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MISE A JOUR DES ETUDES ET ASSISTANCE TECHNIQUE POUR LA CONSTRUCTION DU BARRAGE DE BISRI

BARRAGE BISRI

AVANT PROJET DETAILLE

PIECE 5: UPDATED HYDROLOGY REPORT

May 2013

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CHAPTER 1 SUMMARY

The purpose of this report is to document the investigations that were performed for the hydrology and sediment studies for Bisri Dam. These studies are based on the prefeasibility hydrologic evaluations performed by ECIDAH in the early 1980's and documented in the 1984 Hydrology Appendix and the Feasibility study performed in April 1995. The following are the study objectives:

- Review the work that was performed for the 1984 prefeasibility study and 1995 feasibility study.
- Determine if additional data are available to further the investigation.
- Determine the discharge values required to size the appurtenant structures, such as the diversion facilities, spillway and outlet works.

The data, assumptions, and procedures used in the 1984 prefeasibility study and 1995 feasibility study were reviewed and updated with additional available data. Furthermore, greater clarification is presented regarding assumptions and procedures used for the analyses; and, additional types of analyses have been performed for purposes of verification and cross-checking results of the flood studies.

The methodology for the hydrology studies is presented in the following Chapters in this report. In Chapter 2, a general description is given of the project watershed. Chapter 3 provides the precipitation and other climatic data used in these studies and describes methods used to check these data. In Chapter 4, a description of the findings of the site visite conducted in May 2013 is included. In Chapter 5, a description is given of the methods for establishing monthly streamflow record at the Bisri damsite.

In Chapter 6, the methods of calculating the design floods for the diversion during construction and for the spillway are described. Chapter 7 provides information on sedimentation and provides an estimate of long-term reservoir sedimentation.

CHAPTER 2 PROJECT AREA

2.1 Introduction

The Bisri Dam Project is located in Southern Lebanon, east of the coastal city of Sidon. The proposed dam site is located on the Bisri River, at an elevation of 395 m, just east of the village of Bisri. The area of the project watershed is 215 km^2, mostly draining the western slope of the mountains named Jabal el Barouk and Jabal Niha. These mountains, rising to elevations higher than 1,900 m above mean sea level, are characterized by a continuous snow cover throughout most winter months.

The project watershed is located between latitude 33^o 30' and 33^o 45' North and longitude 35^o 32' and 35^o 46' East. Towns, villages and farms are scattered throughout the watershed primarily below 1,300 m in elevation. The town of Jezzine is the largest population center in the watershed.

Downstream of the Bisri damsite at elevation 230 m is the Aouali (Awali) hydropower plant which brings water from the Qaraaoun Reservoir on the Litani River. Up to 25 m^3/s can be diverted into the Bisri River through the power plant. The tailrace of the Aouali plant discharges into a 200,000 m^3 storage reservoir which forms the forebay of the Joun hydropower plant located at elevation 33 m, approximately 8 km downstream. Water from the Bisri River can also be diverted into this forebay to increase flow to the Joun powerplant. The Joun plant discharges into an afterbay and then back into the Aouali River, the name given to the Bisri River in its lower reach near the Mediterranean Sea. Thus the Aouali River, in the last 5 km before the sea, normally has a substantial flow even during the dry summer months.

2.2 Watershed Description

The location of the project watershed is shown in Figure 2.1. The figure shows the general topography of the basin. The general shape of the basin is long and narrow. The northern two thirds of the watershed is drained by the El Barouk River which flows in a southerly direction to the Bisri River. The southern one third of the basin is drained by the Aariye River which flows in a northerly direction. Most of the flow entering each of these streams originates in the Niha and El Barouk Mountains which form the eastern boundary of the watershed. The slopes of the channels draining westerly from these mountains are extremely steep, dropping up to 1,200 m in a 5 km reach.

Soils are thin to nonexistent throughout much of the watershed, with large exposures of rock outcrop. Both clastic and carbonate geologic outcropping is found within the basin. The significant number of springs found throughout the Bisri watershed is characteristic of the karstic nature of the limestone in Lebanon.

Much of the land up to elevations as high as 1,200 m has been farmed during the last century. Because the land is generally quite steep, the farming has been done on terraces cut into the hillsides. Today, many of these terraces lie fallow. The effect of these terraces is to slow the velocity of runoff during storms and to maximize the amount of infiltration into the soil. Nevertheless during heavy storms, terraces being farmed can contribute significant amounts of sediment to the streams.

Crops grown on these terraces include a variety of vegetables in addition to grapes and olives. A mixture of hardwood and softwood trees is found in various locations throughout the watershed up to an elevation of about 1,000 m, but only where soil depths are adequate. Where soils are thinner, vegetation typical of desert climates can be found year round. This includes thorny bushes usually less than a meter high and succulents which reach up to a couple meters in height. This vegetation is the result of the long, very dry summer. During the wet winter season, a ground cover of grasses and weeds takes hold anywhere there is thin soil.

The report, Soils of Lebanon, by Sayegh et al. (no date) offers insight into soils derived from the predominate limestone deposits. In previous eras, the Cedars of Lebanon were prized throughout the Mediterranean. At that time, Mount Lebanon was described as densely wooded. The deforestation over a period of time resulted in the loss of the upper most beneficial layers of the soil. The present day cedar zone on Mount Lebanon lies above elevation 1,400 m. Below this elevation, the land is described as mainly waste and with a poor herbaceous stratum.

2.3 Watershed Hydrology

The watershed hydrology is characterized by a rainy season of approximately seven months which begins in October or November of each year and lasts into April or May. Rainfall during the months of June through August is extremely rare. Streamflow is normally highest in February. During September, the average is lowest.

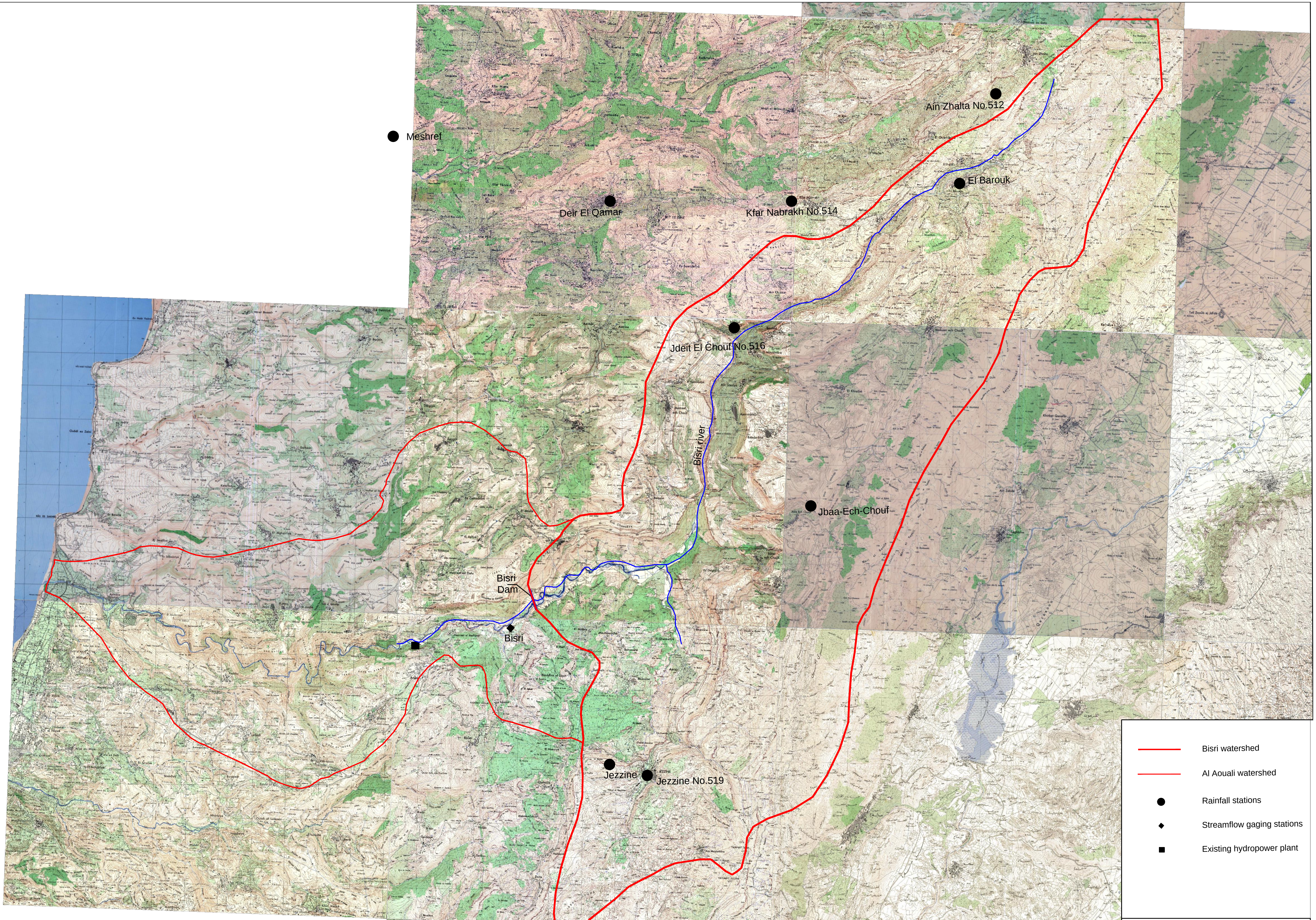


Fig 2.1 BISRI WATERSHED

CHAPTER 3 CLIMATE

3.1 Introduction

The Bisri Dam Project is located approximately 17 km inland from the coast of the Mediterranean Sea at an elevation of 395 meters above mean sea level. The elevation in the drainage basin ranges from 395 m at the damsite to over 1,900 m above mean sea level. The climate in the project area is moderately cold, windy and wet in the winter and warm and dry in the summer and fall.

Before any assessment of the water resources of a region can possibly be performed, current and past climate information pertaining to temperature, humidity, wind, and evaporation must be evaluated.

3.2 Station Location

The climatological information on the Bisri Basin were obtained from the following stations:

Weather Element	Name of Stations
Temperature	Bhamdoun and Kfar-Nabrakh
Relative Humidity	Bhamdoun and Kfar-Nabrakh
Wind	Ksara Observatory, A.U.B., and College of Machmouche
Evaporation	Kfar-Nabrakh and Bhamdoun

The stations from which precipitation data were collected and analyzed are listed in Chapter 4. The weather elements, with the exception of precipitation, are discussed in the following section.

3.3 Climatology

The historical climatological records including temperature, relative humidity, evaporation, and precipitation indicate how the proposed system will respond in the future. The temperature and relative humidity are associated with the reservoir surface evaporation. Precipitation is directly related to runoff.

3.3.1 Temperature

Recorded temperatures at the stations of Bhamdoun and Kfar-Nabrakh were collected and analyzed. Both of these stations are close to the Bisri damsite as indicated in Figure 2.1. The monthly mean temperatures at both stations are presented in Tables 3.1 and 3.2. The monthly mean temperatures are also plotted in Figures 3.1 and 3.2.

The mean temperatures at Bhamdoun vary from a low of 7.2^{O}C in January to a high of 22.2^{O}C during the month of August. At Kfar-Nabrakh the mean temperatures vary from 8.3^{O}C in January to 23.1^{O}C in August.

3.3.2 Relative Humidity

The relative humidity data for the Bisri Dam Project were available at the Bhamdoun and Kfar-Nabrakh stations. These data are presented in Tables 3.3 and 3.4 and are plotted in Figures 3.3 and 3.4. The mean of the monthly relative humidity at these two stations varies from a minimum of 55.6 percent in the month of May at Kfar-Nabrakh to a maximum of 72.1 percent in the month of January at Kfar-Nabrakh. The measured absolute monthly minimum was 30 percent in the month of May at Kfar-Nabrakh, and the measured absolute monthly maximum was 88 percent in the month of January at Kfar-Nabrakh.

3.3.3 Wind

The wind records are available at KSARA observatory, A.U.B., and at a station located in the project watershed at the College of Machmouche near Jezzine. Maximum wind recorded at the College of Machmouche was a gust with a velocity of 47 m/s.

3.3.4 Evaporation

The available evaporation data measured at the stations of Bhamdoun and Kfar-Nabrakh were also collected for analysis. These data are presented in Tables 3.5 and 3.6 and are plotted in Figures 3.5 and 3.6. The evaporation measured at the station of Bhamdoun ranges between 19 mm and 196 mm per month, and the evaporation measured at Kfar-Nabrakh ranges between 15 mm and 175 mm per month. Of the two stations, Kfar-Nabrakh is closer to the damsite. The recorded evaporation at this station provides an indication of expected evaporation from the reservoir surface. The mean, the minimum, and the maximum of the measured monthly evaporation at the two stations are also presented in Tables 3.5 and 3.6.

3.4 Precipitation

3.4.1 Station Network

The locations of the rainfall stations used in the feasibility study of 1995 for computing mean monthly and mean annual basin precipitation for Bisri Dam Project in addition to the new stations established in the recent years used to update the data in the current study are shown in Figure 2.1. The names of the stations, their identification numbers, and the period of available records are listed below:

Name of Station	Identification No.	Period of Available Record
Aain-Zhalta	512	1939-40 - 1970-71
Kfar-Nabrakh	514	1944-45 - 1970-71
Jdeit-ech-Chouf	516	1943-44 - 1970-71
Jezzine	519	1927-28 - 1936-37 and 1939-40 - 1970-71
Jezzine		2001-02 – 2008-09
El Barouk Fraidis		2001-02 – 2008-09
Deir El Kamar		2001-02 – 2008-09

Name of Station	Identification No.	Period of Available Record
Jbaa Ech Chouf		1964-65 – 1969-70 and 1991-92 – 2008-09
Meshref		2002-03– 2008-09

3.4.2 Double Mass Analysis

The double mass analysis is a useful method of detecting an inconsistency in a data set. It is often used to check rainfall data by comparing each rain gage individually against the cumulative total of several nearby gages. If the rainfall record is consistent, a straight line is generally obtained. If, however, the rain gage has been moved or replaced, the double mass plot will often have a break in continuity. The double mass analyses that were performed for the 1984 Prefeasibility Report were reevaluated and were determined to be appropriate for this study.

A new double mass analysis was conducted on the stations recently established. The results of this analysis were inconsistent.

At each of the four stations of the feasibility study, the records from the years 1944-45 through 1970-71 were selected for analysis. For that period, precipitation records for the months of March, April and May in 1963 at station 514 were missing. Precipitation records for the months of September, October and November 1958, September and October 1959, and January 1960 at station 519 were also missing. The precipitation during the unrecorded months at station 514 was estimated from the records for those months at neighboring stations 513, 515 and 516. The precipitation for the unrecorded months at station 519 were estimated from the records at neighboring stations 514, 515 and 516. With missing data estimated, the four selected stations provided a continuous 27-years of record for testing the consistency of the data by double mass analyses. The precipitation data for each of the four selected stations during the years 1944-45 through 1970-71 are presented in Tables 3.7 through 3.10. The double mass analyses for annual precipitation for the four stations shows that the precipitation data are consistent and reasonably valid.

3.4.3 Basin Precipitation

To compute the basin precipitation, the Thiessen method was used for the Bisri Basin with the four selected stations in the feasibility study of 1995 as a first approach and the most three representative recently established stations as a second approach. The two Thiessen polygon diagrams are shown in Figure 3.16. The Thiessen method assumes that at any point in the watershed the rainfall is the same as that at the nearest gage. Therefore, the depth recorded at a given gage is applied out to a distance halfway to the next station in any direction. The relative weights for each gage are computed from the corresponding polygon areas within the network. The Thiessen method does not directly account for orographic influences on rainfall but it is generally more accurate than using the arithmetic mean of the gages. The Thiessen method is the accepted procedure when the available data are limited.

The percentage of the total area assigned to each station was computed by planimetering each polygon. The following is the percent distribution of areas (area factors) for the four stations, showing also the mean annual precipitation at each of the recent stations and elevation of each.

Name	Station No.	Percent Distribution	Mean Annual Precipitation	Station Elevation
Stations used in the Feasibility Study of 1995				
Aain Zhalta	512	17.0	1,226 mm	1,080 m
Kfar-Nabrakh	514	12.8	1,300 mm	810 m
Jdeit-ech-Chouf	516	28.7	1,326 mm	770 m
Jezzine	519	41.5	1,299 mm	945 m
Recently Established Stations Used				
Jezzine	-	26.4	1,060 mm	1070 m
El Barouk Fraidis	-	28.4	998 mm	1114 m
Jbaa Ech Chouf	-	45.2	1,202 mm	1130 m

The basin precipitation was computed by multiplying the precipitation at each of the stations by its respective area factor for the corresponding years of available data. The resulting monthly and annual precipitation for Bisri Basin is presented in Table 3.16. The monthly precipitation for Bisri Basin is plotted in Figure 3.17. The 35-year mean annual basin precipitation calculated by this method is 1,255 mm with an average of 1,294 mm for the old stations and 1,107 mm for the recently established stations. The average monthly precipitation varied from a minimum of zero in the month of July to a maximum of 283 mm in the month of January. Figure 3.18 compares the average annual precipitation data for all the available stations with the Bisri Basin computed data.

The mean annual precipitation for the basin was also planimetered from the national rainfall isohyetal map (F.A.0., 1973). The mean annual precipitation for the basin obtained by this procedure is 1,244 mm, which is about 1 percent lower than the mean annual basin precipitation obtained above. This indicates that basin precipitation calculated from the selected stations is representative of true basin precipitation. It also indicates that orographic influences of the mountain ranges are negligible in determining average precipitation for the Bisri Basin since orographic effects are reflected in the isohyetal map.

