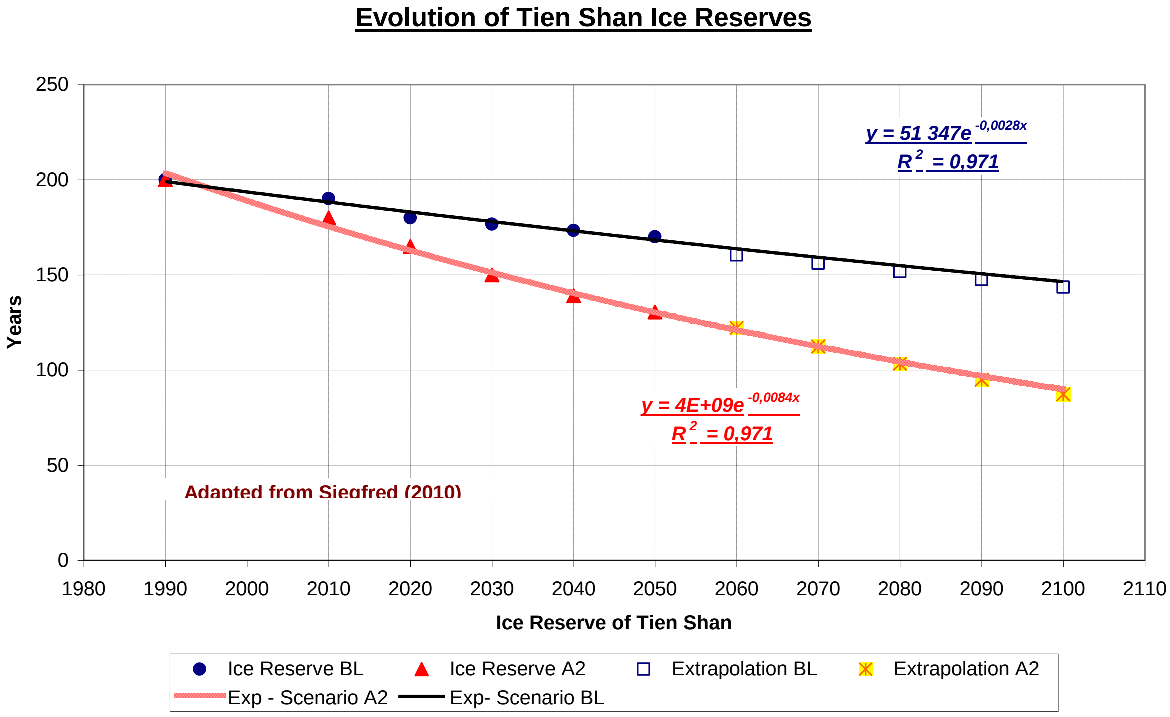
Adapted from René Roy (2009) and Agalsteva (2008).



C. Evolution of Ice Reserve – Tien Shan

	Scenario BL			Scenario A2		
Year	**Ice Reserve BL**	**Extrapolation BL**	**%**	**Ice Reserve A2**	**Extrapolation A2**	**%**
1990	200		100	200		100
2010	190		95	180		90
2020	180		90	165		83
2030	177		88	150		75
2040	173		87	139		70
2050	170		85	131		65
2060		*161*	*80*		*122*	*61*
2070		*156*	*78*		*112*	*56*
2080		*152*	*76*		*103*	*52*
2090		*148*	*74*		*95*	*47*
2100		*144*	*72*		*87*	*44*

Adapted from Siegfried (2010) – Units (km3)



D. Synthesis on Ice Reserves

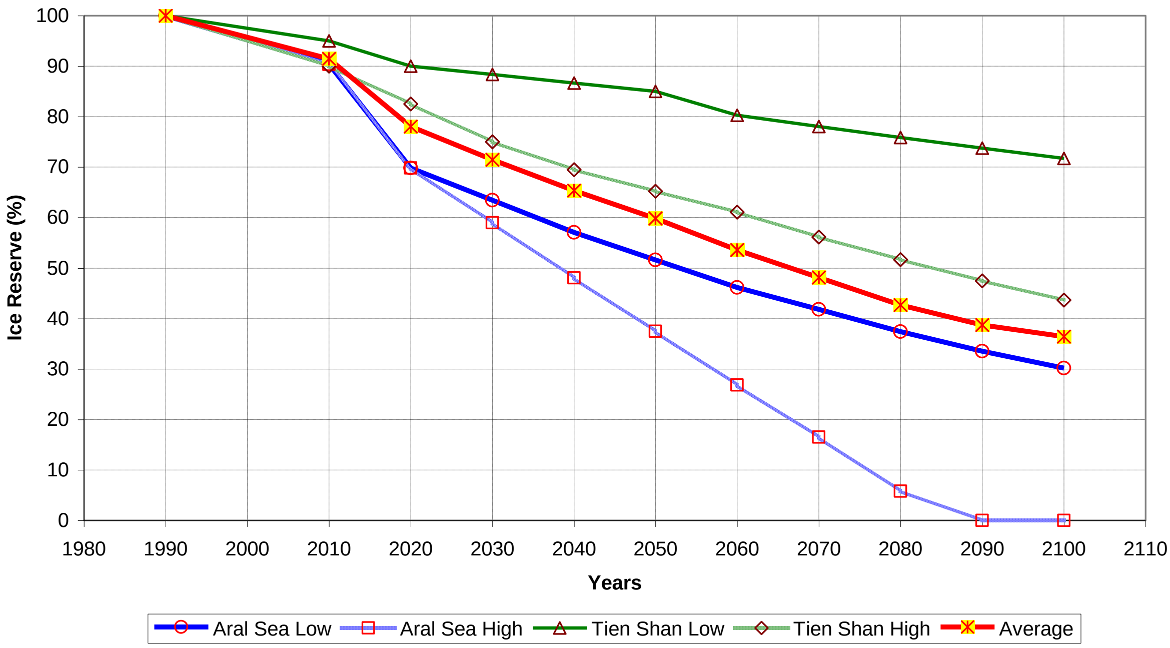
Year	Aral Sea Low	Aral Sea High	Tien Shan Low	Tien Shan High
1990	570	570	200	200
2010	515	515	190	180
2020	398	398	180	165
2030	*362*	*336*	177	150
2040	*325*	*274*	173	139
2050	*294*	*214*	170	131
2060	*263*	*153*	*161*	*122*
2070	*238*	*94*	*156*	*112*
2080	*213*	*33*	*152*	*103*
2090	*191*	0	*148*	*95*
2100	*172*	0	*144*	*87*

(km3)

Year	Aral Sea Low	Aral Sea High	Tien Shan Low	Tien Shan High	Average
1990	100	100	100	100	100
2010	90	90	95	90	91
2020	70	70	90	83	78
2030	63	59	88	75	71
2040	57	48	87	70	65
2050	52	37	85	65	60
2060	46	27	80	61	54
2070	42	16	78	56	48
2080	37	6	76	52	43
2090	34	0	74	47	39
2100	30	0	72	44	36

(%)

Central Asia - Evolution of Ice Reserves



5.3.2. Analysis of Tajikistan and Vakhsh Contexts

In the next Table 19 a number of relevant information about Tajikistan and Vakhsh river basin was gathered after a review of existing information. These data have been abstracted and / or adapted from the several references quoted above: Homidov, Hydroproject, Lahmeyer, Makhmadaliev and Novikov, Roy.