Figure 3.1: Monthly Mean Temperatures (°C) at Bhamdoun

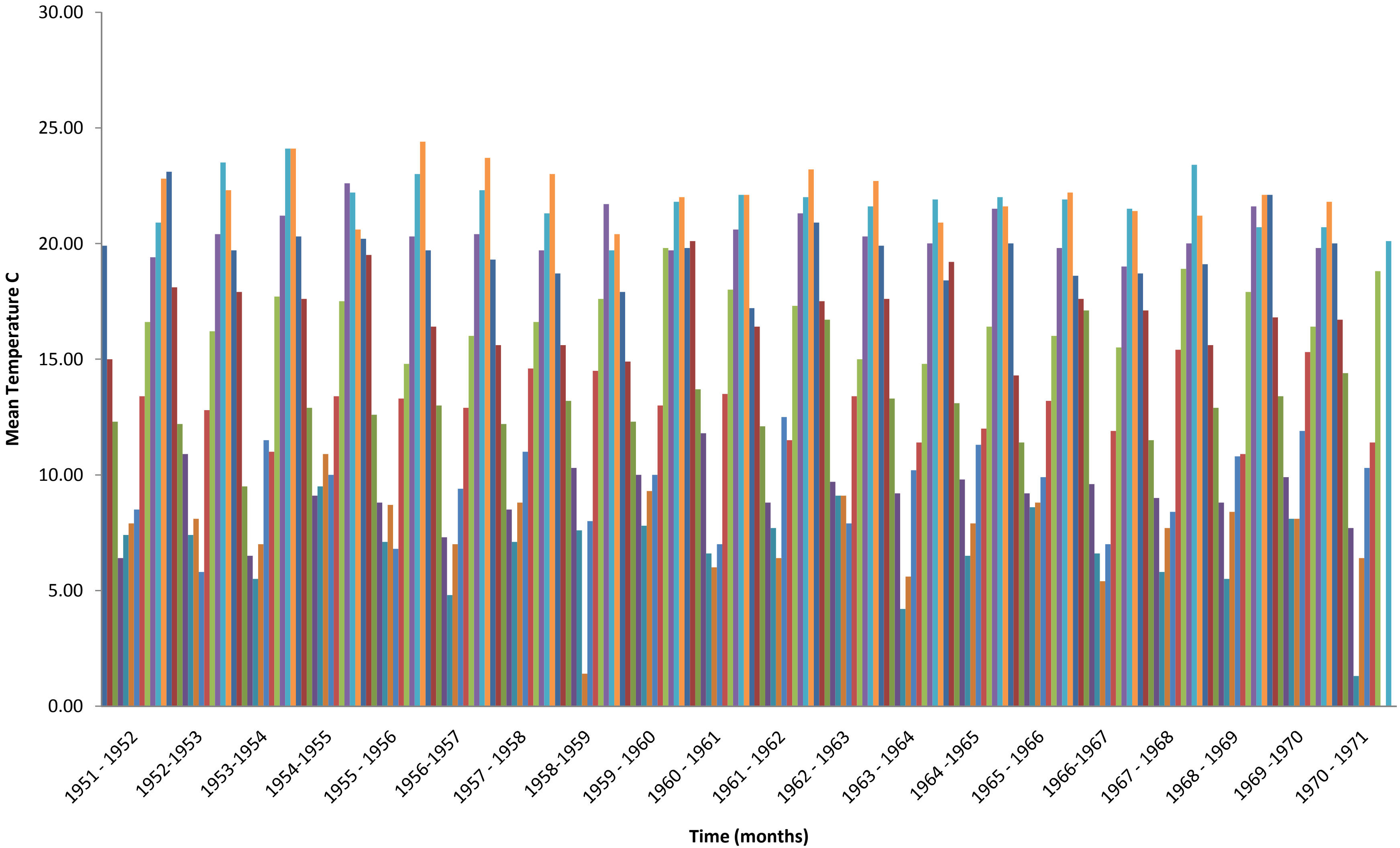


Figure 3.2: Monthly Mean Temperatures (ºC) at Kfar Nabrakh

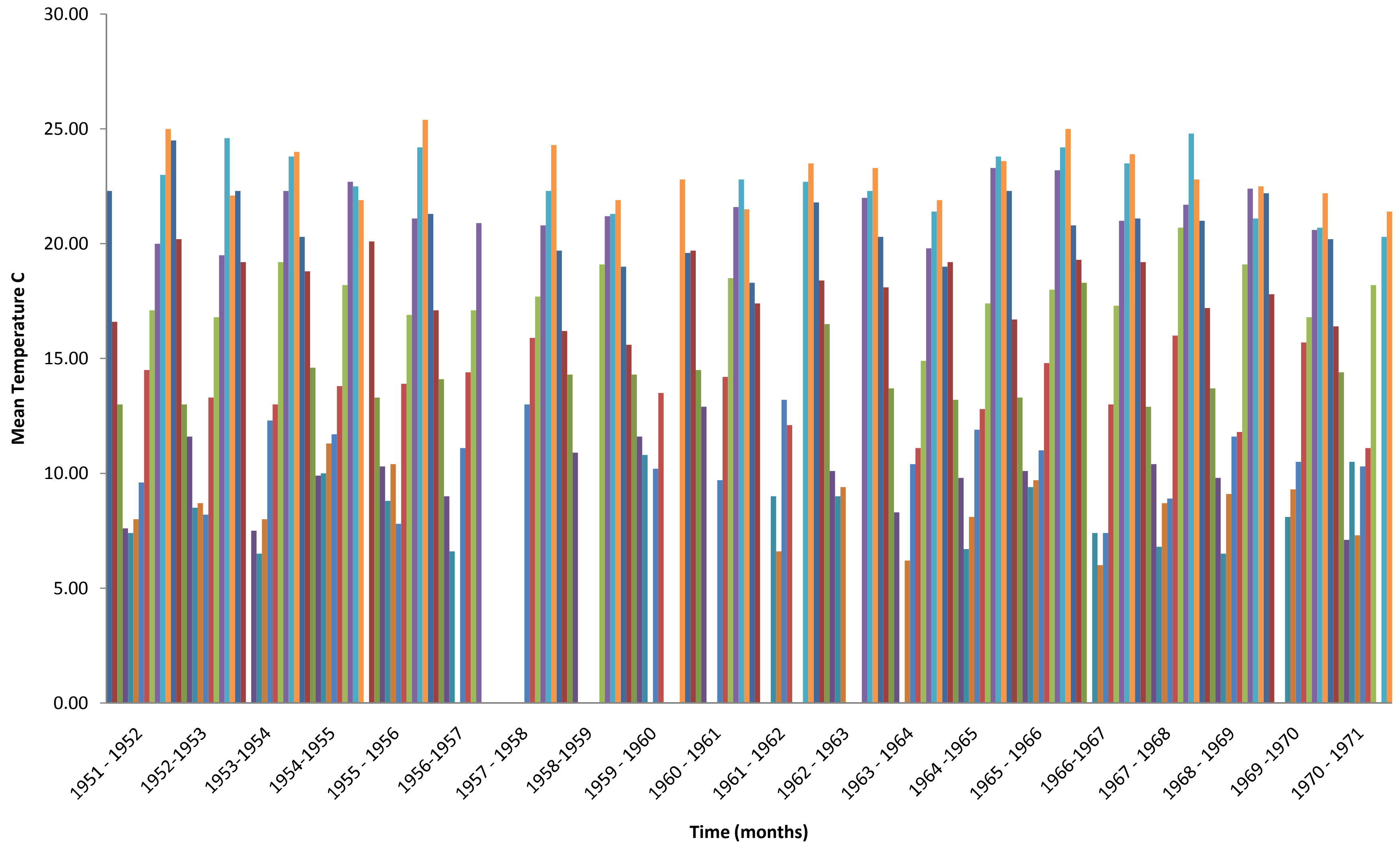


Figure 3.3: Relative Humidity at Bhamdoun

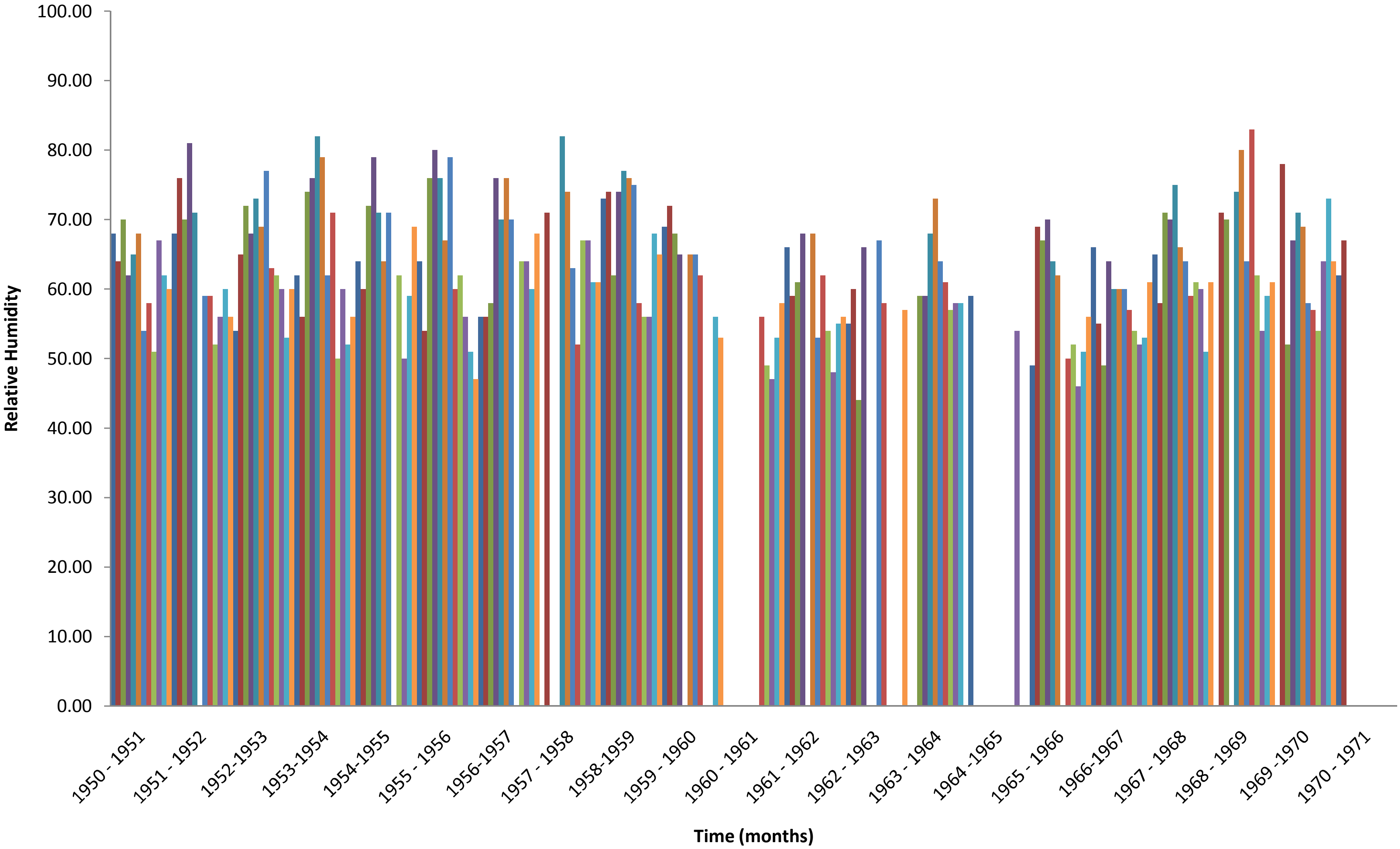


Figure 3.4: Relative Humidity at Kfar Nabrakh

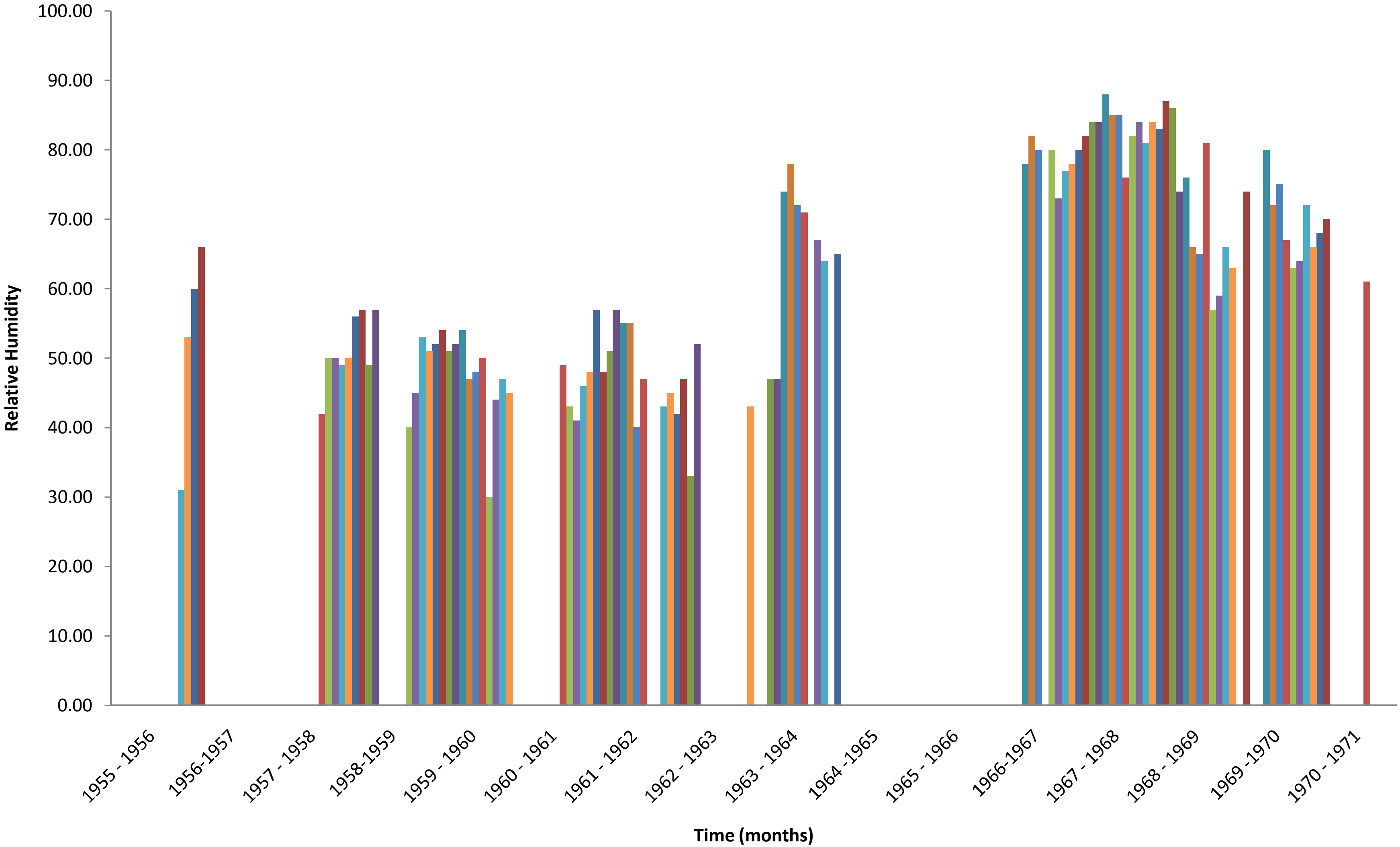


Figure 3.5: Monthly Evaporation at Bhamdoun

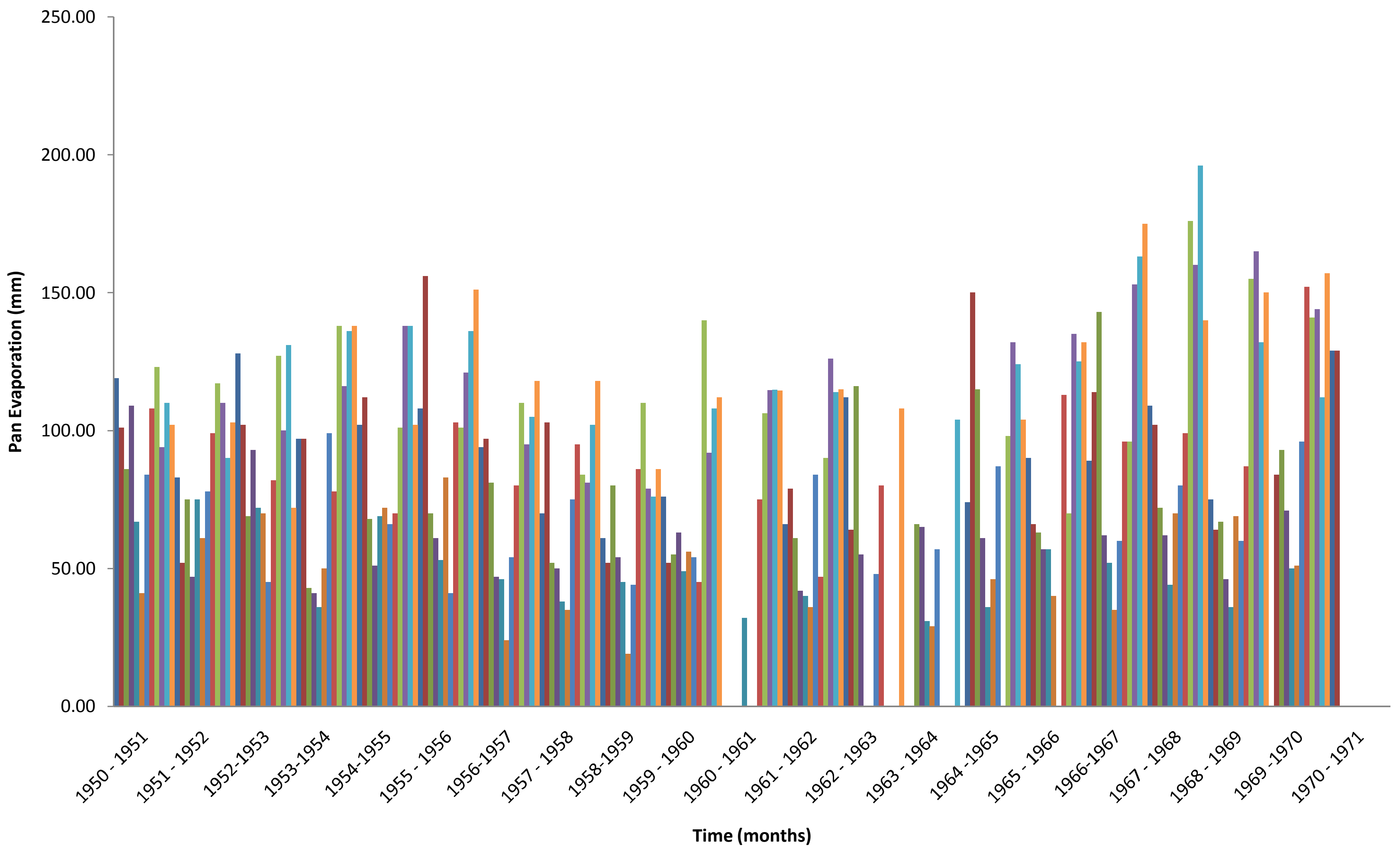


Figure 3.6: Monthly Evaporation at Kfar Nabrakh

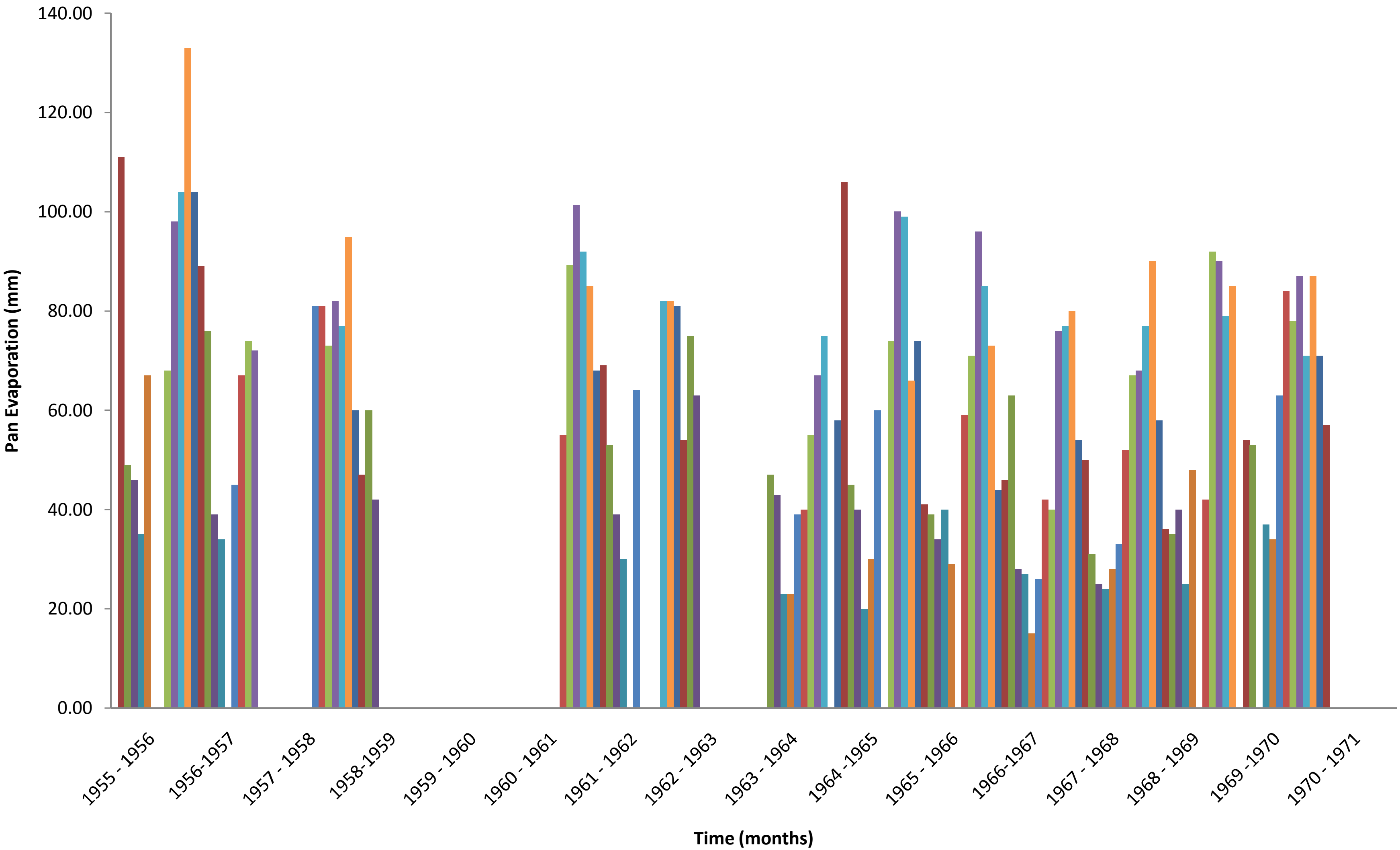


Figure 3.7: Monthly And Annual Precipitation at Aain-Zahlta

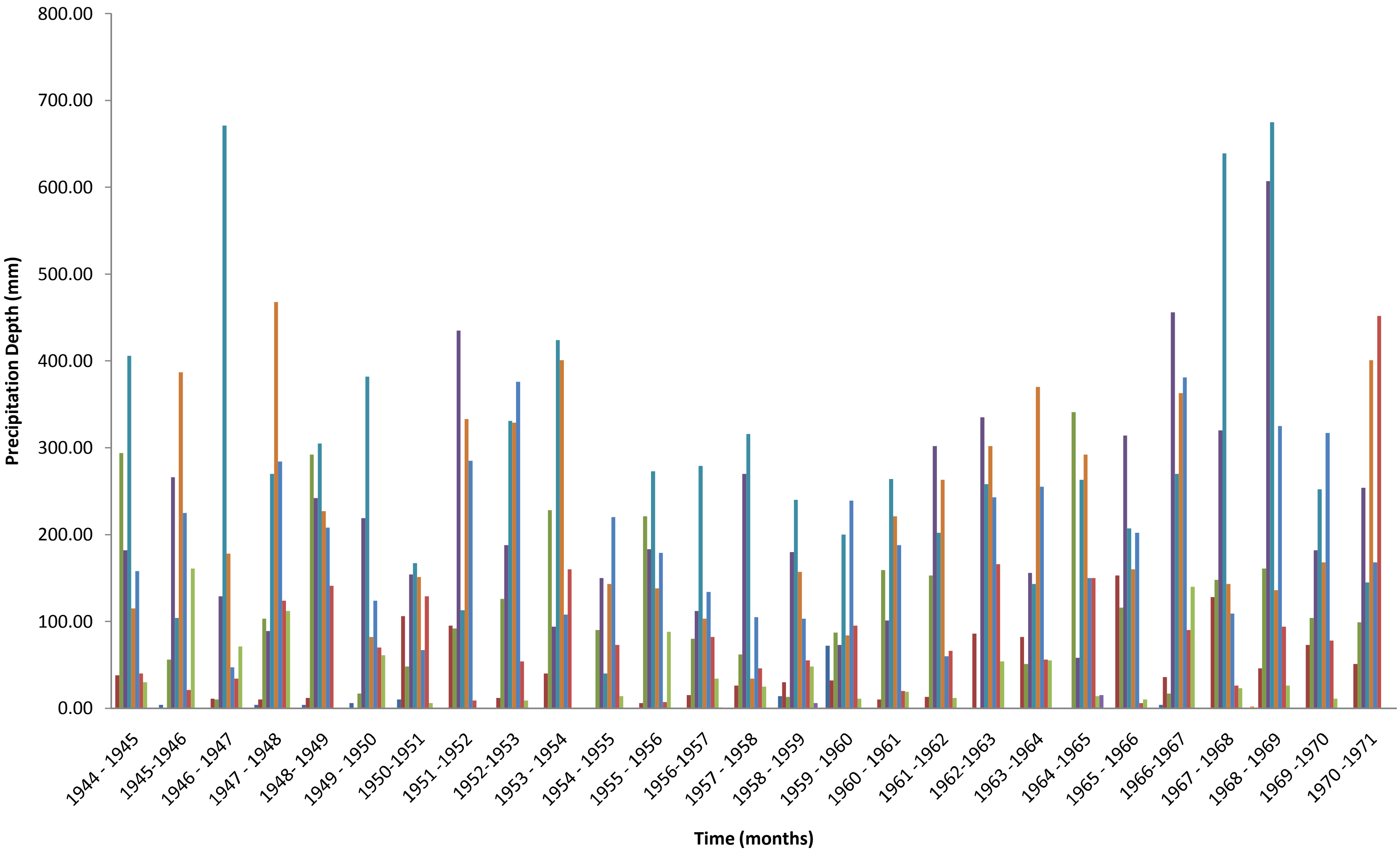


Figure 3.8: Monthly And Annual Precipitation at Kfar Nabrakh

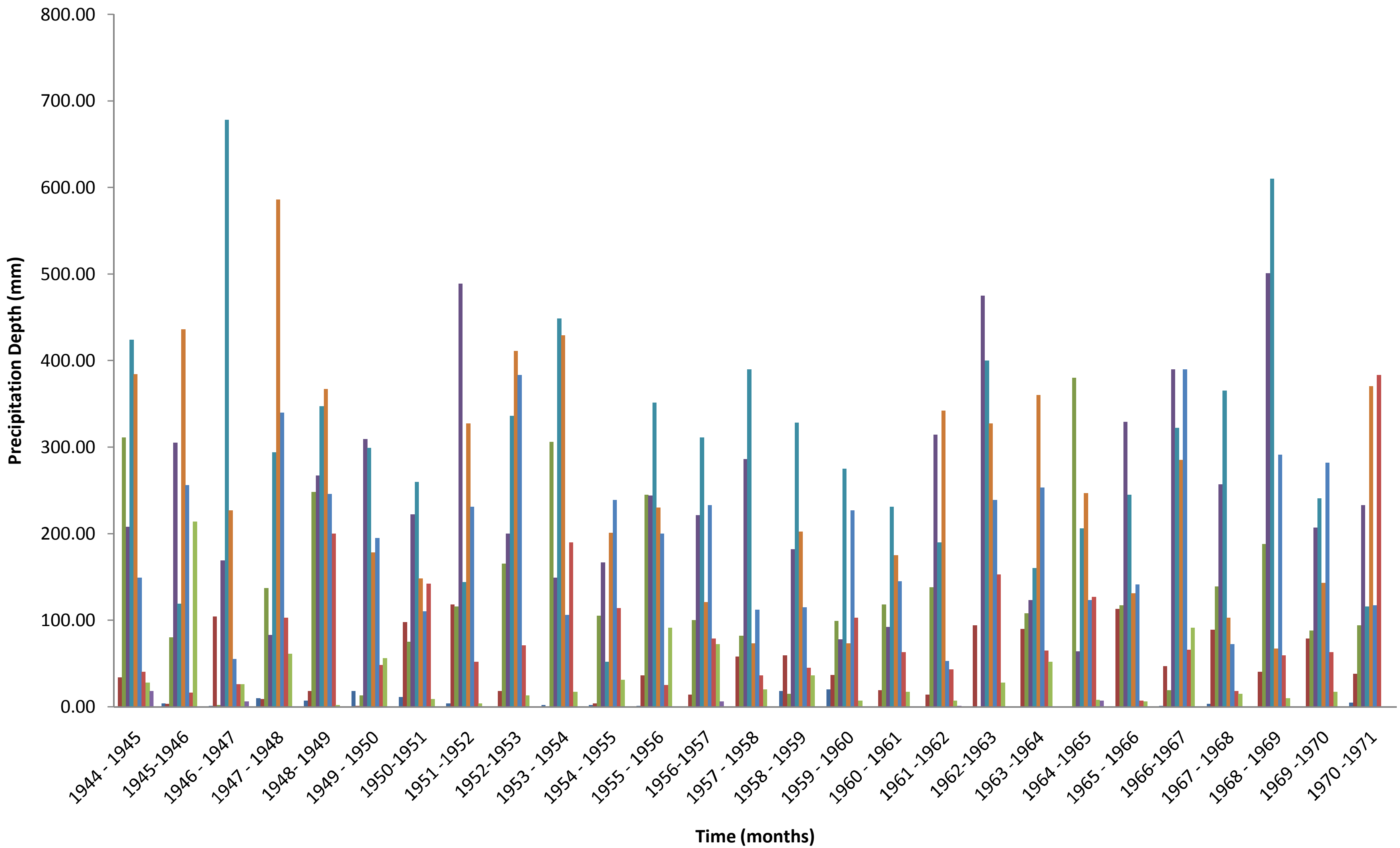


Figure 3.9: Monthly And Annual Precipitation at Jdeit-Ech-Chouf

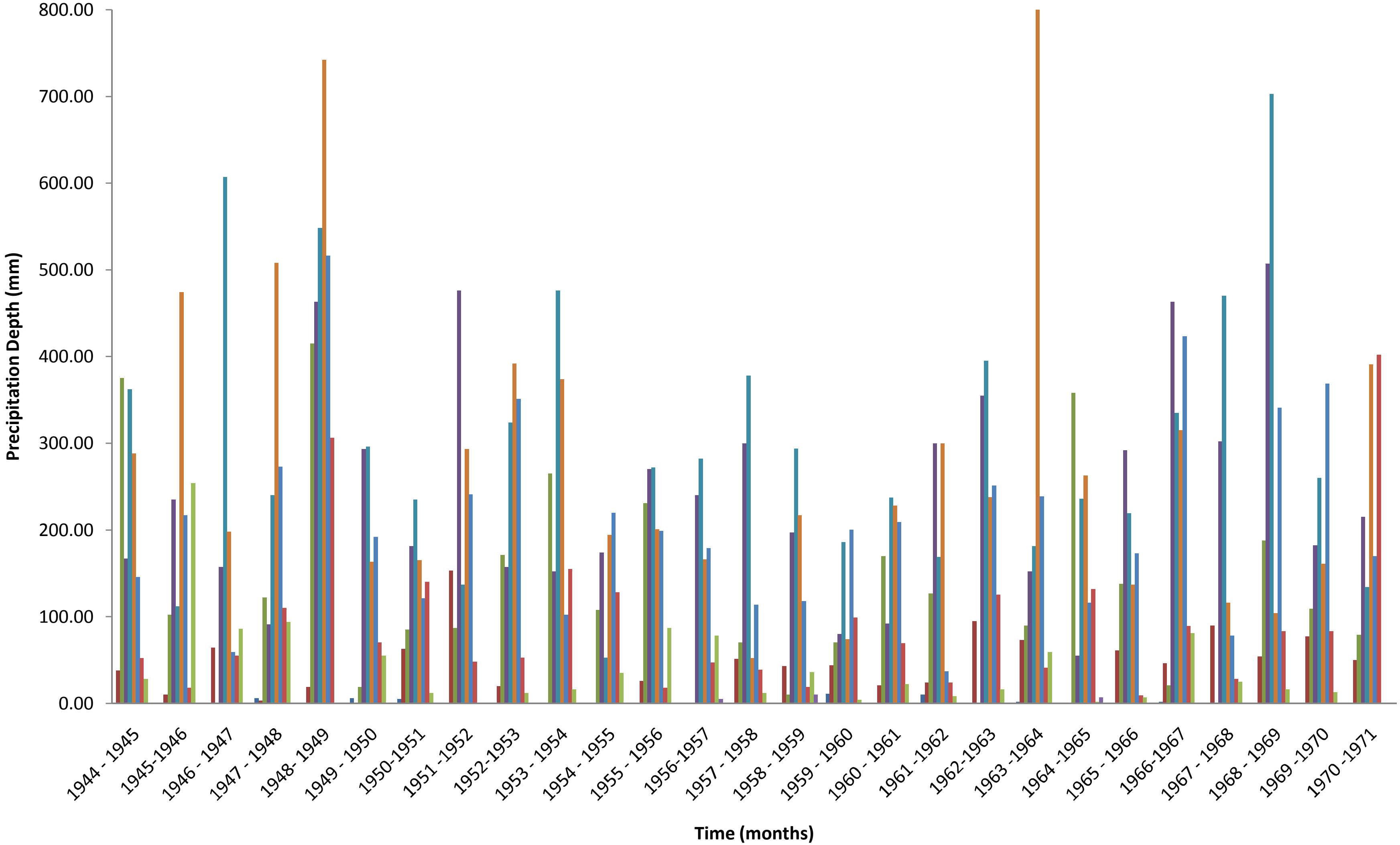


Figure 3.10: Monthly And Annual Precipitation at Jezzine