Part A details data about Glaciers. It should be noted that Vakhsh glaciers have an area of about 3 900 km² (see part B) which is about 50% of the area of Tajik glaciers. Time for depleting ice stock is highly variable. For Tajikistan, the value is low (38 years), this low values reflects the fact that the low elevation glaciers are vanishing. Yearly loss for Fedchenko and Garmo glaciers amounts to about 0.8 m3/s. The increasing trend of Vakhsh discharge is 0.3 m3/s which is not contradictory since the loss contributes to melt (river discharge), evaporation and contribution to groundwater flow.

Part B details the glacier areas within Vakhsh catchment. Abramov, Garmo and Fedchenko glaciers are the most prominent glaciers within the Vakhsh catchment. Note that the glacier area amounts to 13% of Vakhsh catchment area and to 26% of Vakhsh discharge.

Part C describes the main features of Vakhsh river basin in terms of elevation, temperature and precipitation. Average temperature of the catchment is -0,2°C and average precipitation is 1 090 mm/year.

Part D details the evolution of the 0°C line and the snow / Ice areas according to the 50% evolution of temperature quoted by Roy for Central Asia. Glacier areas and discharge trends are also given in this part. The 0°C line will rise progressively from 3 170 m in 1990 to 3 900 m in 2100. Thus, the snow and ice caps will decrease from 15 200 to 7 500 km². Assuming a uniform distribution, the glacier area will decrease from 3 880 km² to 1 900 km² which means 49% of the initial glacier area. Making use of the historic trend of discharge, the discharge would increase from 638 m^3/s to 663 m^3/s.

Table 19: Tajikistan and Vakhsh Contexts

A. General Information About Tajikistan Glaciers

Item	Unit	Value
Tajikistan Glaciers		
Area	km²	8 000 ± 400
Stock	cub.km	500
Melt	cub.km	13
	m3/s	412
Melt / Stock	%	2,60
Melt / Area	m	1,63
Ice Thickness	m	62,5
Time for depleting stock	years	38
Fedchenko Glacier		
Fedchenko Loss (100 years)	10^6 m3	2 000
Fedchenko Loss (yearly)	10^6 m3	20
	m3/s	0,634
L (Fedchenko-Muksu)	km	171
Garmo Glacier		
Garmo Loss (69 / 86)		
L(Garmo)	km	73
Stock	10^6 m3	1 235
Yearly Loss	10^6 m3	5,81
	m3/s	0,184
Melt/Stock	%	0,47
Time for depleting stock	years	213
Fedchenko + Garmo Loss	m3/s	0,818
Vakhsh Glaciers		
Glacier feeding	cub.km	5
	m3/s	159
	%	26
Snow and ground feeding	cub.km	14
	m3/s	444
	%	74
Total	cub.km	19
	m3/s	602
	%	100

B. Vakhsh Glaciers

Basin	Glacier Area (km²)	% (Total)	% (Rogun)
Western Kysilsu	649	16,7	2,1
Muksu	2 120	54,6	7,0
Surkhob (Vaksh) DS of Kysilsu and Muksu	401	10,3	1,3
Obihingou	712	18,3	2,3
Vakhsh (Total)	3 882	100,0	12,8

C. Description of Vakhsh River Basin

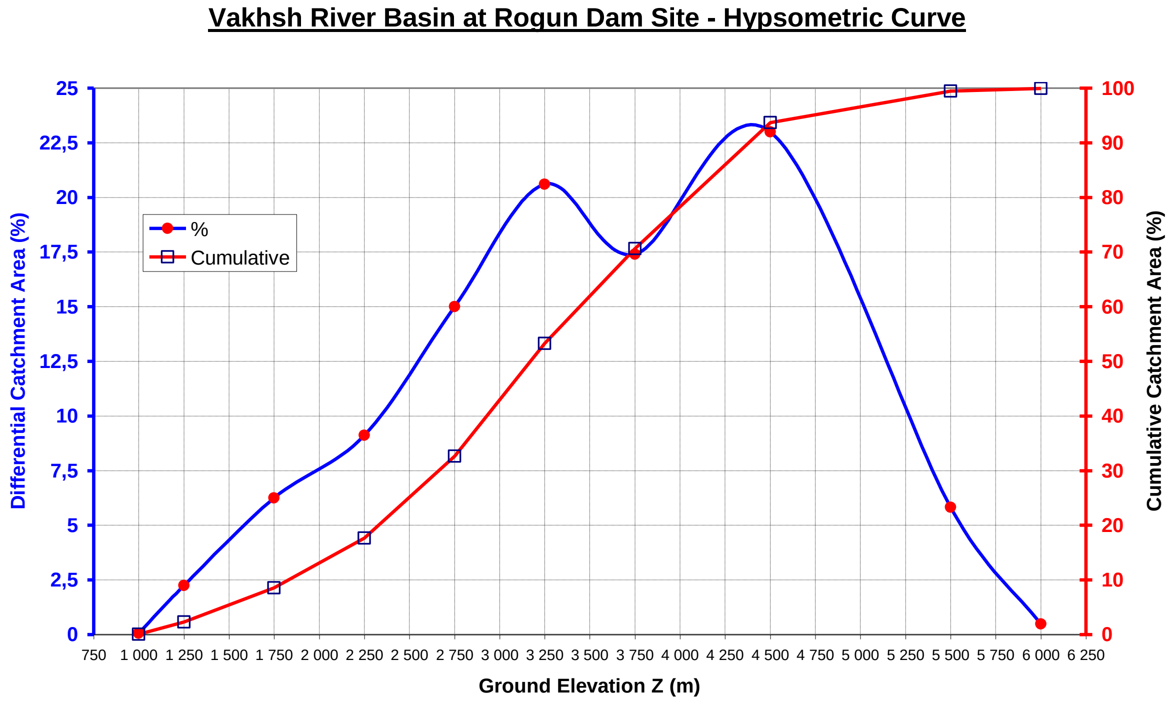
Hypsometric Curve

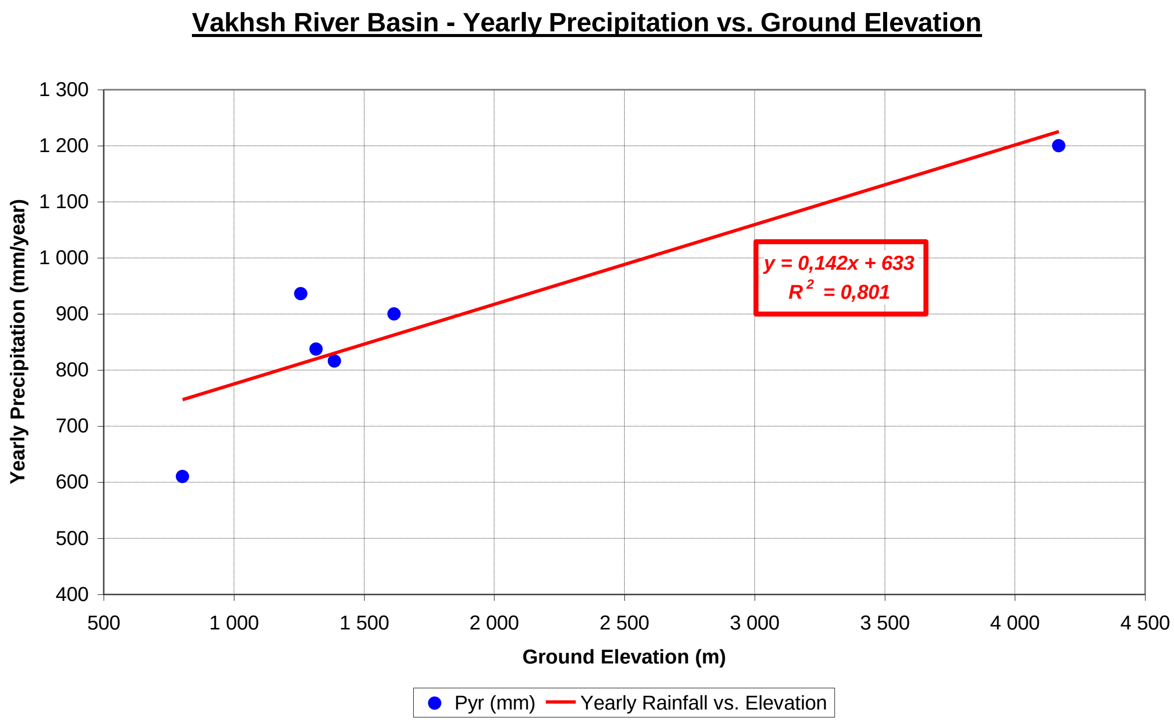
Z (m)	%	Cumulative
1 000	0,06	0,1
1 250	2,24	2,3
1 750	6,25	8,6
2 250	9,11	17,7
2 750	15,00	32,7
3 250	20,60	53,3
3 750	17,40	70,7
4 500	23,00	93,7
5 500	5,82	99,5
6 000	0,48	100,0