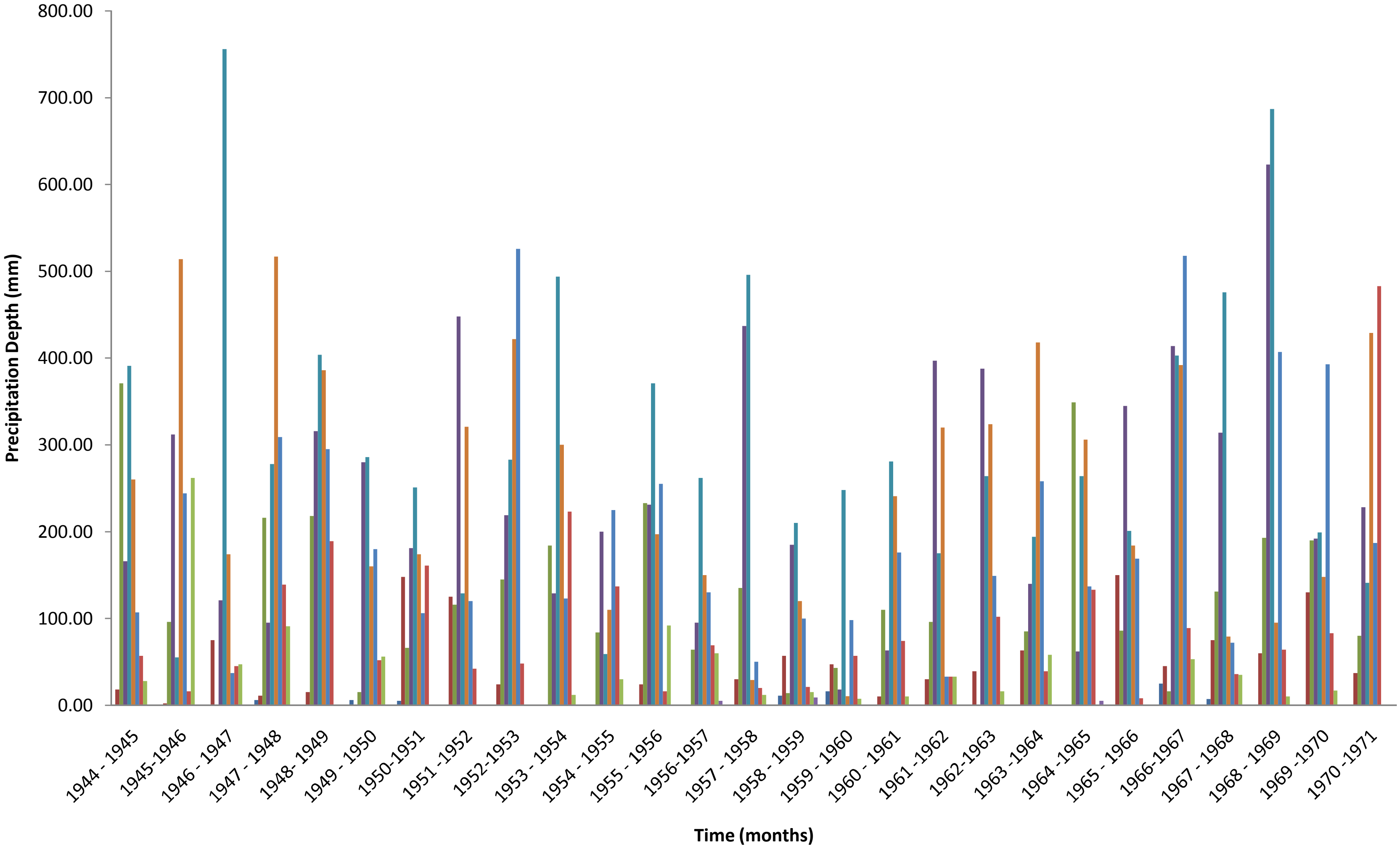


Figure 3.11: Monthly And Annual Precipitation at Jezzine

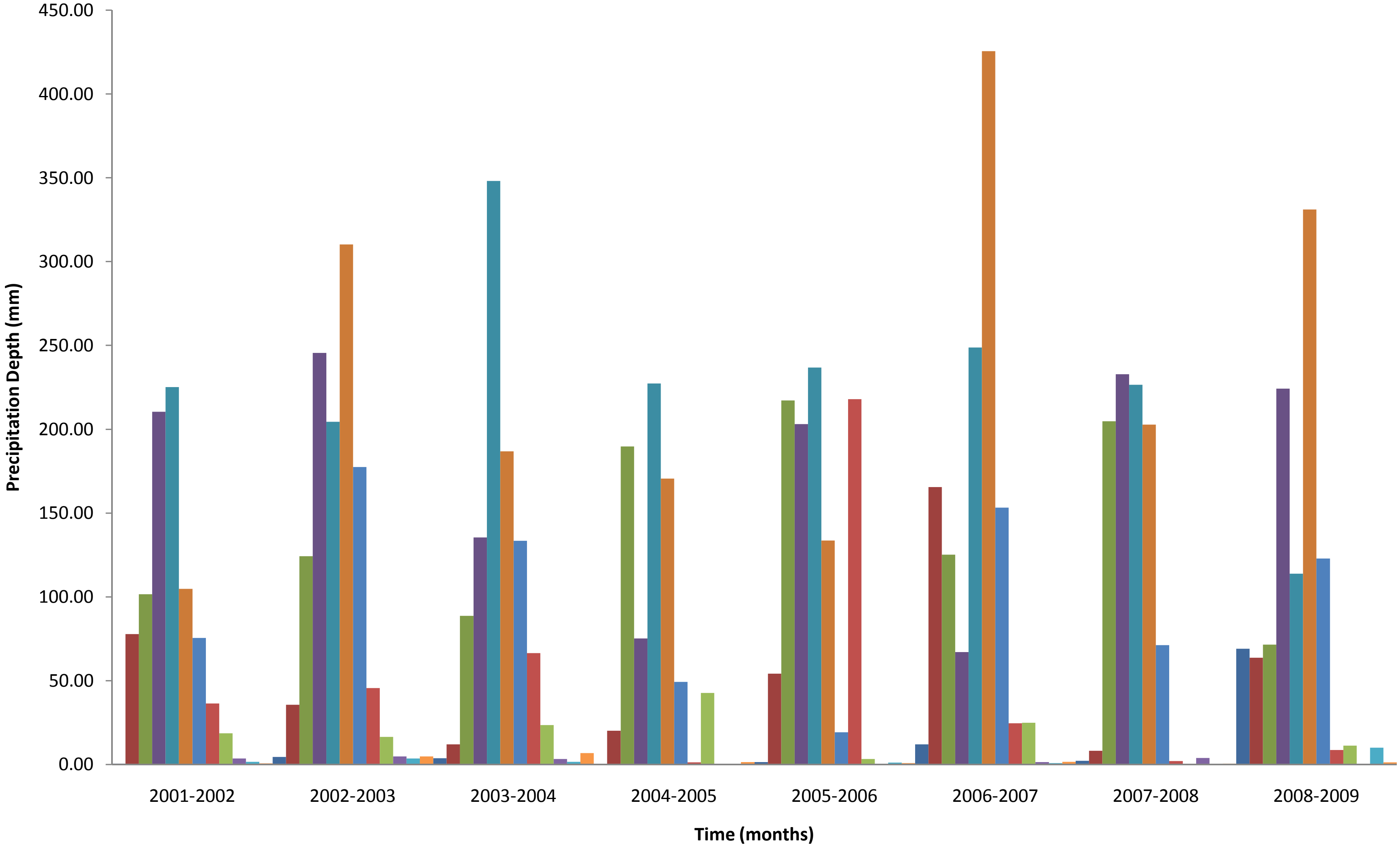


Figure 3.12: Monthly And Annual Precipitation at El-Barouk_Fraidis

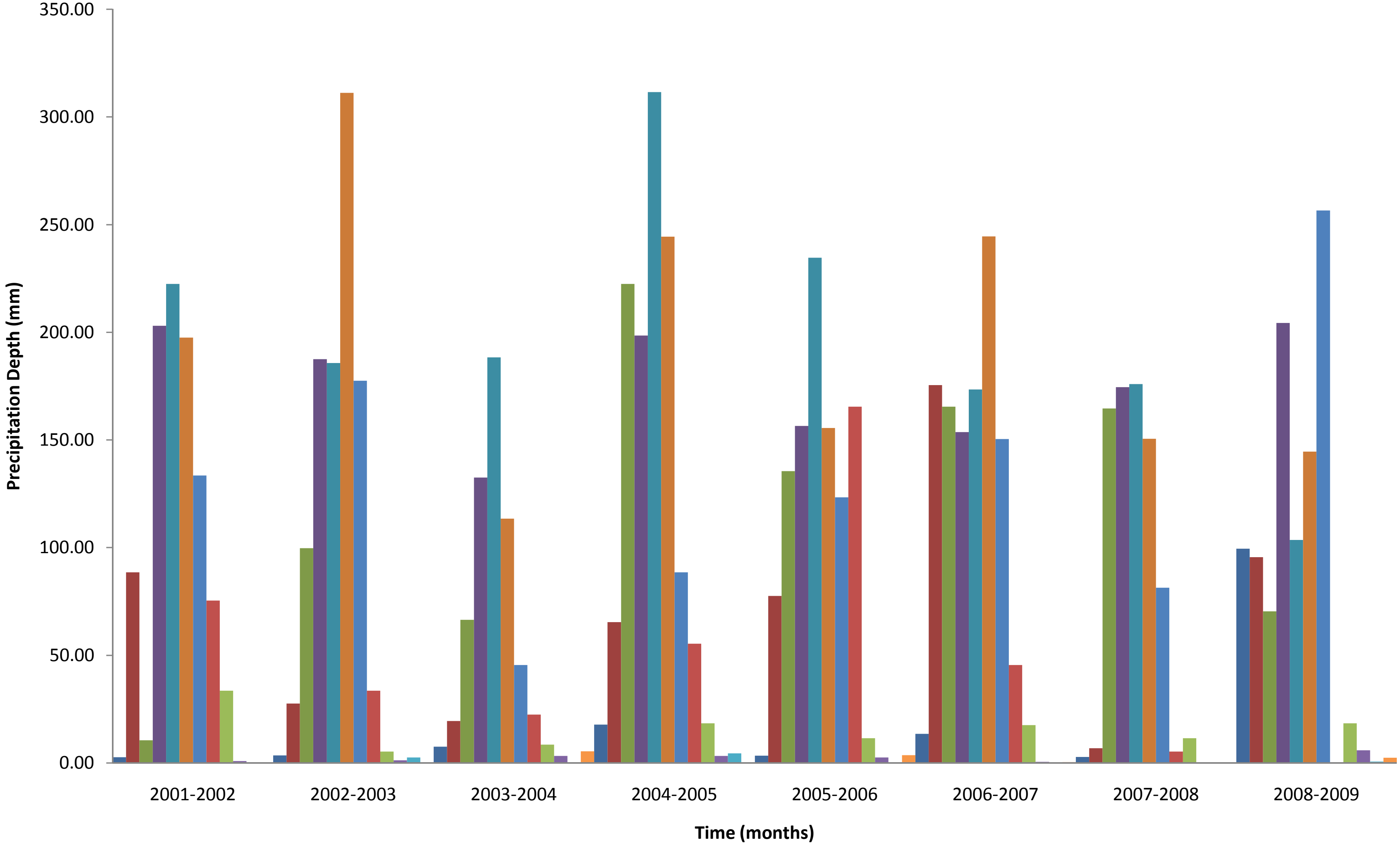


Figure 3.13: Monthly Precipitation at Deir El-kamar

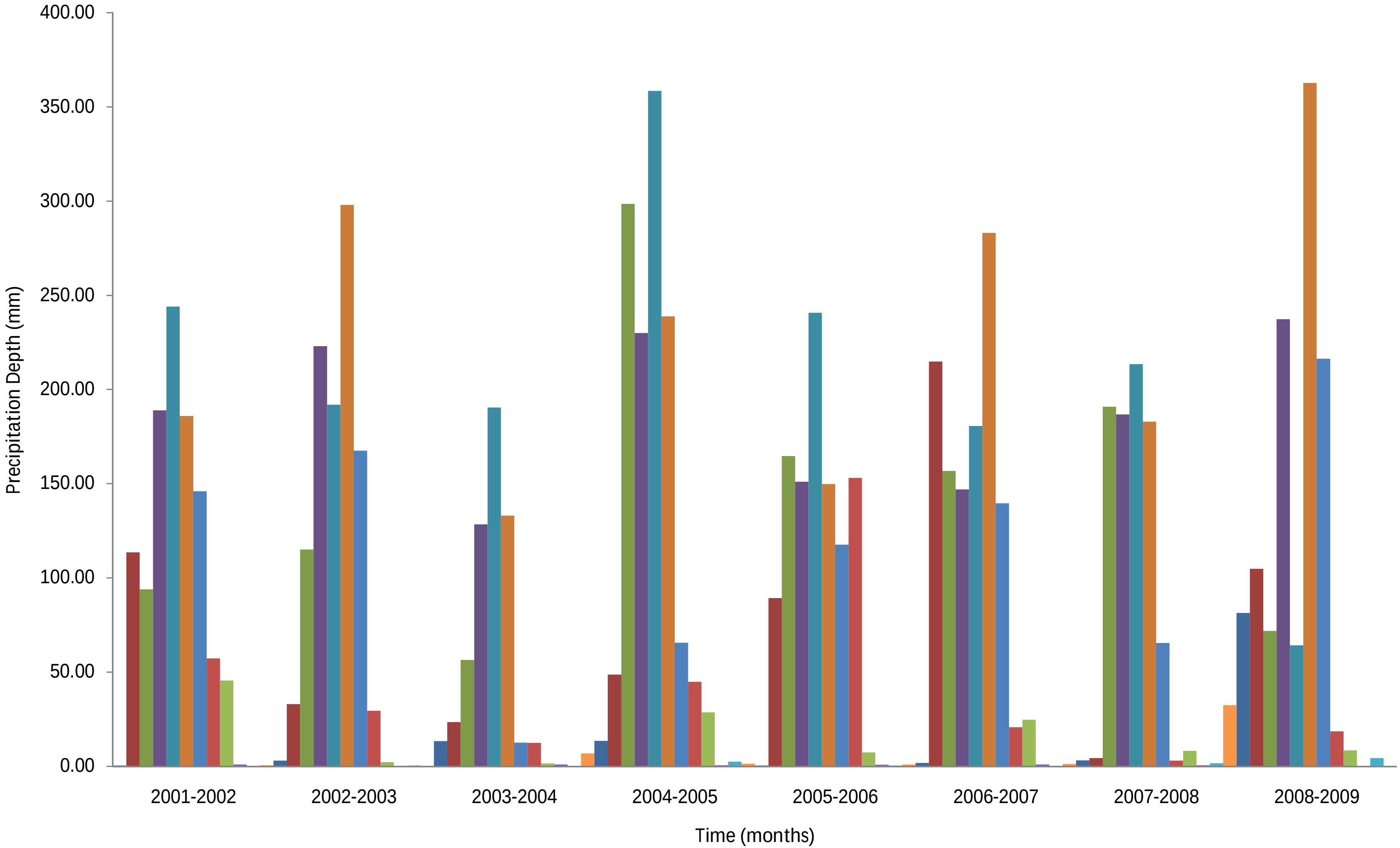


Figure 3.14: Monthly Precipitation at Jbaa-Ech-Chouf

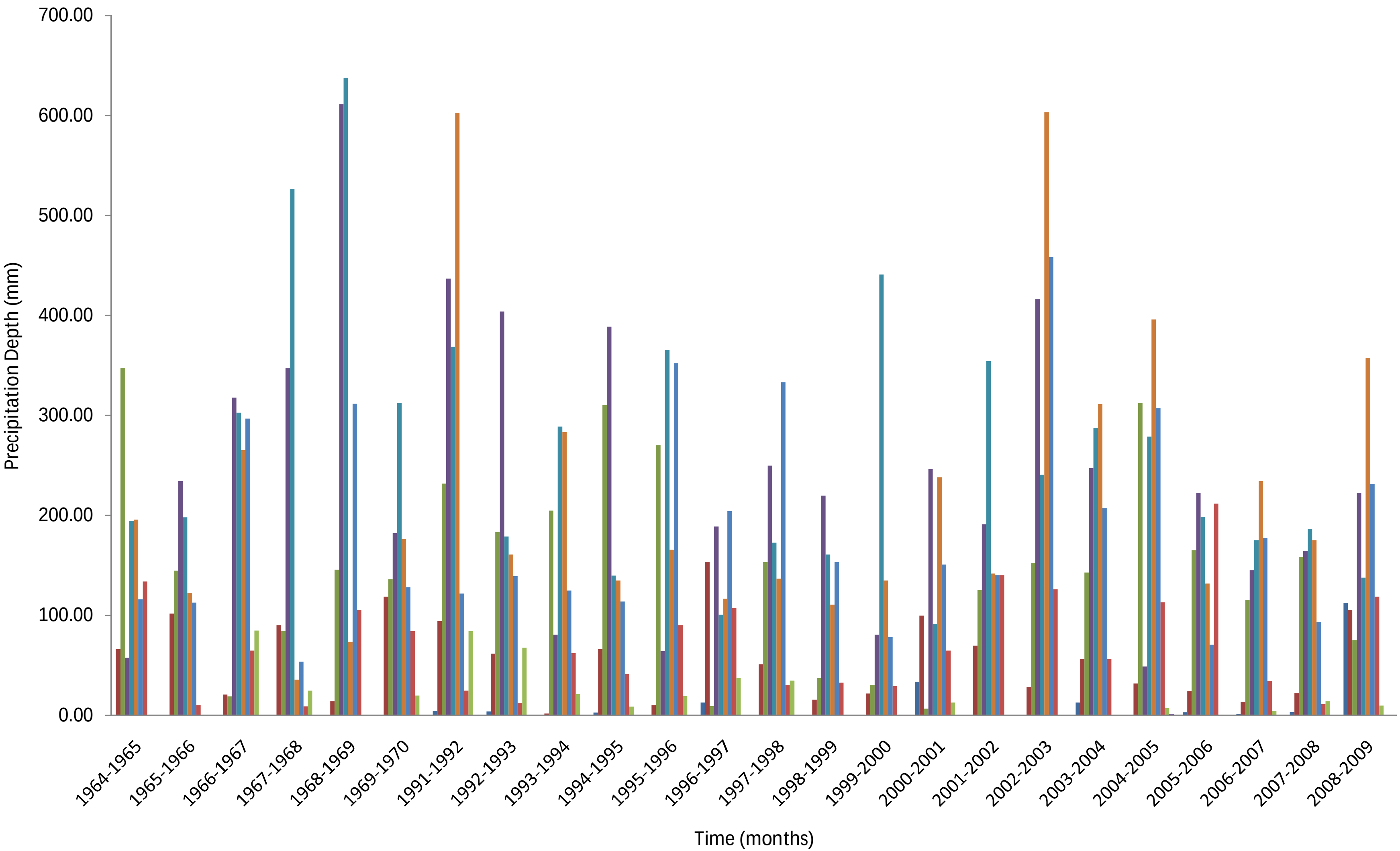
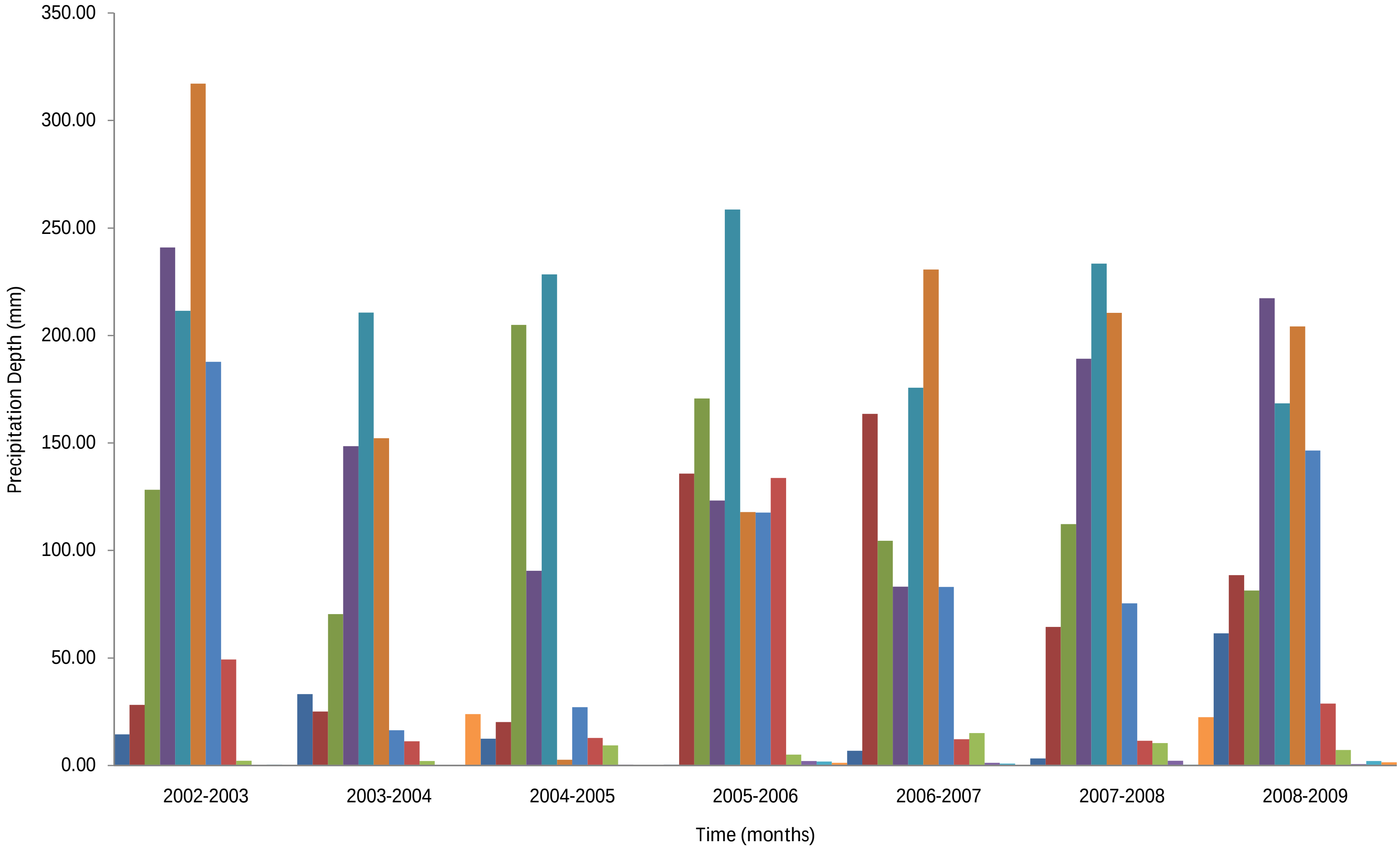


Figure 3.15: Monthly Precipitation at Meshref



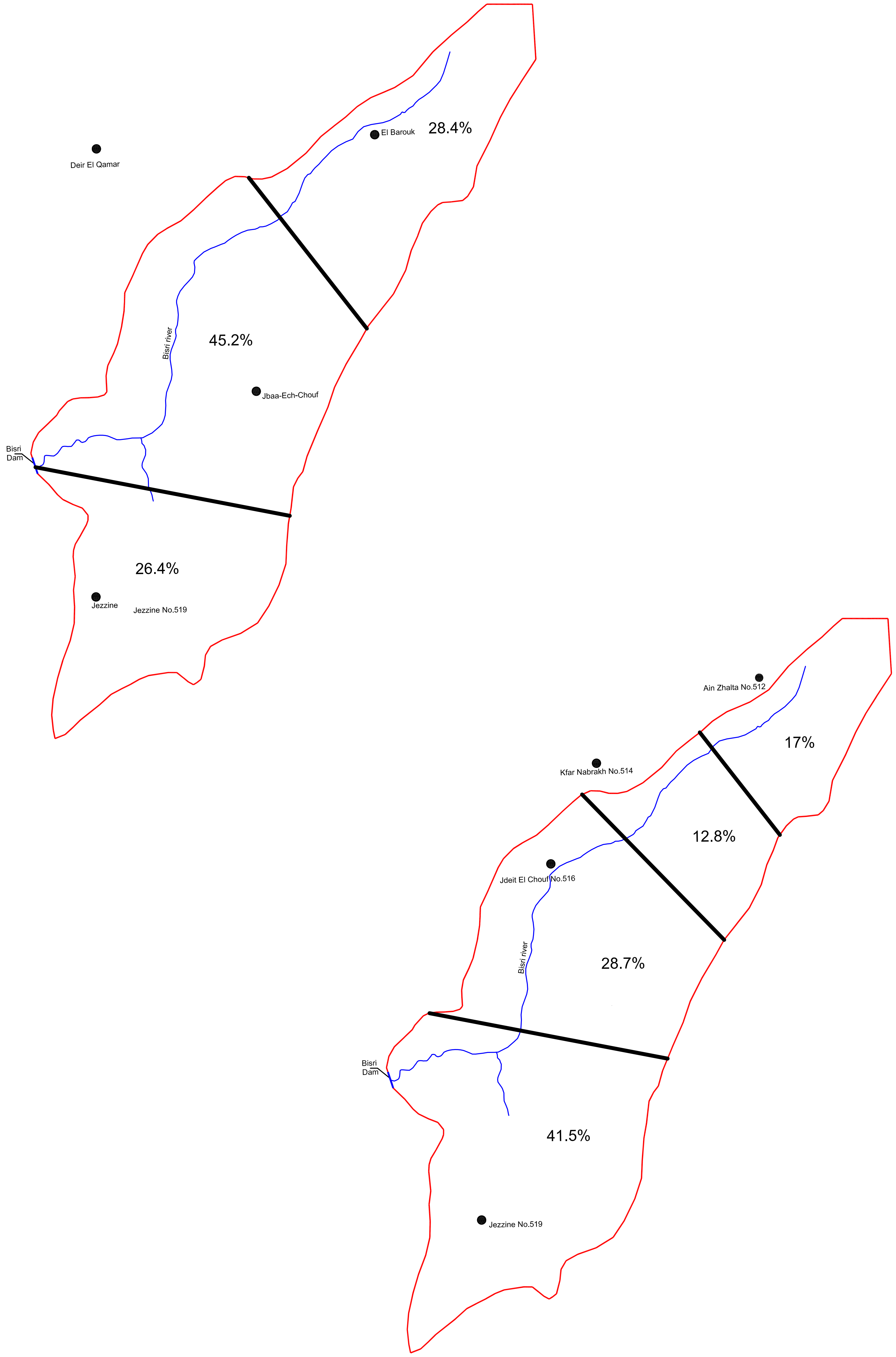


Fig 3.16 Bisri Basin; Theissen Polygon Network

Figure 3.17: Bisri Basin Precipitation

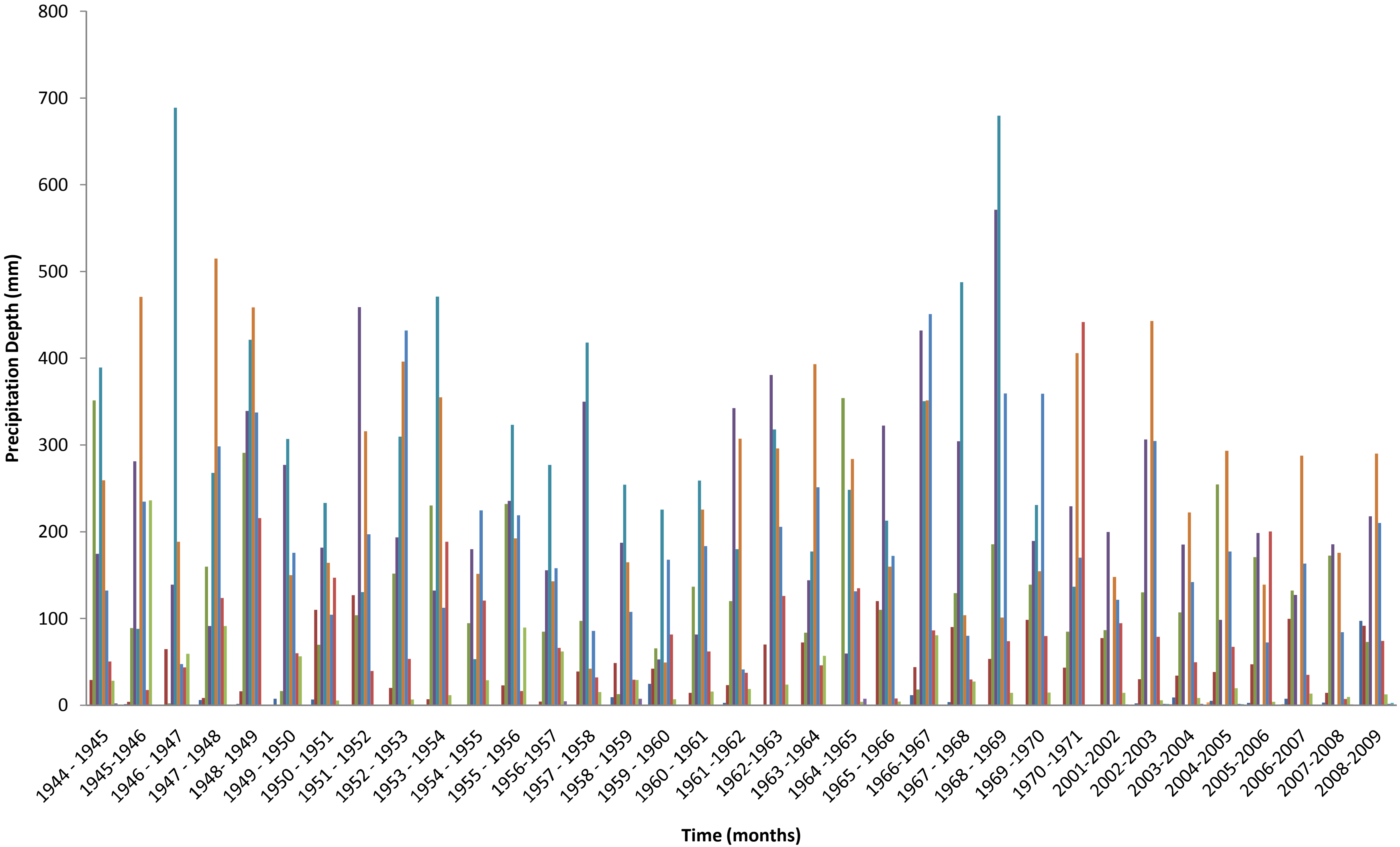


Figure 3.18: Annual Precipitation - Rainfall Stations

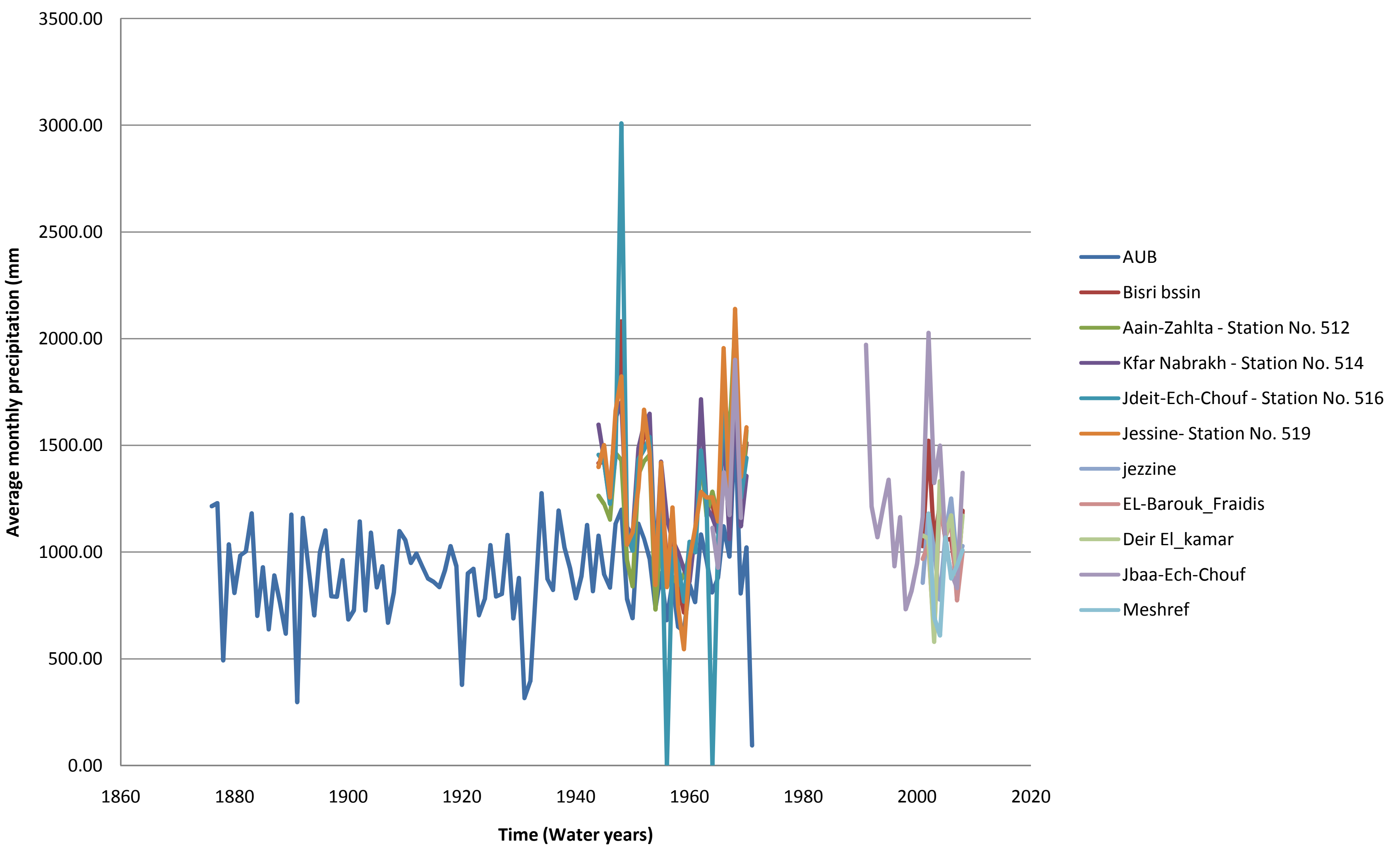


Table 3.1 Monthly Mean Temperatures (°C) - Station Bhamdoun

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	MAY	AUG
1951 - 1952	19.9	15	12.3	6.4	7.4	7.9	8.5	13.4	16.6	19.4	20.9	22.8
1952-1953	23.1	18.1	12.2	10.9	7.4	8.1	5.8	12.8	16.2	20.4	23.5	22.3
1953-1954	19.7	17.9	9.5	6.5	5.5	7	11.5	11	17.7	21.2	24.1	24.1
1954-1955	20.3	17.6	12.9	9.1	9.5	10.9	10	13.4	17.5	22.6	22.2	20.6
1955 - 1956	20.2	19.5	12.6	8.8	7.1	8.7	6.8	13.3	14.8	20.3	23	24.4
1956-1957	19.7	16.4	13	7.3	4.8	7	9.4	12.9	16	20.4	22.3	23.7
1957 - 1958	19.3	15.6	12.2	8.5	7.1	8.8	11	14.6	16.6	19.7	21.3	23
1958-1959	18.7	15.6	13.2	10.3	7.6	1.4	8	14.5	17.6	21.7	19.7	20.4
1959 - 1960	17.9	14.9	12.3	10	7.8	9.3	10	13	19.8	19.7	21.8	22
1960 - 1961	19.8	20.1	13.7	11.8	6.6	6	7	13.5	18	20.6	22.1	22.1
1961 - 1962	17.2	16.4	12.1	8.8	7.7	6.4	12.5	11.5	17.3	21.3	22	23.2
1962 - 1963	20.9	17.5	16.7	9.7	9.1	9.1	7.9	13.4	15	20.3	21.6	22.7
1963 - 1964	19.9	17.6	13.3	9.2	4.2	5.6	10.2	11.4	14.8	20	21.9	20.9
1964 -1965	18.4	19.2	13.1	9.8	6.5	7.9	11.3	12	16.4	21.5	22	21.6
1965 - 1966	20	14.3	11.4	9.2	8.6	8.8	9.9	13.2	16	19.8	21.9	22.2
1966-1967	18.6	17.6	17.1	9.6	6.6	5.4	7	11.9	15.5	19	21.5	21.4
1967 - 1968	18.7	17.1	11.5	9	5.8	7.7	8.4	15.4	18.9	20	23.4	21.2
1968 - 1969	19.1	15.6	12.9	8.8	5.5	8.4	10.8	10.9	17.9	21.6	20.7	22.1
1969 -1970	22.1	16.8	13.4	9.9	8.1	8.1	11.9	15.3	16.4	19.8	20.7	21.8
1970 - 1971	20	16.7	14.4	7.7	1.3	6.4	10.3	11.4	18.8	----	20.1	----
AVERAGE	19.68	16.98	12.99	9.07	7.16	7.45	9.41	12.94	16.89	20.49	21.84	22.24
MEDIAN	19.75	16.95	12.9	9.15	7.25	7.9	9.95	13.1	16.6	20.3	21.9	22.1
MINIMUM	17.2	14.3	9.5	6.4	4.2	1.4	5.8	10.9	14.8	19	19.7	20.4
MAXIMUM	23.1	20.1	17.1	11.8	10.3	10.9	12.5	15.4	19.8	22.6	24.1	24.4
STD. DEV.	1.31	1.52	1.64	1.31	1.51	1.93	1.84	1.32	1.36	0.9	1.09	1.09
SKEWNESS	0.67	0.24	0.82	-0.3	0.06	-1.26	-0.25	0.19	0.27	0.57	0.11	0.26

Table 3.2 Monthly Mean Temperatures (ºC) - Station Kfar Nabrakh

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG
1951 - 1952	22.3	16.6	13	7.6	7.4	8	9.6	14.5	17.1	20	23	25
1952-1953	24.5	20.2	13	11.6	8.5	8.7	8.2	13.3	16.8	19.5	24.6	22.1
1953-1954	22.3	19.2	----	7.5	6.5	8	12.3	13	19.2	22.3	23.8	24
1954-1955	20.3	18.8	14.6	9.9	10	11.3	11.7	13.8	18.2	22.7	22.5	21.9
1955 - 1956	----	20.1	13.3	10.3	8.8	10.4	7.8	13.9	16.9	21.1	24.2	25.4
1956-1957	21.3	17.1	14.1	9	6.6	----	11.1	14.4	17.1	20.9	----	----
1957 - 1958	----	----	----	----	----	----	13	15.9	17.7	20.8	22.3	24.3
1958-1959	19.7	16.2	14.3	10.9		----	----	----	19.1	21.2	21.3	21.9
1959 - 1960	19	15.6	14.3	11.6	10.8	----	10.2	13.5	----	----	----	22.8
1960 - 1961	19.6	19.7	14.5	12.9	---	----	9.7	14.2	18.5	21.6	22.8	21.5
1961 - 1962	18.3	17.4	---	---	9	6.6	13.2	12.1	----	---	22.7	23.5
1962 - 1963	21.8	18.4	16.5	10.1	9	9.4	----	----	----	22	22.3	23.3
1963 - 1964	20.3	18.1	13.7	8.3	----	6.2	10.4	11.1	14.9	19.8	21.4	21.9
1964 -1965	19	19.2	13.2	9.8	6.7	8.1	11.9	12.8	17.4	23.3	23.8	23.6
1965 - 1966	22.3	16.7	13.3	10.1	9.4	9.7	11	14.8	18	23.2	24.2	25
1966-1967	20.8	19.3	18.3	]0.5	7.4	6	7.4	13	17.3	21	23.5	23.9
1967 - 1968	21.1	19.2	12.9	10.4	6.8	8.7	8.9	16	20.7	21.7	24.8	22.8
1968 - 1969	21	17.2	13.7	9.8	6.5	9.1	11.6	11.8	19.1	22.4	21.1	22.5
1969 -1970	22.2	17.8	----	----	8.1	9.3	10.5	15.7	16.8	20.6	20.7	22.2
1970 - 1971	20.2	16.4	14.4	7.1	10.5	7.3	10.3	11.1	18.2	----	20.3	21.4
AVERAGE	20.89	18.06	14.19	9.85	8.25	8.45	10.49	13.61	17.82	21.42	22.74	23.11
MEDIAN	20.9	18.1	13.9	10.1	8.3	8.7	10.45	13.65	17.7	21.2	22.75	22.8
MINIMUM	18.3	15.6	12.9	7.1	6.5	6	7.4	11.1	14.9	19.5	20.3	21.4
MAXIMUM	24.5	20.2	18.3	12.9	10.8	11.3	13.2	16	20.7	23.3	24.8	25.4
STD. DEV.	1.49	1.38	1.37	1.51	1.42	1.46	1.64	1.46	1.27	1.1	1.33	1.21
SKEWNESS	0.39	-0.08	1.78	-0.14	0.28	0	-0.23	-0.06	0.06	0.05	-0.2	0.37

Table 3.3 Relative Humidity - Station Bhamdoun

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG
1950 - 1951	68	64	70	62	65	68	54	58	51	67	62	60
1951 - 1952	68	76	70	81	71	no	59	59	52	56	60	56
1952-1953	54	65	72	68	73	69	77	63	62	60	53	60
1953-1954	62	56	74	76	82	79	62	71	50	60	52	56
1954-1955	64	60	72	79	71	64	71	----	62	50	59	69
1955 - 1956	64	54	76	80	76	67	79	60	62	56	51	47
1956-1957	56	56	58	76	70	76	70	----	64	64	60	68
1957 - 1958	----	71	----	----	82	74	63	52	67	67	61	61
1958-1959	73	74	62	74	77	76	75	58	56	56	68	65
1959 - 1960	69	72	68	65	----	65	65	62	----	----	56	53
1960 - 1961	----	----	----	----	----	----	----	56	49	47	53	58
1961 - 1962	66	59	61	68	----	68	53	62	54	48	55	56
1962 - 1963	55	60	44	66	----	----	67	58	----	----	----	57
1963 - 1964	---	----	59	59	68	73	64	61	57	58	58	----
1964 -1965	59	----	----	----	----	----	----	----	----	54	----	----
1965 - 1966	49	69	67	70	64	62		50	52	46	51	56
1966-1967	66	55	49	64	60	60	60	57	54	52	53	61
1967 - 1968	65	58	71	70	75	66	64	59	61	60	51	61
1968 - 1969	----	71	70	no	74	80	64	83	62	54	59	61
1969 -1970	----	78	52	67	71	69	58	57	54	64	73	64
1970 - 1971	62	67	----	----	----	----	----	----	----	----	----	----
AVERAGE	62.5	64.72	64.41	70.71	71.93	70.18	65	60.35	57	56.61	57.5	59.39
MEDIAN	64	64.5	68	70	71	69	64	59	56	56	57	60
MINIMUM	49	54	44	59	60	60	53	50	49	46	51	47
MAXIMUM	73	78	76	81	82	80	79	83	67	67	73	69
STD. DEV.	6.19	7.56	9.06	6.46	5.97	5.87	7.26	7.19	5.38	6.33	5.9	5.15
SKEWNESS	-0.51	0.18	-0.82	0.02	-0.1	0.09	0.31	1.74	0.19	0.01	1.02	-0.21

Table 3.4 Relative Humidity - Station Kfar Nabrakh

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG
1955 - 1956	----	----	----	----	----	----	----	----	----	----	31	53
1956-1957	60	66	----	----	----	----	----	----	----	----	----	----
1957 - 1958	----	----	----	----	----	----	----	42	50	50	49	50
1958-1959	56	57	49	57	----	----	----	----	40	45	53	51
1959 - 1960	52	54	51	52	54	47	48	50	30	44	47	45
1960 - 1961	----	----	----	----	----	----	----	49	43	41	46	48
1961 - 1962	57	48	51	57	55	55	40	47	----	----	43	45
1962 - 1963	42	47	33	52	----	----	----	----	----	----	----	43
1963 - 1964	----	----	47	47	74	78	72	71	----	67	64	----
1964 -1965	65	----	----	----	----	----	----	----	----	----	----	----
1965 - 1966	----	----	----	----	----	----	----	----	----	----	----	----
1966-1967	----	----	----	----	78	82	80	---	80	73	77	78
1967 - 1968	80	82	84	84	88	85	85	76	82	84	81	84
1968 - 1969	83	87	86	74	76	66	65	81	57	59	66	63
1969 -1970	----	74	----	----	80	72	75	67	63	64	72	66
1970 - 1971	68	70	----	----	----	----	----	61	----	----	----	----
AVERAGE	62.56	65	57.29	60.43	72.14	69.29	66.43	60.44	55.63	58.56	57.18	56.91
MEDIAN	60	66	51	57	76	72	72	61	53.5	59	53	51
MINIMUM	42	47	33	47	54	47	40	42	30	41	31	43
MAXIMUM	83	87	86	84	88	85	85	81	82	84	81	84
STD. DEV.	12.35	13.65	18.44	12.45	11.89	13.11	15.46	13.25	17.46	13.88	15.09	13.32
SKEWNESS	0.22	0.17	0.6	0.88	-0.53	0.41	-0.58	0.12	0.24	0.36	0.04	0.88

Table 3.5 Monthly Evaporation - Station Bhamdoun

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG
1950 - 1951	119	101	86	109	67	41	84	108	123	94	110	102
1951 - 1952	83	52	75	47	75	61	78	99	117	110	90	103
1952-1953	128	102	69	93	72	70	45	82	127	100	131	72
1953-1954	97	97	43	41	36	50	99	78	138	116	136	138
1954-1955	102	112	68	51	69	72	66	70	101	138	138	102
1955 - 1956	108	156	70	61	53	83	41	103	101	121	136	151
1956-1957	94	97	81	47	46	24	54	80	110	95	105	118
1957 - 1958	70	103	52	50	38	35	75	95	84	81	102	118
1958-1959	61	52	80	54	45	19	44	86	110	79	76	86
1959 - 1960	76	52	55	63	49	56	54	45	140	92	108	112
1960 - 1961	----	----	----	----	32.1	----	----	75	106.2	114.6	114.7	114.5
1961 - 1962	66	79	61	42	40	36	84	47	90	126	114	115
1962 - 1963	112	64	116	55	----	----	48	80	----	----	----	108
1963 - 1964	----	----	66	65	31	29	57	----	----	----	104	----
1964 -1965	74	150	115	61	36	46	87	----	98	132	124	104
1965 - 1966	90	66	63	57	57	40	----	113	70	135	125	132
1966-1967	89	114	143	62	52	35	60	96	96	153	163	175
1967 - 1968	109	102	72	62	44	70	80	99	176	160	196	140
1968 - 1969	75	64	67	46	36	69	60	87	155	165	132	150
1969 -1970	----	84	93	71	50	51	96	152	141	144	112	157
1970 - 1971	129	129	----	----	----	----	----	----	----	----	----	----
AVERAGE	93.44	93.47	77.63	59.84	48.85	49.28	67.33	88.61	115.73	119.76	121.93	120.92
MEDIAN	93	93.5	78	60	49	49	67	89	116	120	122	121
MINIMUM	61	52	43	41	31	19	41	45	70	79	76	72
MAXIMUM	129	150	143	109	72	83	99	152	176	165	196	175
STD. DEV.	21	31	24.5	17	14	18.5	18.4	24	26.7	26.4	26.6	26
SKEWNESS	0.19	0.38	1.2	1.61	0.58	0.15	0.19	0.49	0.5	0.11	1.01	0.27

Table 3.6 Monthly Evaporation - Station Kfar Nabrakh

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG
1955 - 1956	----	111	49	46	35	67	----	----	68	98	104	133
1956-1957	104	89	76	39	34	----	45	67	74	72	----	----
1957 - 1958	----	----	----	----	----	----	81	81	73	82	77	95
1958-1959	60	47	60	42	----	----	----	----	----	----	----	----
1959 - 1960	----	----	----	----	----	----	----	----	----	----	----	----
1960 - 1961	----	----	----	----	----	----	----	55	89.2	101.3	92	85
1961 - 1962	68	69	53	39	30	----	64	----	----	----	82	82
1962 - 1963	81	54	75	63	----	----	----	----	----	----	----	----
1963 - 1964	----	----	47	43	23	23	39	40	55	67	75	----
1964 -1965	58	106	45	40	20	30	60	----	74	100	99	66
1965 - 1966	74	41	39	34	40	29	----	59	71	96	85	73
1966-1967	44	46	63	28	27	15	26	42	40	76	77	80
1967 - 1968	54	50	31	25	24	28	33	52	67	68	77	90
1968 - 1969	58	36	35	40	25	48	175(?)	42	92	90	79	85
1969 -1970	----	54	53	----	37	34	63	84	78	87	71	87
1970 - 1971	71	57	----	----	----	----	----	----	----	----	----	----
AVERAGE	67.2	63.33	52.17	39.91	29.5	34.25	45.67	58	71.02	85.21	83.45	87.6
MEDIAN	67	63	52	40	29.5	34	65	58	71	85	83.5	87.6
MINIMUM	54	36	31	25	20	15	26	40	40	67	71	66
MAXIMUM	104	111	76	63	40	67	175	84	92	101	104	133
STD. DEV.	16.8	25.2	14.4	10	6.7	16.2	44.7	16.5	14.4	12.9	10.5	18
SKEWNESS	0.89	0.93	0.31	0.79	0.17	1.03	-0.43	0.48	-0.64	-0.16	0.86	1.62

Table 3.7 Monthly And Annual Precipitation 1944-45 Through 1970-71 – Aain-Zahlta - Station No. 512