Yearly Temperature and Precipitation

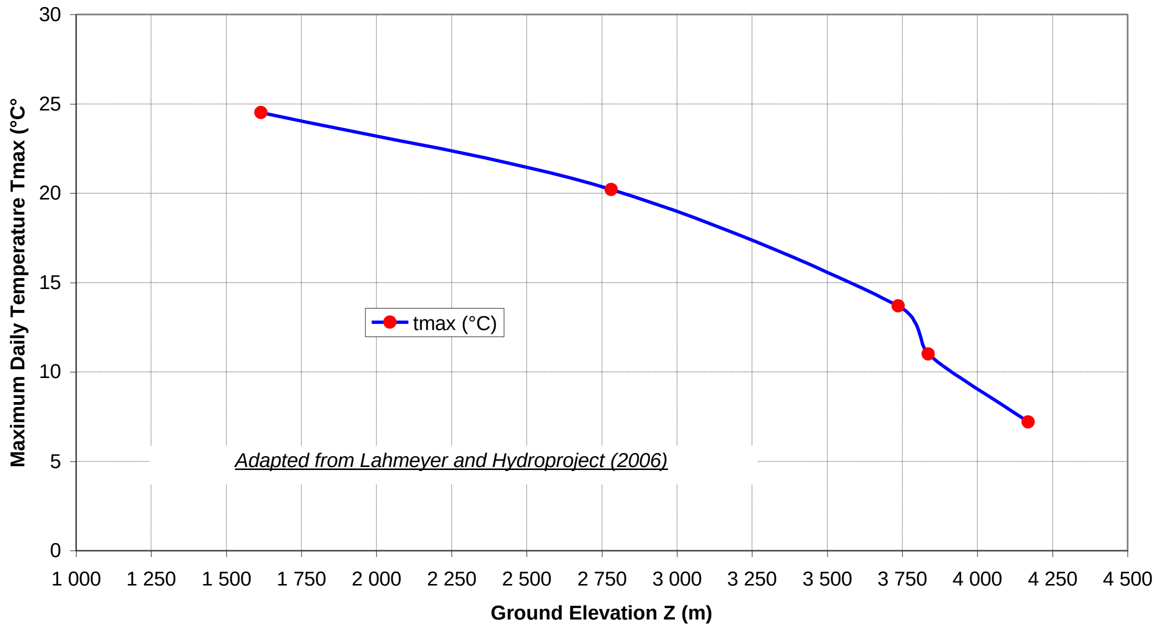
%	Z	T(°C)	Tm (°C)	Pyr (mm)	Pm (mm)
0	1 000	12,8		775	
10	1 900	7,5	10,1	903	839
20	2 300	5,1	6,3	960	931
30	2 700	2,8	4,0	1 016	988
40	2 900	1,6	2,2	1 045	1 031
50	3 150	0,1	0,9	1 080	1 063
60	3 400	-1,4	-0,6	1 116	1 098
70	3 750	-3,4	-2,4	1 166	1 141
80	4 100	-5,5	-4,5	1 215	1 190
90	4 300	-6,7	-6,1	1 244	1 229
100	6 000	-16,7	-11,7	1 485	1 364
Average			-0,2		1 087
				rounded to	1 090

Station	Z	Pyr (mm)	Gradient (mm/ 1 00m)	Source
Duchambe	803	610		Makhmadaliev, 2002
Komsomolabad	1 258	936	71,6	LI, 2006
Garm	1 316	837	-170,7	LI, 2006
Obigarm	1 387	816	-29,6	LI, 2006
Tavildara	1 616	900	36,7	Makhmadaliev, 2002
Fedchenko Glacier	4 169	1 200	11,8	Makhmadaliev, 2002


Vakhsh River Basin at Rogun Dam Site - Hypsometric Curve
Differential Catchment Area (%)
Cumulative Catchment Area (%)
Ground Elevation Z (m)
%
Cumulative
25
22,5
20
17,5
15
12,5
10
7,5
5
2,5
0
100
90
80
70
60
50
40
30
20
10
0
750
1 000
1 250
1 500
1 750
2 000
2 250
2 500
2 750
3 000
3 250
3 500
3 750
4 000
4 250
4 500
4 750
5 000
5 250
5 500
5 750
6 000
6 250


Vakhsh River Basin - Yearly Precipitation vs. Ground Elevation
Yearly Precipitation (mm/year)
Ground Elevation (m)
y = 0,142x + 633
R² = 0,801
Pyr (mm)
Yearly Rainfall vs. Elevation
1 300
1 200
1 100
1 000
900
800
700
600
500
400
500
1 000
1 500
2 000
2 500
3 000
3 500
4 000
4 500

Maximum Daily Temperature vs. Ground Elevation

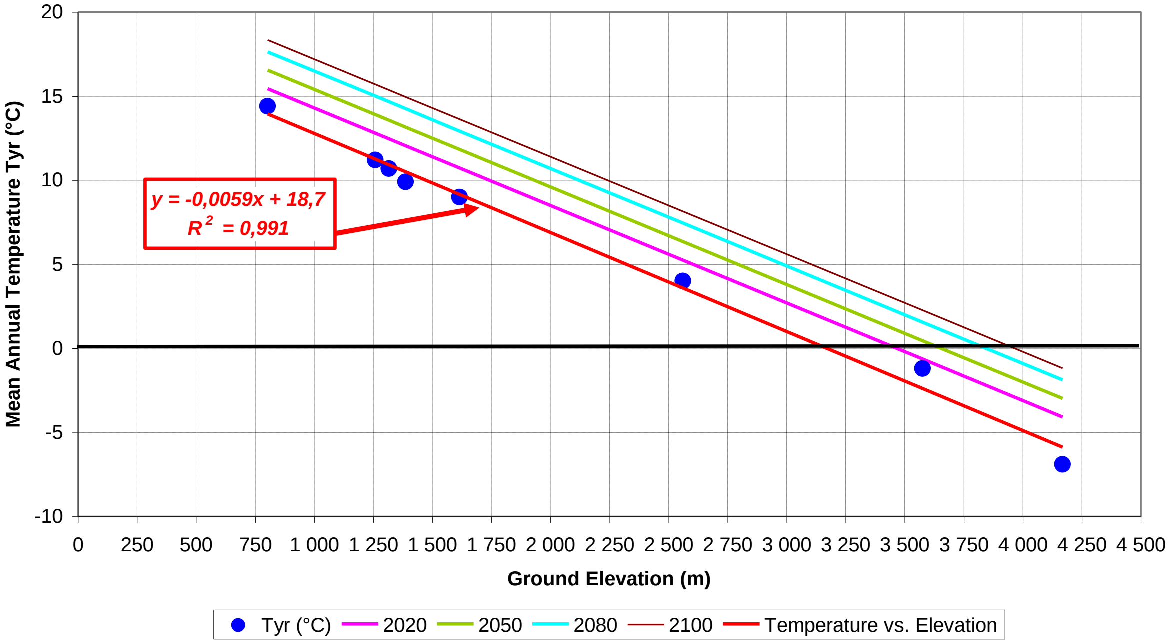


D. Projections of Temperature and Snow / Ice Areas until 2100

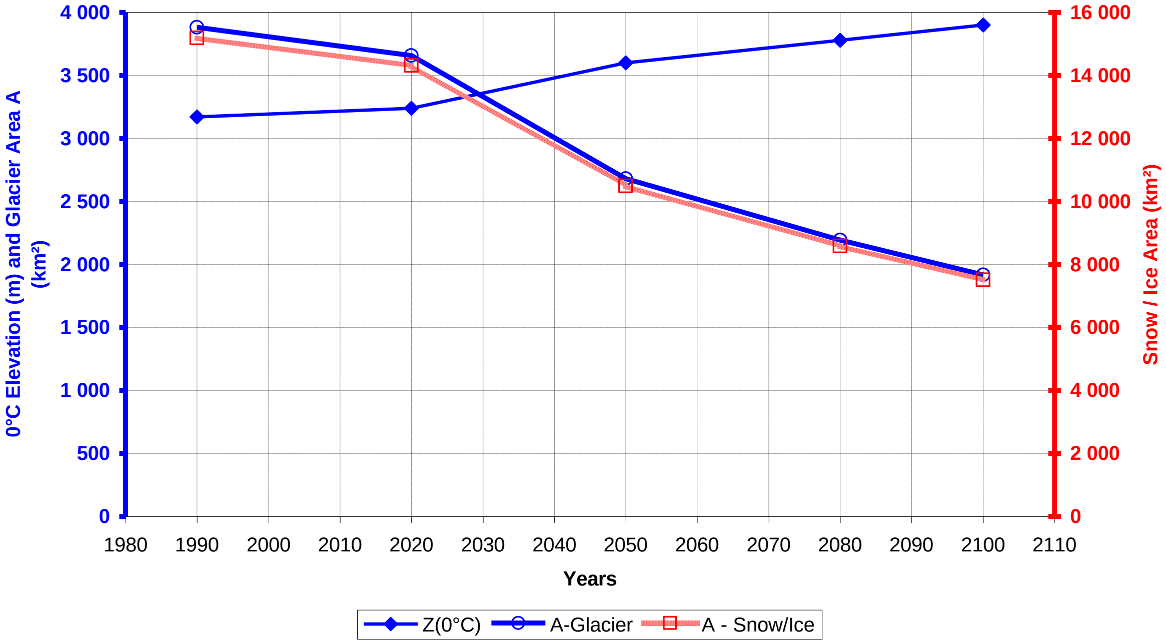
Station	Z	Tyr (°C)	2020	2050	2080	2100	Gradient (°C/1 00m)	Source
Duchambe	803	14,4	15,4	16,5	17,6	18,3		Makhmadaliev, 2002
Komsomolabad	1 258	11,2	12,8	13,9	15,0	15,7	-0,70	LI, 2006
Garm	1 316	10,7	12,5	13,6	14,7	15,4	-0,86	LI, 2006
Obigarm	1 387	9,9	12,1	13,2	14,3	15,0	-1,13	LI, 2006
Tavildara	1 616	9,0	10,7	11,8	12,9	13,6	-0,39	Makhmadaliev, 2002
Dehavz	2 561	4,0	5,2	6,3	7,4	8,1	-0,53	Makhmadaliev, 2002
Murgab	3 576	-1,2	-0,6	0,5	1,6	2,3	-0,51	Makhmadaliev, 2002
Fedchenko Glacier	4 169	-6,9	-4,1	-3,0	-1,9	-1,2	-0,96	Makhmadaliev, 2002
Z(0°C)		*3 170*	*3 240*	*3 600*	*3 780*	*3 900*		

Year	Z(0°C) (m)	A - Snow/Ice (km²)	A/A(1990) (%)	3882/A-S/I (%)	A-Glacier (km²)	Change (%)	Discharge (trend) (m^3/s)
1990	3 170	15 194	100	26	3 882	0	638
2020	3 240	14 317	94	27	3 658	6	641
2050	3 600	10 491	69	37	2 680	31	649
2080	3 780	8 588	57	45	2 194	43	657
2100	3 900	7 506	49	52	1 918	51	663

Vakhsh River Basin - Temperature vs. Ground Elevation



Vakhsh River Basin - Evolution of Snow and Ice Areas until 2100



5.3.3. Scenario 1: Impacts of Glacier Disappearance

In this part, the Consultant assessed the impacts of glacier disappearance, assuming all other hydrological parameters staying the same as present, as supported by several climate models. This will not be the case in the future as Climate Change impact is a more complex phenomenon. However, by doing so, it is believed that this scenario gives a preliminary estimate of the maximum perturbation in Vakhsh hydrology.

Data about Aral Sea might lead to the conclusion that in 2080 / 2100, the Aral Sea glaciers could disappear. Studies carried out by Tajik institutes show clearly that the glaciers are receding.

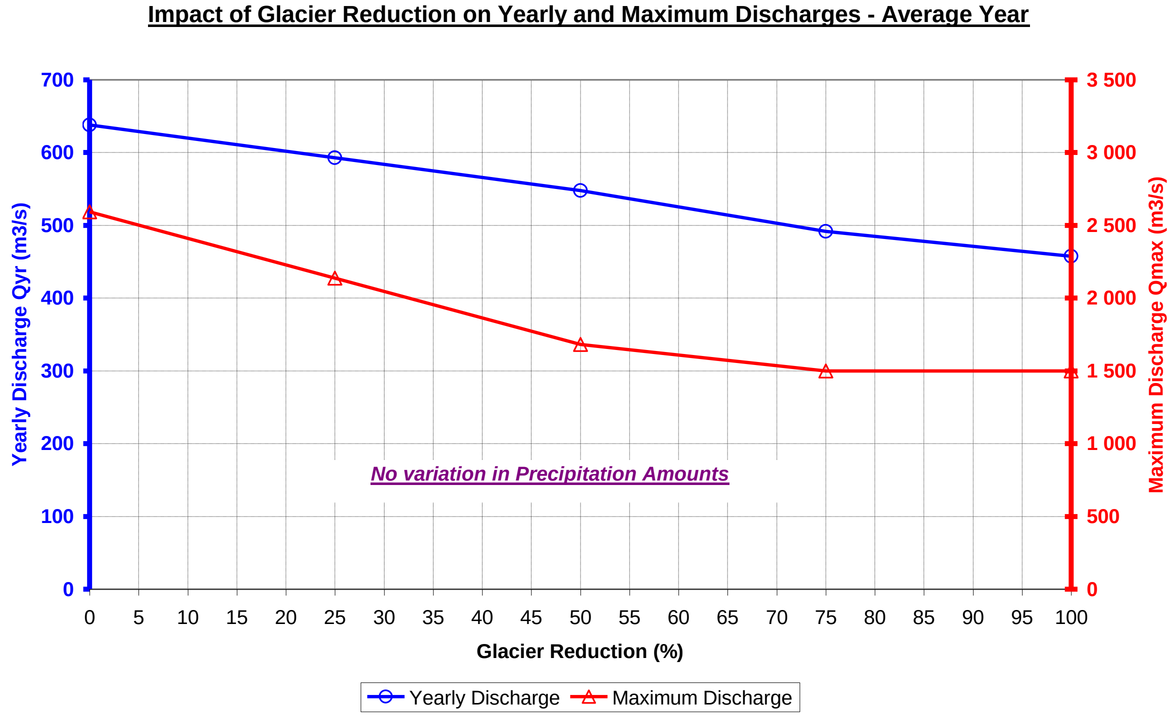
The total discharge is the sum of three components as shown in the following graphs, a ground component, a snow component and an ice component.