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
1944 - 1945	0	38	294	182	406	115	158	40	30	0	0	0	1263
1945-1946	4	0	56	266	104	387	225	21	161	0	0	0	1224
1946 - 1947	0	11	10	129	671	178	47	34	71	0	0	0	1151
1947 - 1948	4	10	103	89	270	468	284	124	112	0	0	0	1464
1948- 1949	4	12	292	242	305	227	208	141	0	0	0	0	1431
1949 - 1950	6	0	17	219	382	82	124	70	61	0	0	0	961
1950-1951	10	106	48	154	167	151	67	129	6	0	0	0	838
1951 -1952	0	95	92	435	113	333	285	9	0	0	0	0	1362
1952-1953	0	12	126	188	331	329	376	54	9	0	0	0	1425
1953 - 1954	0	40	228	94	424	401	108	160	0	0	0	0	1455
1954 - 1955	0	0	90	150	40	143	220	73	14	0	0	0	730
1955 - 1956	0	6	221	183	273	138	179	7	88	0	0	0	1095
1956-1957	0	15	80	112	279	103	134	82	34	1	0	0	840
1957 - 1958	0	26	62	270	316	34	105	46	25	0	0	0	884
1958 - 1959	14	30	13	180	240	157	103	55	48	6	0	0	846
1959 - 1960	72	32	87	73	200	84	239	95	11	0	0	0	893
1960 - 1961	0	10	159	101	264	221	188	20	19	0	0	0	982
1961 -1962	0	13	153	302	202	263	60	66	12	0	0	0	1071
1962-1963	0	86	0	335	258	302	243	166	54	0	0	0	1444
1963 -1964	0	82	51	156	143	370	255	56	55	0	0	0	1168
1964 -1965	0	0	341	58	263	292	150	150	14	15	0	0	1283
1965 - 1966	0	153	116	314	207	160	202	6	10	0	0	0	1168
1966-1967	4	36	17	456	270	363	381	90	140	0	0	0	1757
1967 - 1968	0	128	148	320	639	143	109	26	23	0	0	2	1538
1968 - 1969	0	46	161	607	675	136	325	94	26	0	0	0	2070
1969 -1970	0	73	104	182	252	168	317	78	11	0	0	0	1185
1970 -1971	0	51	99	254	145	401	168	452	0	0	0	0	1570
TOTAL	118	1111	3168	6051	7839	6149	5260	2344	1034	22	0	2	33098
AVERAGE	4.37	41.15	117.33	224.11	290.33	227.74	194.81	86.81	38.3	0.81	0	0.07	1225.85
MEDIAN	0	30	99	183	264	178	188	70	23	0	0	0	1185
MINIMUM	0	0	0	58	40	34	47	6	0	0	0	0	730
MAXIMUM	72	153	341	607	675	468	381	452	161	15	0	2	2070
STD. DEV.	13.7	41.49	89.74	126.42	158.01	117.69	91.48	85.49	42.37	3.01	0	0.38	308.77
SKEWNESS	4.45	1.12	0.9	1.16	1.14	0.36	0.34	2.81	1.5	4.06	0	4.9	0.59

Table 3.8 Monthly And Annual Precipitation 1944-45 Through 1970-71 – Kfar Nabrakh - Station No. 514

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
1944 - 1945	0	34	311	208	424	384	149	40	28	18	0	0	1596
1945-1946	4	3	80	305	119	436	256	16	214	0	0	0	1433
1946 - 1947	1	104	2	169	678	227	55	26	26	6	0	0	1294
1947 - 1948	10	9	137	83	294	586	340	103	61	0	0	0	1623
1948- 1949	7	18	248	267	347	367	246	200	2	0	0	0	1702
1949 - 1950	18	1	13	309	299	178	195	48	56	0	0	0	1117
1950-1951	11	98	75	222	260	148	110	142	9	0	0	0	1075
1951 -1952	4	118	116	489	144	327	231	52	4	0	0	0	1485
1952-1953	0	18	165	200	336	411	383	71	13	0	0	0	1597
1953 - 1954	2	0	306	149	449	429	106	190	17	0	0	0	1648
1954 - 1955	2	4	105	167	52	201	239	114	31	0	0	0	915
1955 - 1956	1	36	245	244	351	230	200	25	91	0	0	0	1423
1956-1957	0	14	100	221	311	121	233	79	72	6	0	0	1157
1957 - 1958	0	58	82	286	390	73	112	36	20	0	0	0	1057
1958 - 1959	18	59	15	182	328	202	115	45	36	0	0	0	1000
1959 - 1960	20	37	99	78	275	73	227	103	7	0	0	0	919
1960 - 1961	0	19	118	92	231	175	145	63	17	0	0	0	860
1961 -1962	0	14	138	314	190	342	53	43	7	1	0	0	1102
1962-1963	0	94	0	475	400	327	239	153	28	0	0	0	1716
1963 -1964	0	90	108	123	160	360	253	65	52	0	0	0	1211
1964 -1965	0	0	380	64	206	247	123	127	8	7	0	0	1162
1965 - 1966	0	113	117	329	245	131	141	7	6	0	0	0	1089
1966-1967	1	47	19	390	322	285	390	66	91	0	0	0	1611
1967 - 1968	3	89	139	257	365	103	72	18	15	0	0	0	1061
1968 - 1969	0	40	188	501	610	67	291	59	10	0	0	0	1766
1969 -1970	0	79	88	207	241	143	282	63	17	0	0	0	1120
1970 -1971	5	38	94	233	116	370	117	383	0	0	0	0	1356
TOTAL	107	1234	3488	6564	8143	6943	5303	2337	938	38	0	0	35095
AVERAGE	3.96	45.7	129.19	243.11	301.59	257.15	196.41	86.56	34.74	1.41	0	0	1299.81
MEDIAN	1	37	108	222	299	230	200	63	17	0	0	0	1211
MINIMUM	0	0	0	64	52	67	53	7	0	0	0	0	860
MAXIMUM	20	118	380	501	678	586	390	383	214	18	0	0	1766
STD. DEV.	6	38.12	95.27	118.17	137.82	132.03	92.42	76.84	43.49	3.81	0	0	276.27
SKEWNESS	1.62	0.49	0.93	0.62	0.74	0.41	0.35	2.2	2.67	3.26	0	0	0.19

Table 3.9 Monthly And Annual Precipitation 1944-45 Through 1970-71 – Jdeit-Ech-Chouf - Station No. 516

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
1944 - 1945	0	38	375	167	362	288	146	52	28	0	0	0	1456
1945-1946	0	10	102	235	112	474	217	18	254	0	0	0	1422
1946 - 1947	0	64	0	157	607	198	59	55	86	0	0	0	1226
1947 - 1948	6	3	122	91	240	508	273	110	94	0	0	0	1447
1948- 1949	0	19	415	463	548	742	516	306	0	0	0	0	3009
1949 - 1950	6	0	19	293	296	163	192	70	55	0	0	0	1094
1950-1951	5	63	85	181	235	165	121	140	12	0	0	0	1007
1951 -1952	0	153	87	476	137	293	241	48	0	0	0	0	1435
1952-1953	0	20	171	157	324	392	351	53	12	0	0	0	1480
1953 - 1954	0	0	265	152	476	374	102	155	16	0	0	0	1540
1954 - 1955	0	0	108	174	53	194	220	128	35	0	0	0	912
1955 - 1956	0	26	231	270	272	201	199	18	87	0	0	0	1304
1956-1957	0	0	111	240	282	166	179	47	78	5	0	0	1108
1957 - 1958	0	51	70	300	378	52	114	39	12	0	0	0	1016
1958 - 1959	0	43	10	197	294	217	118	19	36	10	0	0	944
1959 - 1960	11	44	70	80	186	74	200	99	4	0	0	0	768
1960 - 1961	0	21	170	92	237	228	209	69	22	0	0	0	1048
1961 -1962	10	24	127	300	169	300	37	24	8	0	0	0	999
1962-1963	0	95	1	355	395	238	251	125	16	0	0	0	1476
1963 -1964	2	73	90	152	181	386	239	41	59	0	0	0	1223
1964 -1965	1	1	358	55	236	263	116	132	2	7	0	0	1171
1965 - 1966	0	61	138	292	219	137	173	9	7	0	0	0	1036
1966-1967	2	46	21	463	335	315	423	89	81	0	0	0	1775
1967 - 1968	1	90	111	302	470	116	78	28	25	0	0	0	1221
1968 - 1969	0	54	188	507	703	104	341	83	16	0	0	0	1996
1969 -1970	0	77	109	182	260	161	369	83	13	0	0	0	1254
1970 -1971	0	50	79	215	134	391	170	402	1	0	0	0	1442
TOTAL	44	1126	3633	6548	8141	7140	5654	2442	1059	22	0	0	35809
AVERAGE	1.63	41.7	134.56	242.52	301.52	264.44	209.41	90.44	39.22	0.81	0	0	1326.26
MEDIAN	0	43	109	215	272	228	199	69	16	0	0	0	1226
MINIMUM	0	0	0	55	53	52	37	9	0	0	0	0	768
MAXIMUM	11	153	415	507	703	742	516	402	254	10	0	0	3009
STD. DEV.	3.08	35.77	108.48	123.1	151.38	148.97	111.18	85.94	51.59	2.4	0	0	425.95
SKEWNESS	1.95	1.02	1.15	0.66	0.87	1.22	0.88	2.22	2.69	2.86	0	0	2.26

Table 3.10 Monthly And Annual Precipitation 1944-45 Through 1970-71 – Jezzine- Station No. 519

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
1944 - 1945	0	18	371	166	391	260	107	57	28	0	0	0	1398
1945-1946	0	2	96	312	55	514	244	16	262	0	0	0	1501
1946 - 1947	0	75	0	121	756	174	37	45	47	0	0	0	1255
1947 - 1948	6	11	216	95	278	517	309	139	91	0	0	0	1662
1948- 1949	0	15	218	316	404	386	295	189	0	0	0	0	1823
1949 - 1950	6	0	15	280	286	160	180	52	56	0	0	0	1035
1950-1951	5	148	66	181	251	174	106	161	0	0	0	0	1092
1951 -1952	0	125	116	448	129	321	120	42	0	0	0	0	1301
1952-1953	0	24	145	219	283	422	526	48	0	0	0	0	1667
1953 - 1954	0	0	184	129	494	300	123	223	12	0	0	0	1465
1954 - 1955	0	0	84	200	59	110	225	137	30	0	0	0	845
1955 - 1956	0	24	233	231	371	197	255	16	92	0	0	0	1419
1956-1957	0	0	64	95	262	150	130	69	60	5	0	0	835
1957 - 1958	0	30	135	437	496	29	50	20	12	0	0	0	1209
1958 - 1959	11	57	14	185	210	120	100	21	15	9	0	0	742
1959 - 1960	16	47	43	18	248	10.3	98	57	7.3	0	0	0	544.6
1960 - 1961	0	10	110	63	281	241	176	74	10	0	0	0	965
1961 -1962	0	30	96	397	175	320	33	33	33	0	0	0	1117
1962-1963	0	39	0	388	264	324	149	102	16	0	0	0	1282
1963 -1964	0	63	85	140	194	418	258	39	58	0	0	0	1255
1964 -1965	0	0	349	62	264	306	137	133	0	5	0	0	1256
1965 - 1966	0	150	86	345	201	184	169	8	0	0	0	0	1143
1966-1967	25	45	16	414	403	392	518	89	53	0	0	0	1955
1967 - 1968	7	75	131	314	476	79	72	36	35	0	0	0	1225
1968 - 1969	0	60	193	623	687	95	407	64	10	0	0	0	2139
1969 -1970	0	130	190	192	199	148	393	83	17	0	0	0	1352
1970 -1971	0	37	80	228	141	429	187	483	0	0	0	0	1585
TOTAL	76	1215	3336	6599	8258	6780.3	5404	2436	944.3	19	0	0	35067.6
AVERAGE	2.81	45	123.56	244.41	305.85	251.12	200.15	90.22	34.97	0.7	0	0	1298.8
MEDIAN	0	30	96	219	264	241	169	57	16	0	0	0	1256
MINIMUM	0	0	0	18	55	10.3	33	8	0	0	0	0	544.6
MAXIMUM	25	150	371	623	756	517	526	483	262	9	0	0	2139
STD. DEV.	5.88	45.2	94.75	141.62	165.17	140.63	132.57	94.44	51.92	2.09	0	0	357.81
SKEWNESS	2.45	1.1	0.94	0.62	0.98	0.21	1.04	2.71	3.1	2.94	0	0	0.23

Table 3.11 Monthly And Annual Precipitation 2001-2002 Through 2008-2009 – Jezzine

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
2001-2002	0.4	77.8	101.5	210.5	225.1	104.8	75.5	36.4	18.5	3.5	1.5	0.6	856.1
2002-2003	4.5	35.6	124.2	245.5	204.5	310.3	177.5	45.5	16.4	4.8	3.6	4.8	1177.2
2003-2004	3.7	12	88.6	135.5	348.2	186.8	133.5	66.4	23.4	3.2	1.5	6.8	1009.6
2004-2005	0	20.1	189.8	75.1	227.3	170.5	49.2	1.2	42.7	0.2	0	1.4	777.5
2005-2006	1.4	54.1	217.2	203.1	236.8	133.6	19.2	218	3.2	0	1	0.8	1088.4
2006-2007	11.9	165.5	125.1	67	248.7	425.6	153.2	24.6	24.8	1.4	0.8	1.6	1250.2
2007-2008	2.2	8.2	204.8	232.8	226.6	202.8	71.2	2	0	3.8	0	0.4	954.8
2008-2009	69	63.6	71.4	224.3	113.8	331.2	122.8	8.6	11.2	0.2	10	1.2	1027.3
TOTAL	93.1	436.9	1122.6	1393.8	1831	1865.6	802.1	402.7	140.2	17.1	18.4	17.6	8141.1
AVERAGE	11.64	54.61	140.33	174.23	228.88	233.2	100.2	50.34	17.53	2.14	2.3	2.2	1017.64
MEDIAN	2.95	44.85	124.65	206.8	226.95	194.8	99.15	30.5	17.45	2.3	1.25	1.3	1018.45
MINIMUM	0	8.2	71.4	67	113.8	104.8	19.2	1.2	0	0	0	0.4	777.5
MAXIMUM	69	165.5	217.2	245.5	348.2	425.6	177.5	218	42.7	4.8	10	6.8	1250.2
STD. DEV.	23.48	51.32	55.98	71.7	63.87	110.83	54.79	71.46	13.5	1.91	3.31	2.32	156.94
SKEWNESS	2.69	1.62	0.34	-0.78	0.12	0.71	-0.06	2.29	0.62	0.07	2.24	1.53	-0.06

Table 3.12 Monthly And Annual Precipitation 2001-2002 Through 2008-2009 – EL-Barouk_Fraidis

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
2001-2002	2.6	88.5	10.5	203	222.5	197.5	133.5	75.4	33.5	0.8	0	0	967.8
2002-2003	3.5	27.5	99.7	187.5	185.7	311.2	177.5	33.5	5.3	1.2	2.5	0	1035.1
2003-2004	7.5	19.5	66.4	132.5	188.4	113.4	45.5	22.4	8.5	3.2	0	5.4	612.7
2004-2005	17.8	65.4	222.5	198.5	311.6	244.4	88.5	55.4	18.4	3.2	4.4	0	1230.1
2005-2006	3.3	77.5	135.5	156.5	234.7	155.5	123.4	165.4	11.4	2.5	0	3.6	1069.3
2006-2007	13.5	175.5	165.5	153.7	173.4	244.6	150.4	45.5	17.5	0.5	0	0.4	1140.5
2007-2008	2.8	6.8	164.6	174.5	176	150.5	81.3	5.2	11.5	0	0	0.2	773.4
2008-2009	99.5	95.5	70.4	204.3	103.5	144.6	256.6	63.3	18.4	5.8	0.6	2.4	1001.6
TOTAL	150.5	556.2	935.1	1410.5	1595.8	1561.7	1056.7	402.8	124.5	17.2	7.5	12	7830.5
AVERAGE	18.81	69.53	116.89	176.31	199.48	195.21	132.09	57.54	15.56	2.15	0.94	1.5	978.81
MEDIAN	5.5	71.45	117.6	181	187.05	176.5	128.45	45.5	14.5	1.85	0	0.3	1018.35
MINIMUM	2.6	6.8	10.5	132.5	103.5	113.4	45.5	5.2	5.3	0	0	0	612.7
MAXIMUM	99.5	175.5	222.5	204.3	311.6	311.2	256.6	165.4	33.5	5.8	4.4	5.4	1230.1
STD. DEV.	33.08	54.18	68.1	26.56	59.88	66.71	65.42	52.69	8.71	1.92	1.64	2.07	199.11
SKEWNESS	2.67	0.92	-0.02	-0.51	0.49	0.62	0.79	1.69	1.23	0.9	1.76	1.19	-0.89

Table 3.13 Monthly And Annual Precipitation 2001-2002 Through 2008-2009 – Deir El_kamar

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
2001-2002	0.4	113.5	94	189	244	186	146	57.3	45.6	1	0	0.6	1077.4
2002-2003	3	33	115	223	192	298	167.5	29.5	2.2	0	0.4	0	1063.6
2003-2004	13.3	23.5	56.4	128.4	190.5	133	12.5	12.4	1.5	1	0	6.8	579.3
2004-2005	13.5	48.7	298.6	230	358.5	238.9	65.6	44.9	28.6	0.6	2.4	1.4	1331.7
2005-2006	0.4	89.3	164.7	151.1	240.8	149.8	117.7	153.1	7.4	0.8	0.4	1	1076.5
2006-2007	1.8	214.9	156.8	147	180.6	283.2	139.6	20.7	24.7	1	0.2	1.2	1171.7
2007-2008	3.2	4.4	190.9	186.8	213.5	183	65.4	3	8.2	0.6	1.6	32.5	893.1
2008-2009	81.4	104.8	71.8	237.3	64.2	362.8	216.4	18.6	8.45	0	4.4	0	1170.15
TOTAL	117	632.1	1148.2	1492.6	1684.1	1834.7	930.7	339.5	126.65	5	9.4	43.5	8363.45
AVERAGE	14.63	79.01	143.53	186.58	210.51	229.34	116.34	42.44	15.83	0.63	1.18	5.44	1045.43
MEDIAN	3.1	69	135.9	187.9	202.75	212.45	128.65	25.1	8.33	0.7	0.4	1.1	1076.95
MINIMUM	0.4	4.4	56.4	128.4	64.2	133	12.5	3	1.5	0	0	0	579.3
MAXIMUM	81.4	214.9	298.6	237.3	358.5	362.8	216.4	153.1	45.6	1	4.4	32.5	1331.7
STD. DEV.	27.51	67.73	78.3	41.4	81.93	80.31	65.47	48.02	15.6	0.42	1.56	11.15	225.59
SKEWNESS	2.62	1.14	1.06	-0.11	0.05	0.47	-0.14	2.14	1.12	-0.83	1.53	2.63	-1.28

Table 3.14 Monthly And Annual Precipitation 1964-1965 Through 1969-1970 and 1991-1992 Trough 2008-2009 – Jbaa-Ech-Chouf

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
1964-1965	0.5	66.5	347.6	57.9	194.8	196	116.3	134	0	0	0	0	1113.6
1965-1966	0	102	145	234.5	198.4	122.6	113	10.5	0	0	0	0	926
1966-1967	0	21	19.2	318	302.8	265.7	297	65	85	0	0	0	1373.7
1967-1968	0	90.5	84.7	347.5	526.6	36	53.9	9.3	25	0	0	0	1173.5
1968-1969	0	14.4	145.8	611.5	637.8	73.7	311.8	105.4	0	0	0	0	1900.4
1969-1970	0	119	136.5	182.4	312.5	176.5	128.4	84.4	20.08	0	0	0	1159.78
1991-1992	4.5	94.5	232	436.9	368.9	603	122	25	84.5	0	0	0	1971.3
1992-1993	4	62	183.7	404	179	161	139.5	12.5	67.7	0	0	0	1213.4
1993-1994	0	2	205	81	289	283.5	125	62.5	21.5	0	0	0	1069.5
1994-1995	3	66.5	310.5	389	140	135	114	41.5	9	0	0	0	1208.5
1995-1996	0	10.5	270.5	64.5	365.5	166	352.5	90.5	19.5	0	0	0	1339.5
1996-1997	13	154	9.5	189	101	117	204.5	107.5	37.5	0	0	0	933
1997-1998	0	51.5	153.5	250	173	137	333.5	30.5	35	0	0	0	1164
1998-1999	0	16	37.5	220	161	111	153.5	33	0	0	0	0	732
1999-2000	0	22	30.5	81	441	135	78.5	29.5	0	0	0	0	817.5
2000-2001	34	100	7	246.5	91.5	238.5	151	65	13	0	0	0	946.5
2001-2002	0	70	125.5	191.5	354.5	142	140.5	140.5	0	0	0	0	1164.5
2002-2003	0	28.5	152.5	416.5	241	603.5	458.5	126.5	0	0	0	0	2027
2003-2004	13	56.46	143.14	247.49	287.5	311.5	207.5	56.5	0	0	0	0	1323.09
2004-2005	0	32	312.5	49	279	396	307.5	113.4	7.5	1.3	0	0	1498.2
2005-2006	3.4	24.5	165.5	222.4	198.7	132	71	212	0	0	0	0	1029.5
2006-2007	1.5	13.8	115.4	145.5	175.5	234.5	177.5	34.5	4.5	0	0	0	902.7
2007-2008	3.5	22.4	158.4	164.5	186.7	175.5	93.4	11.5	14.5	0	0	0	830.4
2008-2009	112.5	105.4	75.4	222.4	138	357.5	231.5	119	10	0	0	0	1371.7
TOTAL	192.9	1345.46	3566.8	5773	6343.7	5310	4481.8	1720	454.28	1.3	0	0	29189.28
AVERAGE	8.04	56.06	148.62	240.54	264.32	221.25	186.74	71.67	18.93	0.05	0	0	1216.22
MEDIAN	0	53.98	145.4	222.4	219.85	170.75	145.75	63.75	9.5	0	0	0	1164.25
MINIMUM	0	2	7	49	91.5	36	53.9	9.3	0	0	0	0	732
MAXIMUM	112.5	154	347.6	611.5	637.8	603.5	458.5	212	85	1.3	0	0	2027
STD. DEV.	23.47	41.25	96.24	139.85	134.51	146.24	104.96	52.27	25.95	0.27	0	0	349.28
SKEWNESS	4.22	0.64	0.41	0.78	1.18	1.57	1.02	0.83	1.71	4.9	0	0	1.08

Table 3.15 Monthly And Annual Precipitation 2002-2003 Through 2008-2009 – Meshref

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
2002-2003	14.4	28.2	128.2	241	211.5	317.2	187.8	49.3	2.2	0	0.4	0	1180.2
2003-2004	33.2	25	70.4	148.5	210.7	152.2	16.4	11.2	2	0.2	0	23.8	693.6
2004-2005	12.4	20.2	205	90.6	228.5	2.6	27.1	12.8	9.3	0.4	0.2	0	609.1
2005-2006	0.4	135.7	170.7	123.2	258.6	117.9	117.6	133.7	5	2	1.8	1.2	1067.8
2006-2007	6.8	163.5	104.5	83.1	175.7	230.7	83	12.2	15	1.2	0.8	0	876.5
2007-2008	3.2	64.4	112.2	189.2	233.5	210.5	75.4	11.5	10.4	2.2	0.4	22.4	935.3
2008-2009	61.4	88.5	81.4	217.4	168.4	204.2	146.5	28.8	7.2	0.6	2	1.4	1007.8
TOTAL	131.8	525.5	872.4	1093	1486.9	1235.3	653.8	259.5	51.1	6.6	5.6	48.8	6370.3
AVERAGE	18.83	75.07	124.63	156.14	212.41	176.47	93.4	37.07	7.3	0.94	0.8	6.97	910.04
MEDIAN	12.4	64.4	112.2	148.5	211.5	204.2	83	12.8	7.2	0.6	0.4	1.2	935.3
MINIMUM	0.4	20.2	70.4	83.1	168.4	2.6	16.4	11.2	2	0	0	0	609.1
MAXIMUM	61.4	163.5	205	241	258.6	317.2	187.8	133.7	15	2.2	2	23.8	1180.2
STD. DEV.	21.63	57.02	48.24	61.67	31.95	99.1	62.01	44.88	4.7	0.88	0.79	11.04	202.73
SKEWNESS	1.57	0.66	0.76	0.17	-0.16	-0.59	0.24	2.17	0.45	0.6	0.88	1.22	-0.36

Table 3.16 Bisri Basin Precipitation

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
1944 - 1945	0	29	351	174	389	259	132	50	28	2	0	0	1417
1945-1946	1	4	89	281	88	471	235	17	236	0	0	0	1423
1946 - 1947	0	65	2	139	689	188	47	44	60	1	0	0	1234
1947 - 1948	6	8	160	91	268	515	298	124	92	0	0	0	1562
1948- 1949	2	16	291	339	421	459	337	216	0	0	0	0	2081
1949 - 1950	8	0	16	277	307	150	176	60	57	0	0	0	1050
1950 - 1951	7	110	70	182	233	164	104	147	6	0	0	0	1022
1951 - 1952	1	127	104	459	130	316	197	39	1	0	0	0	1373
1952 - 1953	0	20	152	194	310	396	432	53	7	0	0	0	1563
1953 - 1954	0	7	230	132	471	355	112	189	12	0	0	0	1508
1954 - 1955	0	1	95	180	53	151	225	121	29	0	0	0	854
1955 - 1956	0	23	232	236	323	192	219	16	90	0	0	0	1331
1956-1957	0	4	85	156	277	143	158	66	62	4	0	0	955
1957 - 1958	0	39	97	350	418	42	86	32	15	0	0	0	1079
1958 - 1959	9	49	13	187	254	165	108	29	29	8	0	0	851
1959 - 1960	25	42	65	53	226	49	168	81	7	0	0	0	716
1960 - 1961	0	14	137	81	259	225	184	62	16	0	0	0	978
1961 -1962	3	23	120	342	180	307	41	37	19	0	0	0	1073
1962-1963	0	70	0	381	318	296	206	126	24	0	0	0	1421
1963 -1964	1	73	84	144	177	393	251	46	57	0	0	0	1225
1964 -1965	0	0	354	60	248	284	131	135	4	8	0	0	1224
1965 - 1966	0	120	110	322	213	160	172	8	4	0	0	0	1110
1966-1967	12	44	18	432	351	351	451	86	81	0	0	0	1826
1967 - 1968	4	90	129	304	488	104	80	30	28	0	0	0	1256
1968 - 1969	0	53	185	571	680	101	359	74	14	0	0	0	2038
1969 -1970	0	99	139	189	231	154	359	80	15	0	0	0	1266
1970 -1971	1	43	85	229	136	406	170	442	0	0	0	0	1512
2001-2002	1	77	87	200	283	148	121	95	14	1	0	0	1027
2002-2003	2	30	130	306	216	443	305	79	6	2	2	1	1521
2003-2004	9	34	107	185	275	222	142	49	9	2	0	3	1039
2004-2005	5	38	255	98	275	293	177	67	20	2	1	0	1232
2005-2006	3	47	171	199	219	139	72	200	4	1	0	1	1056
2006-2007	8	100	132	127	194	288	163	35	14	1	0	1	1062
2007-2008	3	14	172	185	194	176	84	7	10	1	0	0	847
2008-2009	97	92	73	218	122	290	210	74	13	2	3	1	1194
TOTAL	205.77	1607.09	4538.32	8005.27	9916.19	8796.41	6712.90	3015.98	1080.53	32.79	6.99	8.39	43926.63

Table 3.16 Bisri Basin Precipitation

YEAR	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	TOTAL
AVERAGE	5.88	45.92	129.67	228.72	283.32	251.33	191.80	86.17	30.87	0.94	0.20	0.24	1255.05
MINIMUM	0.00	0.13	0.29	52.82	53.15	42.08	41.30	7.20	0.26	0.00	0.00	0.00	715.87
MAXIMUM	97.32	127.04	354.19	571.37	688.80	514.92	451.06	441.68	236.39	7.63	2.81	3.33	2081.25
STD. DEV.	16.67	37.06	88.55	118.26	141.52	124.88	103.86	81.38	44.03	1.91	0.58	0.64	317.40
SKEWNESS	5.18	0.66	0.94	0.91	1.27	0.38	0.89	2.74	3.31	2.76	3.58	3.82	0.86

CHAPTER 4 SITE VISIT

As part of the hydrological study of the watershed of the Bisri Dam Project (Lebanon), the Engineer conducted a tour of the valley of the river downstream of the dam site and the dam axis, in order to retrieve the specifics of the study area.

4.1 Participants

Were present during this mission the following Engineers:

Majida NEJMEDDINE	: Lead Engineer in Hydrology (NOVEC)
Robert BOU NAHED	: Hydraulic Engineer (Dar Al Handasah)
Eyup SABRI	: Geotechnical Engineer (Dar Al Handasah)

4.2 Objectives

The goals of this filed mission are:

- Overview of the nature of the watershed of Bisri Valley (runoff ability, type of discharge, Woodlands, grazing area…);
- Inspection of crossing;
- Discussion with local people if possible.

4.3 Points inspected

Bisri crossed the road passing by the village Bisri by a hydraulic structure consisting of four sections 4m high and 5 m wide. The length is estimated at 12m.

The owners of coffee shops adjacent to the river crossing point of the road highlighted two major floods. The first occurred in the '70s and the latest in 2003. The latter, according to witnesses, is more important. The corresponding water level rose till the wall of the coffee shop located on the left bank.

Marj Bisri Station – Collection Point of Testimonies

Equipments of the Marj Bisri Station : Limnigraph, Rain Gauge and Anemometer

Hydraulic Structure Entrance

Upstream View

The Engineer continued his inspection of the land upstream the Dam to get an idea about the elements of interest for the study: Top soil, velocity, slope, sediment transport.

The pictures below illustrate these characteristics at locations near the axis and in other locations a little further upstream:

Upstream View (Bisri Dam Site)

Downstream View (Bisri Dam Site)

Sediment Transport : Pebble

Top Soil in the Watershed of Bisri

Figure 4.1 Location of the inspected sites

CHAPTER 5 WATER AVAILABILITY

5.1 Introduction

The Bisri Dam Project is intended to store water for municipal and industrial uses within Beirut and surrounding areas. The source of water supply for the project is the Bisri River. The headwaters for the Bisri River are located in the Jabal el Barouk Mountains. Both rainfall and snowmelt contribute to the streamflow in the basin.

The following sections are intended for the determination of the long monthly and annual streamflow series for the Bisri dam site. The main objective is to evaluate the available water resources.

5.2 Stream Flow Data

For this study, we used a database comprising:

- The series of monthly flows of Marj Bisri Station (1952-1973, 1982-1983 and 2001-2012);
- The streamflow series at the Qaraoun dam site.

5.3 Recall of the Results of Water Availability Calculations realized as part of the Feasibility Study of 1995

The mean annual flow available to the project at the dam site Bisri is estimated at 142.05 Mm^3 (4.3 m^3/s), with annual values ranging from a high of 278.40 Mm^3 (8.8 m^3/s) to a low of 53.98 million m^3 (1.7 m^3/s).

The calculation method based on the correlation flow - rain is not desirable, because the natural phenomenon of the transformation rainfall - flow is much more complex.

5.4 Methodology

The methodology adopted by the Engineer for the development of the streamflows at the Bisri Dam Site is based on the ratio of the areas and the average annual rainfall of the watershed Marj Bisri station at the Bisri Dam Site. The Engineer maintain for the transposition from the station to the Dam Site the area factor because the term rain is constant between the two watersheds.

Filling gaps in the series of monthly flow at the Marj Bisri station is based on the data of the series of streamflow at the Qaraoun Dam.

5.5 Elaboration of the streamflow series

The series of Marj Bisri station is characterized by several shortcomings. The in-filled monthly flows at Bisri Dam is extracted from a series of Qaraoun Dam based on a piecewise linear regression as recommended by Dr Ezio Todini (World Bank Hydrology Expert).

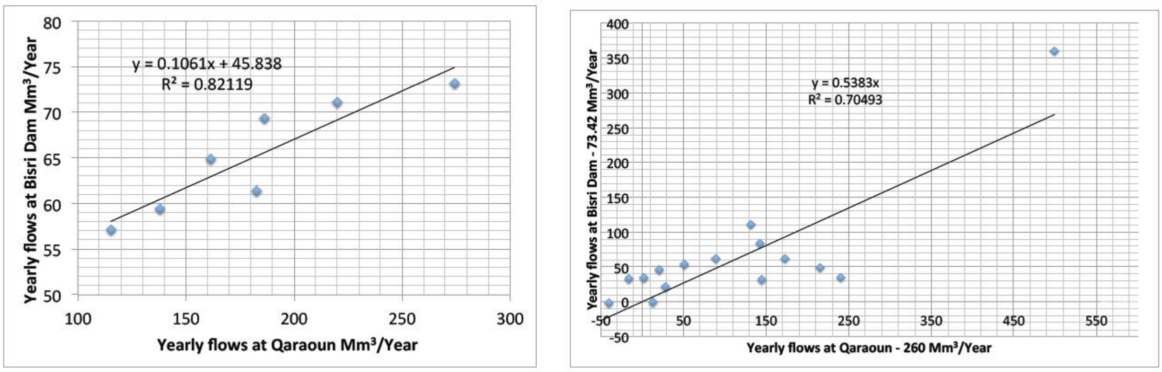
Determining the streamflow series at the Bisri Dam site (S = 215 km ²) will be made by transposition of flows of the Marj Bisri station completed (S = 220 km ²) by a surface ratio because the term average rain is constant between the two basins.

The formula used to calculate the flow at the Bisri site is:

$$Q_{\text{Bisri}} = Q_{\text{Merj Bisri}} * \left(\frac{S_{\text{Bisri}}}{S_{\text{Merj Bisri}}} \right)$$

The linear regression is given in the figure 5.1 below (Refer to Appendix I: Final Report on missing values patching by Ezio Todini, March 7th, 2014):

Figure 5.1 The piecewise regression model, (a) Linear Regression for values of Qaraoun yearly flows lower than 260 Mm^3/year; (b) Linear Regression for values of Qaraoun yearly flows larger than 260 Mm^3/year



(a) (b)

The chosen model is the following:

$$\begin{cases} q_{BD} = 45.838 + 0.10.61\ q_Q & \forall\ q_Q \leq 260 \\ q_{BD} = 73.424 + 0.5383\ (q_Q - 260) & \forall\ q_Q > 260 \end{cases}$$

Where:

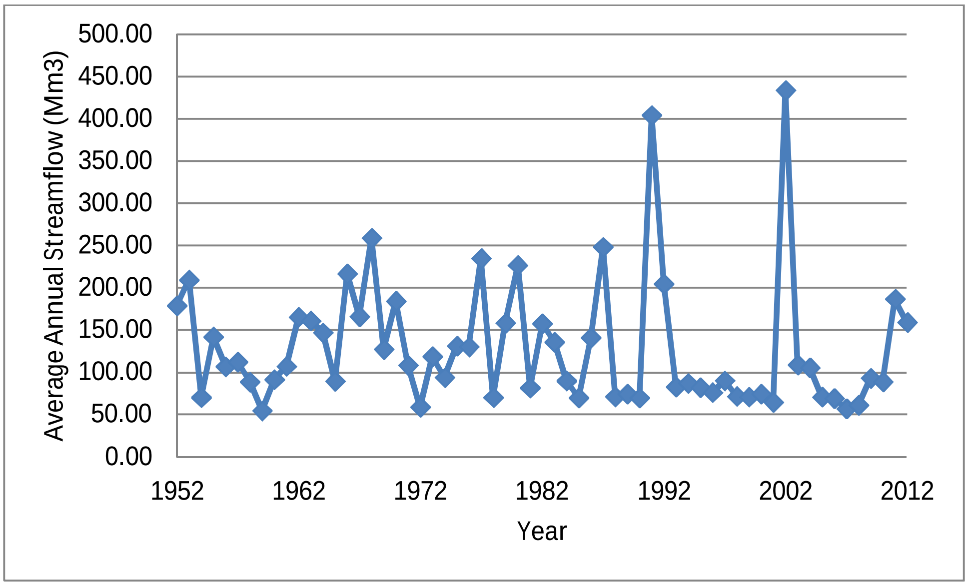
q_{BD} is the yearly flow at Bisri Dam in Mm^3/year

q_Q is the yearly flow at Qaraoun in Mm^3/year

The monthly values are then rescaled according to the Qaraoun monthly percentage for each specific year.

The transposition provides a series of natural streamflow whose characteristics are as follows:

Inter-Annual Module	:	4.1 m3/s (period 1952 - 2012) ;
Average annual streamflow	:	129.5 Mm^3 ;
Maximum	:	434 Mm^3 year 2002;
Minimum	:	55 Mm^3 year 1959.

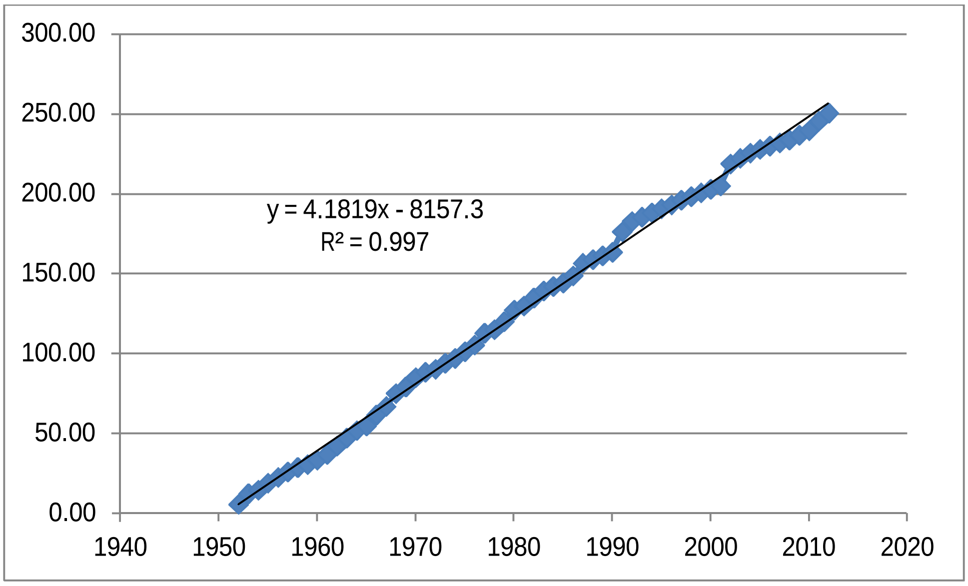


The series of streamflow at Bisri Dam site is illustrated in Table 5.3

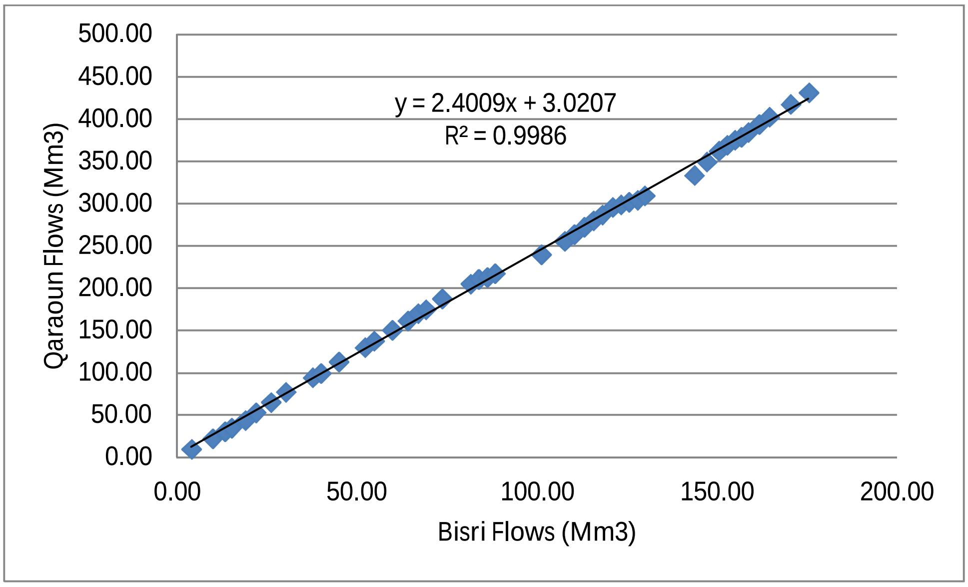
5.6 Validation of the Streamflow Series

To validate the developed streamflow series for the Bisri site, the Engineer used the simple mass and a double mass methods between the series of Bisri and the one of Qaraoun. The table 5.4 and 5.5 below summarize the results.