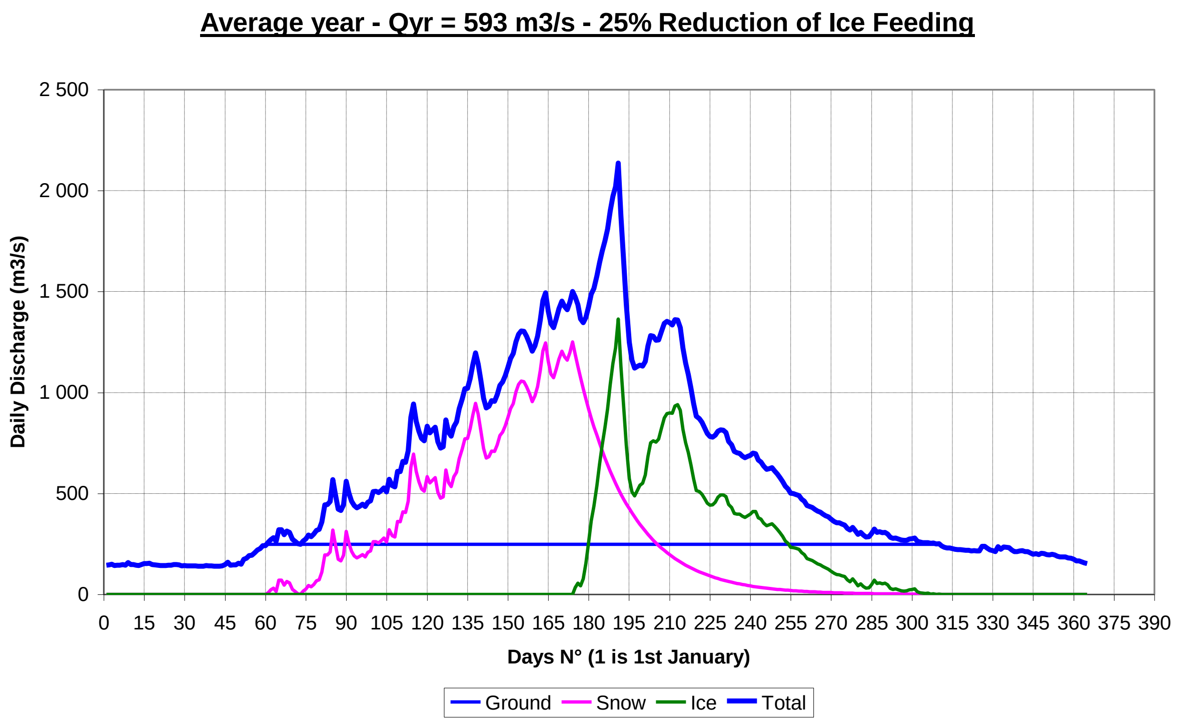
The yearly discharge of Vakhsh is computed for a glacier reduction of 0 % (actual condition) 25 % reduction, 50% reduction, 75% reduction and total disappearance of glacier contribution. It is foreseen, that the total disappearance of glacier in the Vakhsh catchment leads to a decrease of 28% of the ice contribution to the Vakhsh yearly discharge, and a diminution of the mean annual flood linked to the thaw season by 42%.

To illustrate this point, the following Table 20 and Graphs presents the evolution of Vakhsh discharges according to given glacier recession:

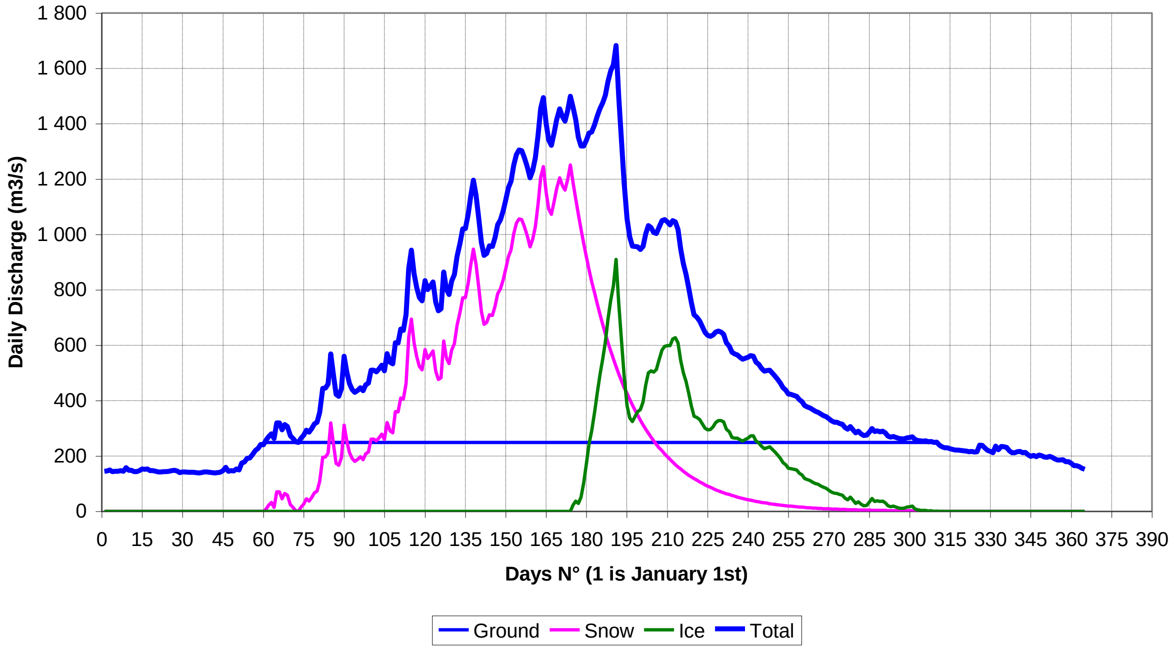
Table 20: Maximum Impact of Glacier Disappearance

Glacier Reduction (%)	Yearly Discharge (m3/s)	%	Maximum Discharge (m3/s)	%
0	638	100	2 592	100
25	593	93	2 137	82
50	548	86	1 682	65
75	492	77	1 500	58
100	458	72	1 500	58

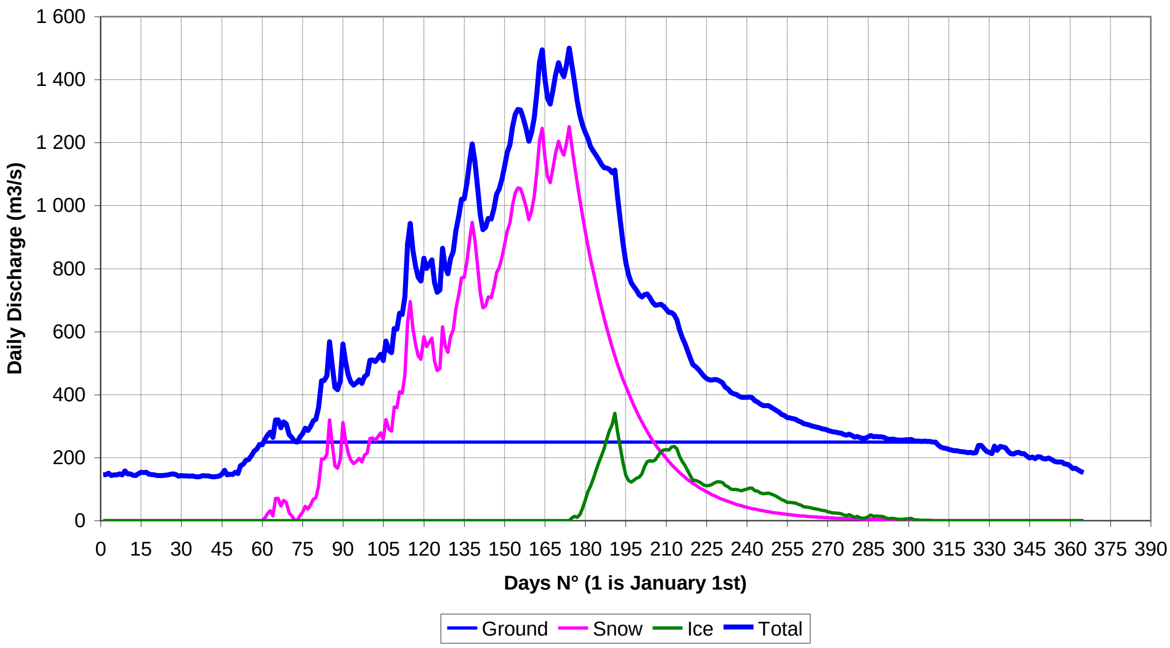

Impact of Glacier Reduction on Yearly and Maximum Discharges - Average Year
Yearly Discharge Qyr (m3/s)
Maximum Discharge Qmax (m3/s)
No variation in Precipitation Amounts
Glacier Reduction (%)
Yearly Discharge
Maximum Discharge

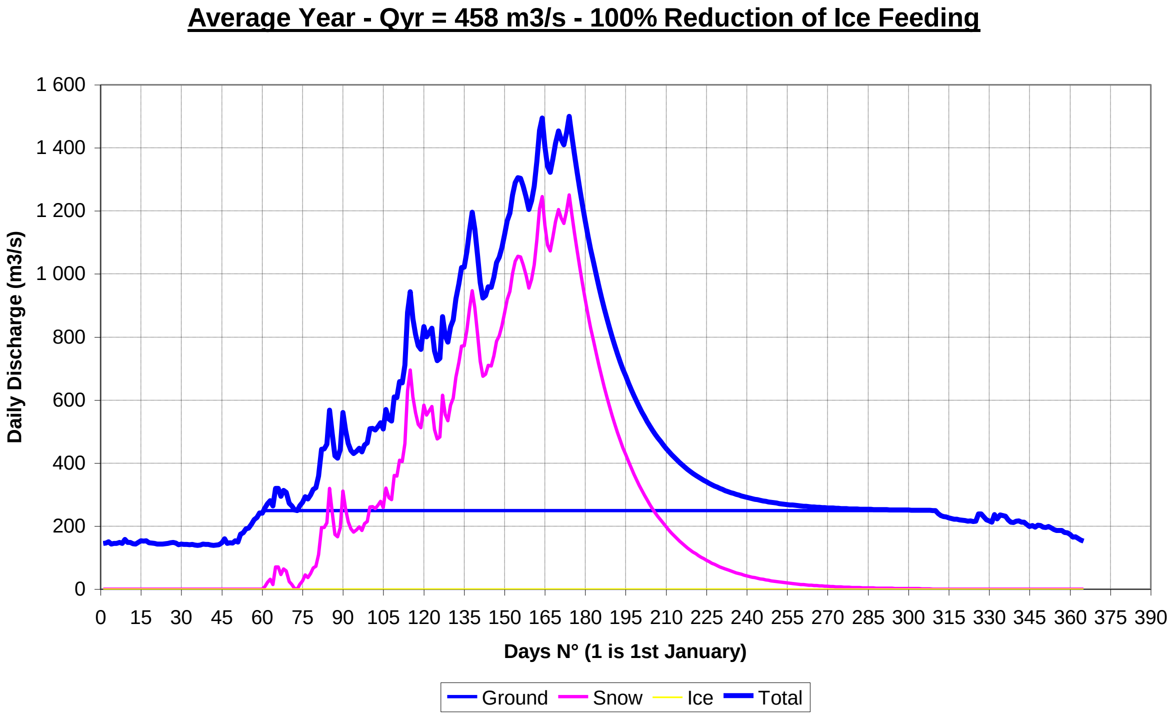

Average year - Qyr = 593 m3/s - 25% Reduction of Ice Feeding
Daily Discharge (m3/s)
Days N° (1 is 1st January)
Ground
Snow
Ice
Total

Average Year - Qyr = 548 m3/s - 50% Reduction of Ice Feeding



Average Year - Qyr = 492 m3/s - 75% Reduction of Ice Feeding




Average Year - Qyr = 458 m3/s - 100% Reduction of Ice Feeding
Daily Discharge (m3/s)
1 600
1 400
1 200
1 000
800
600
400
200
0
0 15 30 45 60 75 90 105 120 135 150 165 180 195 210 225 240 255 270 285 300 315 330 345 360 375 390
Days N° (1 is 1st January)
Ground
Snow
Ice
Total

5.4 Scenario 2: Evolution of Discharges from 1990 to 2100

After this specific study about the vanishing of glacier, an assessment of the evolution of Vakhsh discharges was made by the Consultant under the assumption of a discharge increasing trend (at same level as the historical trend of 0.8°C/century) associated to an ice feeding reduction due to temperature increase as suggested by the Climate Models and presented above. Two phenomenon were therefore coupled in this scenario: an ice feeding reduction due to temperature rise and an increase in ground water contribution following the historical trend.

The following Table 21 illustrates our results. The projections show that the ice feeding contribution will weight in 2100, in the Vakhsh average discharge for 88 m3/s instead of 180 m3/s at the present time (i.e. 50% decrease of ice contribution). Conversely, assuming the ground water contribution increase at the same level as historical trend, its contribution is estimated in 2100 at 344 m3/s (i.e. 50% increase compared to actual ground water contribution).

The impact of this two contribution evolution represents a clear diminution of maximum flood in 2100. However the ground water increase contribution allows preserving a mean annual flow as actual.

Note that a number of uncertainties affect the results:

- The 50% hypothesis for temperature increase might not be right
- The precipitation projections by climate models have such dispersion that the no change option is the most prudent.
- Assuming a continuation of discharge trend might be right for the next 10 to 30 years and wrong on the long term.
- Knowledge of precipitation pattern is limited.

For operation study, a conservative assumption is to keep the present data set as it reflects the glacier recession of past century.

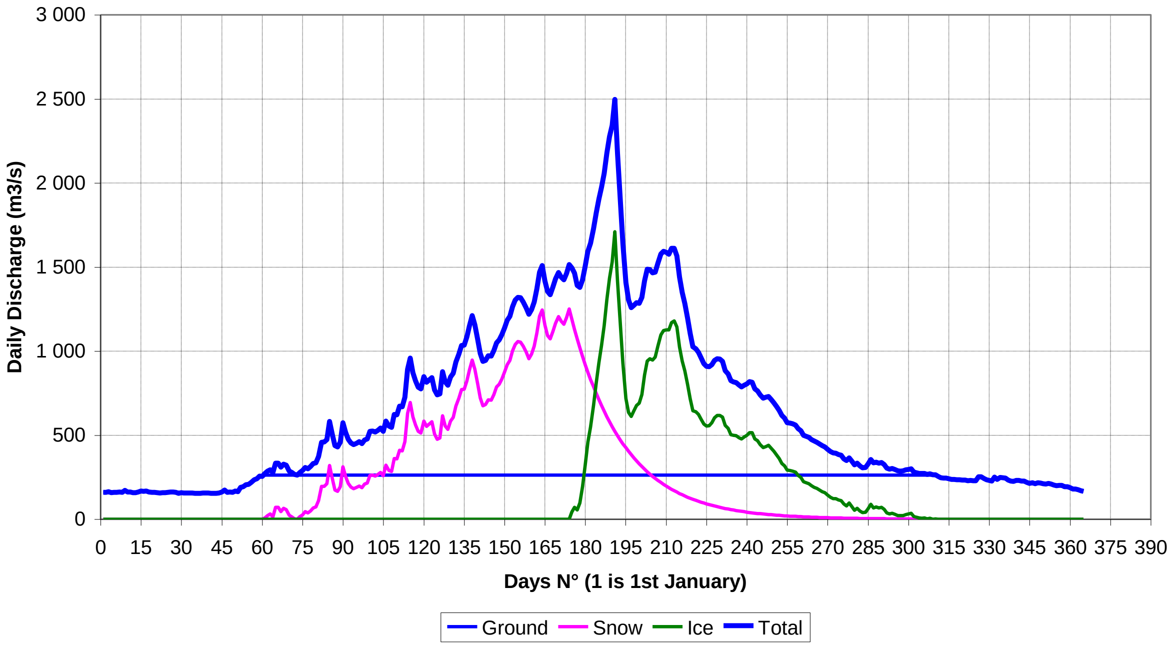
Table 21: Evolution of Discharges from 1990 to 2100

Item	Present (1990)	2020	2050	2080	2100
Average (m3/s)	638	641	649	657	663
%	100	100,5	102	103	104
Daily Peak (m3/s)	2 600	2 500	2 100	1 910	1 790
%	100	96	81	74	69

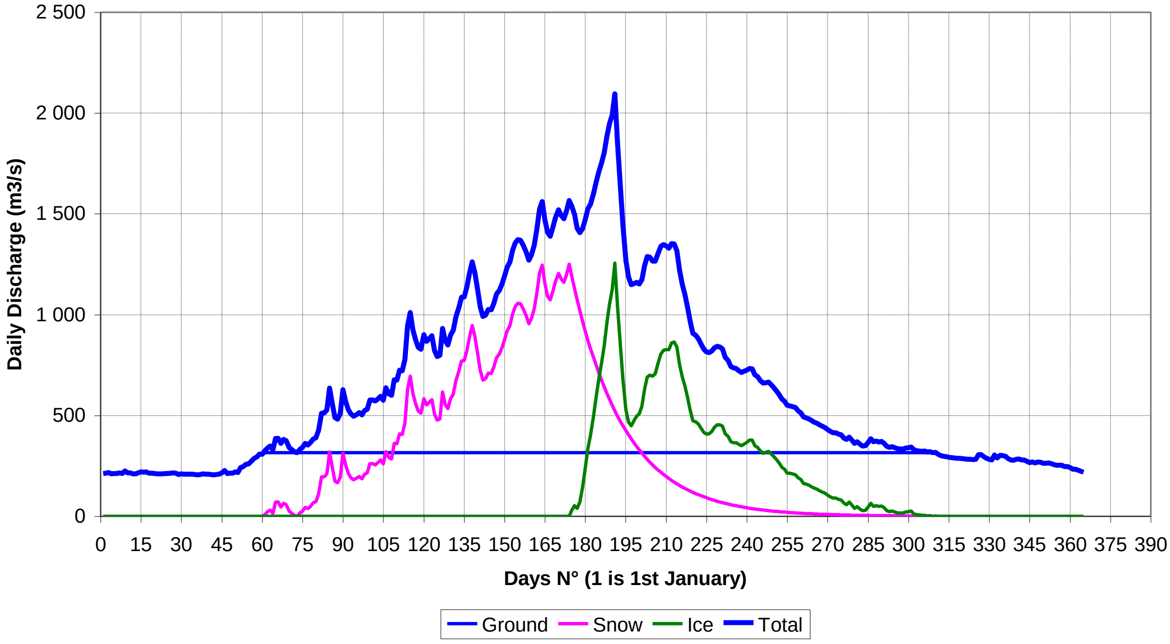
Year	Ground	Snow	Ice	Total	Qdmx
1 990	227	230	180	638	2 600
2 020	241	230	169	641	2 500
2 050	294	230	124	649	2 100
2 080	324	230	103	657	1 910
2 100	344	230	88	663	1 790

(m3/s)

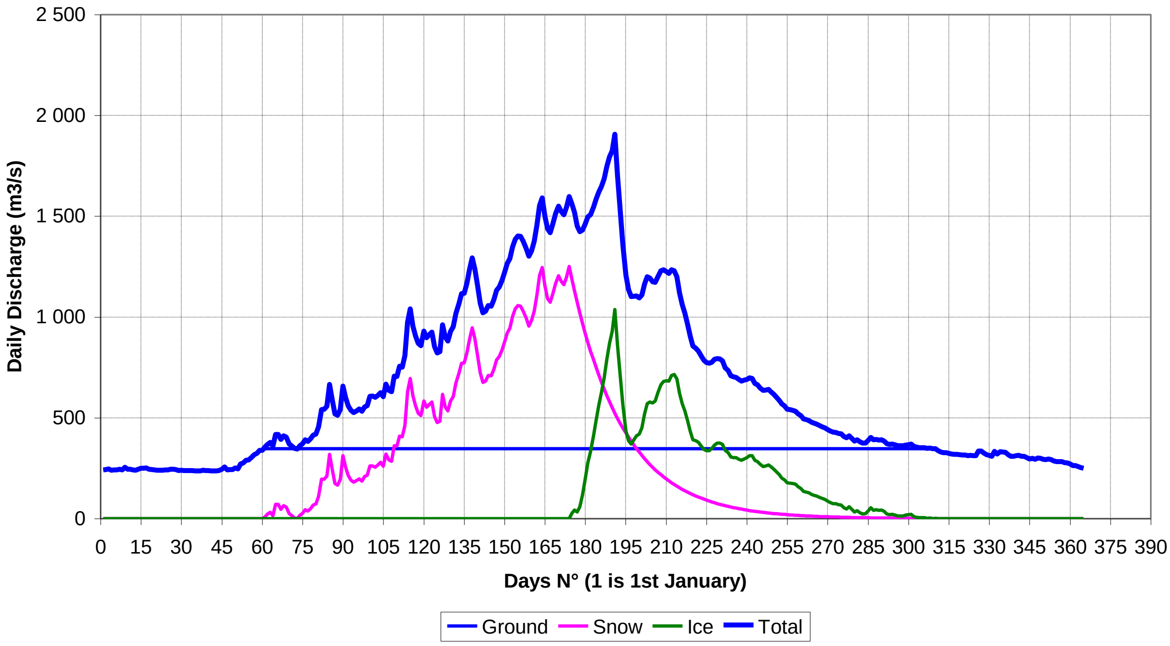
Year 2020 - Average Year - Discharge Trend and Ice Feeding Reduction



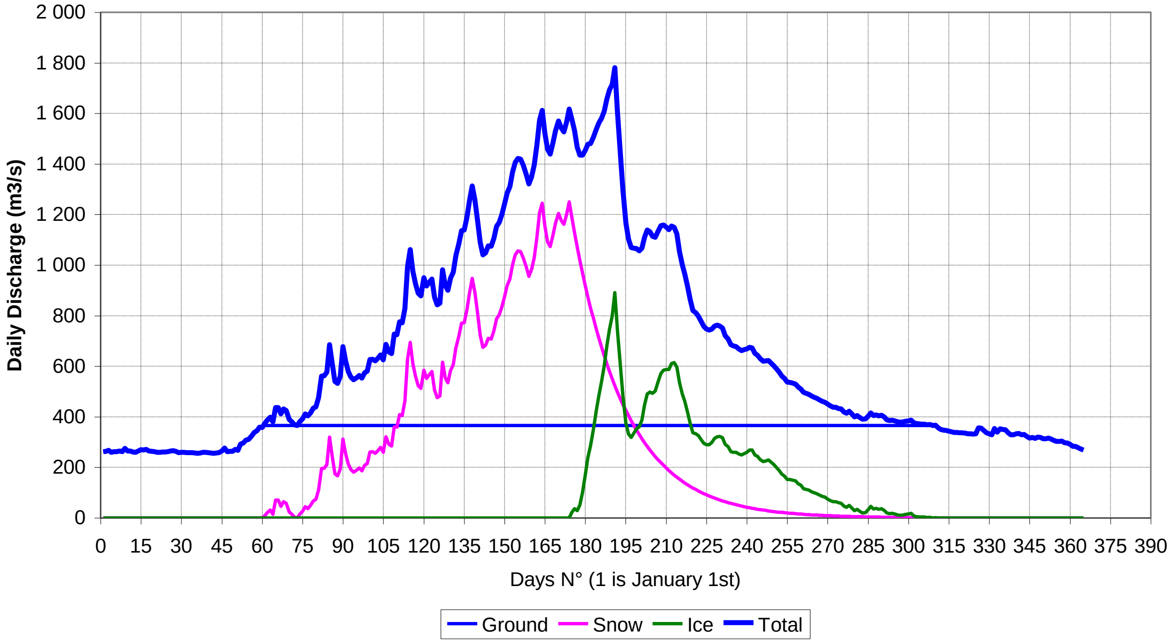
Year 2050 - Average Year - Discharge Trend and Ice Feeding Reduction



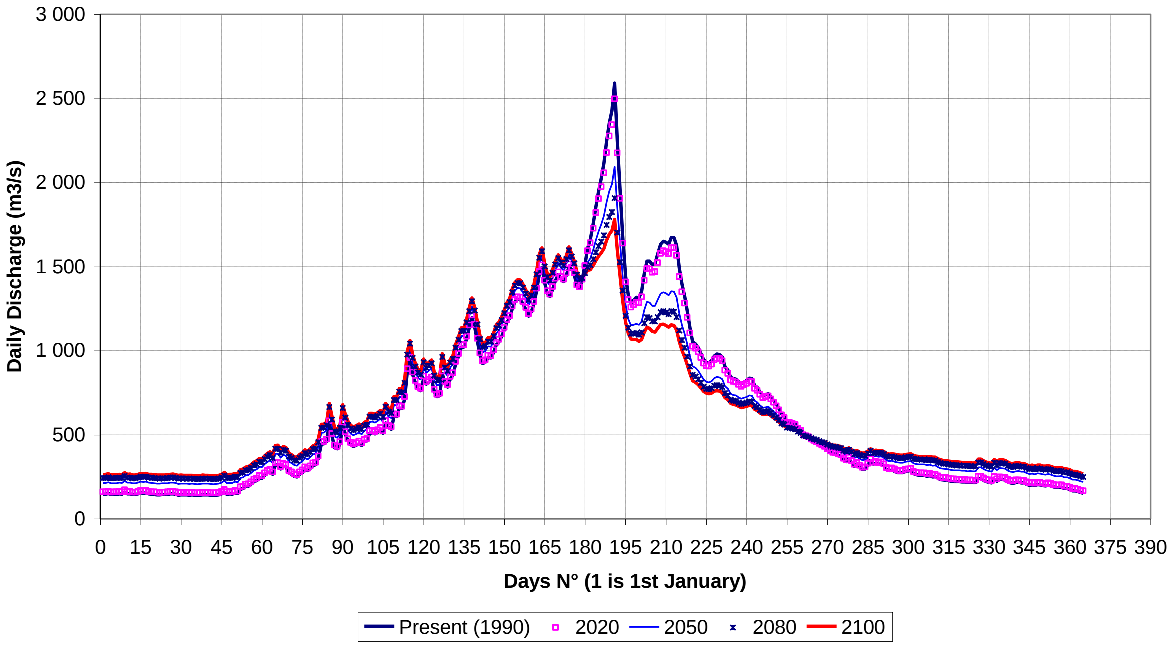
Year 2080 - Average Year - Discharge Trend and Ice Feeding Reduction



Year 2100 - Average Year - Discharge Trend and Ice Feeding Reduction



Average Year - Comparison of Discharges from 1990 to 2100



5.5 Climate Change and Adaptive Management:

5.5.1. Climate Change models as a tool to set up priorities:

Current Climate Change models give meaningful large scale projections that correlate with long term physical observation of dramatic changes in climate, as for example glacier retreat. These models are therefore excellent tools to set up adaption priorities as they already point out major future impacts: changes in flow regimes on glacier melt driven rivers, changes in seasonal discharge distribution, higher extreme event variability etc. These phenomena have a large impact on hydropower facilities and should therefore be considered when planning new projects as Rogun HPP.

However, as shown in the critical review of existing models on Climate Change in Central Asia and in particular in Tajikistan and Amu-Darya basin, there is no doubt that further research is required in order to reduce the uncertainties of the downscaled results, and make them compatible with the level of accuracy required when designing a project as Rogun HPP.

As on today, in particular in terms of precipitation patterns, trends provided by models, are not accurate enough in order to try to understand the local impact of Climate Change on a project as Rogun. Deriving adaptive measures in terms of design criteria based on the current projections at a project level would be inappropriate. However, adaptation to climate change must be incorporated in the overall planning of hydropower and irrigation development in Central Asia.

The peculiarity of a project as Rogun is the transboundary aspect of water resources competing with national interests, requiring integrated approach at a basin level for water use (as already coordinated by ICWC and BVO Amudarya) but also for handling climate change impacts on water regimes. Adaptation to Climate Change will require efficient use and protection of water resources subject to new stresses, improving irrigation technologies for better conservation of the resources and an international cooperation in the use of hydropower resources at national and regional level.

5.5.2. Adaptation measures to Climate Change:

Coping with Climate Change requires high level cooperation based on a step by step approach:

- **Reduce uncertainty:** Research on climate change shall aim at better understanding and modelling climate variations and allow accurate downscaling of results to derive reliable trends on short as well as long term periods. This would allow incorporating trends in the planning of facilities (design criteria) but also in the economic viability of a project (inflow variability could be incorporated in financial and economic forecasts for project viability).

- **Reduce Vulnerability:** Better understanding the potential threats would allow also identifying the most vulnerable populations expected to be affected and incorporate mitigation measures in the planning of projects (flood control etc.).

- **Change use, location etc.:** When such mitigation measures appear to be difficult or non-viable to implement, then direct adjustment to human systems in response to climatic stimuli shall be planned. This could also incorporate potential benefits from climate change impacts as a change in economic opportunities.

- **Adapt measures and inform:** In the current status of knowledge, any measures taken in order to cope with Climate Change are by essence, subject to adaptation on the short term based on observations. Even a very robust and conservative design shall allow some flexibility for updating to cope with the anticipated drastic changes. This requires a strong observation network and environmental monitoring to be sure to revise and renew adaptation measures as for example upgrade existing facilities. This monitoring system could also strengthen weather forecast and early warning system for minimization of natural disaster risks and increase preparedness to extreme phenomena.

These key aspects are being brought up on the international scene for discussions at river basin level to promote cooperation between countries that will be directly affected in quite a short term horizon by Climate Change.