The figure below shows the simple combination of the yearly modules, we note two breaks delimiting three periods (1952-1990, 1991-2001 and 2002-2010). For The last two periods, despite the tendency to lower, remain comparable to the first (respectively 4.7, 4.3 and 4.5 m^3 /s).



The figure below shows within the x-direction the accumulated flows of Bisri and in the y-direction the combination of modules of the Qaraoun Dam underline of the streamflow series of the Bisri Dam with the tendencies of the region:



The analysis of the simple and double mass confirm the validity of the Bisri series.

Table 5-1 Recorded Flows at Station Marj Bisri

Water Year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	May	Aug	Year
1952	2.06	1.97	2.42	5.93	29.07	44.5	58.46	21.2	8.89	4.89	3.17	2.18	184.74
1953	1.74	1.78	9.53	10.78	58	53.66	27.99	32.08	9.99	5.18	3.27	2.33	216.33
1954	1.96	1.93	2.72	4.77	5.73	12.62	21.15	10.62	6.39	2.17	1.57	1.23	72.86
1955	1.15	1.27	7.59	18.58	31.05	31.11	28.93	10.25	9	3.76	2.58	1.56	146.83
1956	1.37	1.54	2.26	8.11	18.69	27.77	23.92	13.4	6.72	3.34	2	1.29	110.41
1957	1.14	1.7	2.27	21.13	38.92	20.18	13.89	7.98	3.95	1.98	1.53	1.33	116
1958	1.4	1.61	1.58	4.8	13.33	20.37	31.4	8.01	4.33	2.1	1.53	1.18	91.64
1959	1.17	1.4	1.79	1.88	9.27	7.56	14.22	11.77	3.71	1.58	1.15	1.07	56.57
1960	0.89	0.96	3.11	3.31	15.78	28.2	16	17.57	4.78	1.81	1.16	1.07	94.64
1961	1.03	1.2	2.78	25.39	18.44	36.84	10.42	5.12	4.15	2.25	1.77	1.43	110.82
1962	0.71	1.33	1.67	21.18	25.27	49.46	32.94	16.68	12.44	4.36	3.02	1.93	170.99
1963	1.72	2.36	2.46	8.44	16.51	53.37	51.8	12.89	8.27	3.95	2.7	1.92	166.39
1964	1.58	1.64	15.56	7.1	24.33	49.15	16.87	23.29	6.32	2.98	1.79	1.21	151.82
1965	0.89	1.58	2	18.28	18.16	20.9	15.64	8.14	3.63	1.82	1.07	0.58	92.69
1966	0.79	1.21	1.07	24.29	29.38	41.61	73.22	25.46	13.8	6.34	4.03	2.65	223.85
1967	1.85	2.58	3.17	20.38	67.04	32.16	19.67	9.85	6.92	3.87	2.44	1.69	171.62
1968	1.22	1.75	3.37	68.86	76.6	43.1	32.08	18.81	11.33	5.24	3.09	1.97	267.42
1969	1.54	2.58	4.06	8.39	36.23	14.56	41.81	10.59	6.18	2.86	1.71	1.03	131.54
1970	0.8	1.23	1.69	11.72	9.11	45.55	29.85	63.45	15.34	6.1	3.71	1.91	190.46
1971	1.43	1.45	2.2	23.33	21.36	27.19	9.52	11.03	7.26	3.61	1.95	1.61	111.94
1972	1.61	1.22	2.15	2.13	5.52	9.01	22.15	9.8	3.72	1.97	1	0.82	61.1
1973	0	1.02	2.41	5.97	24.02	23.32	25.62	26.71	7.56	3.27	1.73	1.08	122.71
1974													
1975													
1976													
1977													
1978													
1979													
1980													
1981													
1982	2.46	2.35	3.72	4.28	22.10	21.16	58.18	20.02	12.63	7.29	4.59	4.34	163.12
1983	3.76	4.69	11.46	7.16	23.97	22.09	25.84	24.50	9.60	3.65	1.86	1.77	140.33
1984													
1985													
1986													
1987													
1988													
1989													
1990													
1991													

Water Year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	May	Aug	Year
1992													
1993													
1994													
1995													
1996													
1997													
1998													
1999													
2000													
2001	0.14	0.17	1.72	3.73	15.44	4.98	9.72	14.45	6.08	4.67	4.22	1.65	66.97
2002	0.38	0.11	0.76	45.25	25.29	110.91	181.62	37.96	21.51	4.36	11.83	7.88	447.86
2003	1.78	1.35	2.73	2.70	32.36	34.61	19.27	6.94	4.45	2.72	2.32	1.43	112.65
2004	0.38	0.58	6.26	3.50	17.18	40.19	17.44	10.52	8.35	2.06	1.50	1.12	109.09
2005	1.12	1.72	4.99	2.81	9.44	11.70	10.70	18.05	5.96	2.45	2.14	2.39	73.47
2006	1.06	1.10	6.86	3.23	9.37	17.12	13.07	11.15	4.82	1.62	1.08	1.15	71.64
2007	2.43	1.95	1.55	2.60	2.18	15.36	9.41	10.68	6.13	3.27	2.10	1.32	59.00
2008	1.43	1.54	1.25	2.68	3.67	16.82	15.68	10.66	4.01	2.21	2.04	1.42	63.42
2009	2.09	1.80	4.44	10.12	26.27	24.49	15.22	6.84	2.69	2.15	0.80	0.53	97.45
2010	1.86	2.00	1.36	5.24	7.73	19.09	21.05	8.98	3.27	2.90	1.70	0.38	75.56
2011	0.84	1.00	1.65	5.42	22.87	24.73	36.73	16.55	9.67	3.71	2.10	1.73	127.00
2012	2.09	1.16	2.80	30.73	39.47	25.56	13.76	13.43	6.54	1.99	1.12	1.14	139.80
AVE	1.39	1.58	3.60	12.62	23.59	30.03	29.59	16.26	7.51	3.35	2.43	1.70	133.63
MED	1.39	1.54	2.44	7.13	21.73	25.14	21.10	12.33	6.46	3.12	1.98	1.42	114.32
MIN	0.00	0.11	0.76	1.88	2.18	4.98	9.41	5.12	2.69	1.58	0.80	0.38	56.57
MAX	3.76	4.69	15.56	68.86	76.60	110.91	181.62	63.45	21.51	7.29	11.83	7.88	447.86
STDEV	0.73	0.77	3.14	13.85	16.66	19.28	30.18	11.02	3.97	1.44	1.87	1.27	74.22
SKEW	0.74	1.65	2.34	2.42	1.53	2.18	3.95	2.60	1.56	0.94	3.83	3.64	2.38

Table 5-2 Streamflow Series at the Qaraoun Dam Site

Water Year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	May	Aug	Year
1952													
1953													
1954													
1955													
1956													
1957													
1958													
1959													
1960													
1961													
1962													
1963													
1964													
1965													
1966													
1967													
1968													
1969	9.10	19.40	20.80	24.20	50.40	50.90	78.60	39.00	13.90	2.10	1.50	1.20	311.10
1970	3.70	6.40	10.00	21.70	18.60	47.60	76.40	137.10	55.30	11.30	2.80	1.50	392.40
1971	4.90	9.50	13.80	43.40	42.20	49.60	37.00	33.90	23.70	1.20	1.80	1.90	262.90
1972	3.70	8.10	9.60	10.60	16.60	20.00	38.20	22.10	5.00	0.10	1.60	2.50	138.10
1973	2.10	3.20	8.60	16.00	44.50	57.30	88.40	43.30	10.90	2.50	3.50	0.90	281.20
1974	3.50	8.00	10.40	15.90	22.80	104.90	75.70	33.10	11.90	0.90	3.40	0.70	291.20
1975	2.10	6.70	10.10	25.60	40.20	69.80	75.00	92.50	48.10	11.80	0.40	0.00	382.30
1976	2.80	8.20	29.20	53.00	1.20	80.20	81.60	73.80	38.00	6.90	0.90	4.90	380.70
1977	5.20	11.80	15.50	53.60	96.50	94.00	116.60	83.00	41.40	13.10	4.00	4.50	539.20
1978	6.70	12.70	16.30	24.20	33.40	23.00	24.70	12.70	4.00	1.30	0.70	0.30	160.00
1979	1.30	5.00	9.50	34.20	53.70	64.80	114.00	93.90	39.90	9.30	3.30	2.90	431.80
1980	6.80	12.60	14.60	29.00	86.00	108.00	126.40	80.20	43.90	11.90	4.80	5.00	529.20
1981	6.60	11.80	16.00	21.90	27.40	61.20	55.50	31.50	12.10	0.00	1.00	0.00	245.00
1982	4.00	6.80	9.70	12.80	31.60	65.00	122.20	77.70	48.20	14.60	4.90	5.80	403.30
1983	4.40	9.90	18.60	19.30	35.50	48.40	94.10	76.40	29.60	8.50	1.50	3.10	349.30
1984	5.60	0.00	1.00	22.60	32.70	103.80	59.90	27.90	12.90	6.80	2.40	2.30	277.90
1985	0.80	4.30	5.80	11.60	31.20	51.40	22.60	10.10	3.20	0.30	0.00	0.00	141.30
1986	0.00	3.20	14.30	29.20	72.20	52.70	106.70	76.10	26.30	12.50	2.30	5.70	401.20
1987	5.20	11.00	16.30	42.20	78.10	87.10	168.70	76.60	36.20	18.10	7.80	8.00	555.30
1988	9.80	13.70	18.10	32.80	35.10	24.40	25.70	12.00	3.10	0.00	0.00	0.00	174.70
1989	0.00	0.60	3.80	6.80	9.50	24.50	19.90	5.60	0.00	0.00	0.00	0.00	70.70
1990	0.00	0.00	2.50	6.40	10.70	30.10	43.20	29.10	15.80	0.00	0.00	0.00	137.80
1991	2.50	6.50	8.30	60.90	103.70	160.50	131.90	97.50	74.60	39.00	12.80	11.10	709.30

Water Year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	May	Aug	Year
1992	10.70	15.60	29.60	79.80	84.50	71.90	104.70	52.10	34.90	11.40	3.20	2.30	500.70
1993	4.30	10.50	18.40	18.40	38.60	62.80	60.80	26.30	7.90	0.00	0.00	2.30	250.30
1994	2.10	7.40	16.90	68.30	54.70	51.30	35.00	25.70	5.10	0.00	0.00	1.20	267.70
1995	2.70	4.60	16.70	13.00	38.70	40.70	70.70	43.20	12.40	1.90	0.00	2.30	246.90
1996	2.70	8.10	10.10	16.10	15.90	34.70	52.60	59.60	13.50	3.00	0.00	0.00	216.30
1997	2.90	5.60	9.70	20.60	37.30	60.20	59.10	59.50	19.60	4.10	0.00	0.00	278.60
1998	0.00	4.60	9.20	12.60	15.40	19.60	18.10	15.10	0.00	0.00	0.00	0.00	94.60
1999	0.00	0.00	0.50	3.00	32.60	27.10	29.10	13.10	0.00	0.00	0.00	0.00	105.40
2000	0.00	0.80	2.50	10.60	10.00	31.60	10.10	3.10	0.00	0.00	0.00	0.00	68.70
2001	0.00	0.00	2.90	10.30	31.00	30.90	35.90	41.00	8.00	1.60	0.00	0.00	161.60
2002	0.00	2.80	7.60	57.80	69.10	200.00	181.70	124.80	59.70	29.20	14.90	11.90	759.50
2003	11.30	18.60	23.80	30.20	94.20	134.80	99.10	40.10	21.40	12.40	7.20	8.00	501.10
2004	8.30	9.50	28.20	30.30	65.10	121.10	65.50	38.10	19.20	10.10	6.80	2.60	404.80
2005	2.80	8.30	16.40	19.80	42.90	48.80	35.70	30.10	10.90	1.00	0.00	3.40	220.10
2006	2.90	7.70	12.00	11.20	20.70	50.10	38.80	26.90	11.60	1.60	2.10	0.90	186.50
2007	0.90	2.00	6.60	14.50	16.00	39.70	30.20	4.90	0.50	0.00	0.00	0.00	115.30
2008	0.70	2.40	4.60	8.10	7.90	33.30	68.20	42.80	11.40	2.00	0.10	1.10	182.60
2009	2.40	4.30	18.30	44.00	88.40	55.70	55.50	12.40	4.90	0.90	0.20	1.40	288.40
2010	1.60	4.90	8.20	20.50	22.10	76.00	80.40	31.70	19.40	5.10	1.50	2.90	274.30
2011	5.94	8.38	14.90	18.83	59.33	101.62	140.16	71.11	29.92	13.63	7.34	4.63	475.79
2012	4.29	9.13	18.05	67.58	124.69	89.25	52.75	39.90	19.57	4.66	1.36	2.06	433.29
AVE	3.58	7.15	12.68	27.12	44.16	65.01	70.62	46.97	20.63	6.25	2.41	2.48	309.05
MED	2.85	7.10	11.20	21.15	36.40	54.20	63.15	39.45	13.70	2.30	1.43	1.70	278.25
MIN	0.00	0.00	0.50	3.00	1.20	19.60	10.10	3.10	0.00	0.00	0.00	0.00	68.70
MAX	11.30	19.40	29.60	79.80	124.69	200.00	181.70	137.10	74.60	39.00	14.90	11.90	759.50
STDEV	3.04	4.78	7.20	18.77	29.53	38.41	41.12	32.40	18.21	8.16	3.38	2.93	164.13
SKEW	0.87	0.52	0.49	1.18	0.87	1.49	0.80	0.87	1.06	2.12	2.10	1.65	0.75

Table 5-3 Streamflow series at the Bisri Dam Site

Water Year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	May	Aug	Year
1952	2.03	1.91	2.35	5.83	28.16	43.10	56.62	20.48	8.61	4.74	3.07	2.10	178.91
1953	1.69	1.72	9.23	10.43	56.21	51.97	27.11	31.90	9.68	5.02	3.17	2.25	209.51
1954	1.90	1.87	2.63	4.62	5.55	12.23	20.48	10.70	6.19	2.09	1.52	1.19	70.56
1955	1.11	1.23	7.35	17.99	30.07	30.13	28.02	9.94	8.72	3.64	2.49	1.50	142.20
1956	1.33	1.49	2.19	7.86	18.10	26.89	23.17	12.98	6.51	3.23	1.94	1.25	106.93
1957	1.10	1.66	2.20	20.46	37.70	19.54	13.45	7.72	3.83	1.92	1.48	1.30	112.34
1958	1.36	1.56	1.53	3.81	12.07	19.73	30.43	7.76	4.18	2.04	1.49	1.15	88.75
1959	1.15	1.37	1.79	1.82	8.98	7.32	13.78	11.77	3.59	1.53	1.11	1.04	54.79
1960	0.86	0.93	3.01	3.21	15.28	27.31	15.49	16.99	4.63	1.75	1.12	1.04	91.66
1961	0.99	1.16	2.70	24.59	17.78	35.68	9.95	4.95	4.01	2.19	1.71	1.39	107.33
1962	0.69	1.29	1.62	20.50	24.47	47.89	36.87	16.15	12.06	4.22	2.92	1.87	165.60
1963	1.67	2.30	2.38	8.17	15.99	49.51	50.17	12.48	8.01	3.95	2.61	1.86	161.14
1964	1.53	1.59	15.07	6.88	23.56	47.60	16.34	22.56	6.12	2.89	1.73	1.17	147.03
1965	0.86	1.53	1.94	17.70	17.59	20.24	15.06	7.88	3.52	1.76	1.04	0.56	89.77
1966	0.77	1.17	1.04	23.52	28.46	40.29	70.91	24.66	13.36	6.13	3.90	2.58	216.79
1967	1.80	2.50	3.07	19.74	64.93	31.15	19.05	9.54	6.70	3.75	2.36	1.65	166.21
1968	1.18	1.69	3.26	66.69	74.18	41.74	31.07	18.22	10.72	5.07	2.98	1.91	258.99
1969	1.59	2.50	3.93	8.13	35.08	14.10	40.49	10.26	5.99	2.76	1.66	1.00	127.39
1970	0.77	1.19	1.64	11.35	8.82	44.10	28.92	61.45	13.96	5.91	3.58	1.85	184.45
1971	1.38	1.40	2.13	22.59	20.69	25.98	9.22	10.68	7.03	3.51	1.89	1.56	108.41
1972	1.53	1.18	2.08	2.06	5.60	8.73	21.45	9.49	3.60	1.90	0.97	0.79	59.17
1973	0.68	0.98	2.33	5.78	23.26	22.58	24.81	25.95	7.32	3.17	1.68	1.05	118.84
1974	2.26	2.33	2.26	7.39	7.06	32.48	23.44	10.25	3.68	0.28	1.05	0.22	94.14
1975	0.76	2.44	3.68	9.32	14.64	25.42	27.32	33.69	17.52	4.30	0.15	0.00	131.26
1976	1.02	2.98	10.61	19.26	0.44	29.15	29.66	26.83	13.81	2.51	0.33	1.78	130.46
1977	2.16	4.90	6.43	22.24	40.04	39.00	48.38	34.44	17.18	5.44	1.66	1.87	234.98
1978	2.63	4.99	6.40	9.50	13.12	9.03	9.70	4.99	1.57	0.51	0.27	0.12	70.48
1979	0.50	1.92	3.65	13.14	20.63	24.89	43.79	36.07	15.33	3.57	1.27	1.11	158.55
1980	2.81	5.54	6.42	12.76	37.84	47.52	55.62	35.29	19.32	5.24	2.64	1.19	226.87
1981	1.88	1.78	3.28	4.81	17.55	28.27	25.11	8.55	4.43	3.39	3.51	3.51	81.79
1982	2.38	2.28	3.60	4.15	21.40	20.49	56.36	19.39	12.23	7.07	4.45	4.20	157.98
1983	3.64	4.54	11.10	6.93	23.21	21.38	25.03	23.73	9.30	3.53	1.80	1.71	135.91
1984	0.95	0.92	2.19	5.19	11.68	31.02	18.70	8.34	3.85	2.03	0.72	0.69	90.13
1985	0.34	1.85	2.50	4.99	13.43	22.13	9.73	4.35	1.38	0.13	0.00	0.00	69.97
1986	0.00	1.19	5.33	10.87	26.89	19.63	39.74	28.34	9.79	4.66	0.86	2.12	141.09
1987	2.18	4.60	6.82	17.66	32.69	36.45	70.60	32.06	15.15	7.57	3.26	3.35	248.47
1988	3.61	5.05	6.67	12.09	12.93	8.99	9.47	4.42	1.14	0.00	0.00	0.00	71.38
1989	0.00	0.45	2.87	5.13	7.17	18.48	15.01	4.22	0.00	0.00	0.00	0.00	74.51
1990	0.00	0.00	1.10	2.81	4.69	13.20	18.94	12.76	6.93	0.00	0.00	0.00	69.96
1991	1.11	2.89	3.69	27.07	46.09	71.34	58.63	43.34	33.16	17.34	5.69	4.93	404.29

Water Year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	May	Aug	Year
1992	4.34	6.32	12.00	32.35	34.26	29.15	42.44	21.12	14.15	4.62	1.30	0.93	204.87
1993	1.24	3.04	5.32	5.32	11.17	18.17	17.59	7.61	2.29	0.00	0.00	0.67	82.99
1994	0.61	2.14	4.90	19.78	15.84	14.86	10.14	7.44	1.48	0.00	0.00	0.35	87.31
1995	0.79	1.34	4.87	3.79	11.29	11.88	20.63	12.61	3.62	0.55	0.00	0.67	82.21
1996	0.86	2.58	3.21	5.12	5.06	11.04	16.73	18.96	4.29	0.95	0.00	0.00	76.32
1997	0.87	1.68	2.91	6.17	11.17	18.03	17.70	17.82	5.87	1.23	0.00	0.00	90.34
1998	0.00	2.72	5.44	7.45	9.10	11.59	10.70	8.93	0.00	0.00	0.00	0.00	71.83
1999	0.00	0.00	0.27	1.62	17.65	14.67	15.75	7.09	0.00	0.00	0.00	0.00	71.01
2000	0.00	0.62	1.93	8.20	7.73	24.44	7.81	2.40	0.00	0.00	0.00	0.00	74.79
2001	0.14	0.16	1.67	3.61	14.95	4.82	9.41	13.99	5.88	4.53	4.09	1.60	64.86
2002	0.37	0.11	0.74	43.82	24.49	107.41	175.89	36.76	20.83	4.22	11.46	7.63	433.74
2003	1.72	1.32	2.64	2.61	31.34	33.52	18.66	6.72	4.31	2.63	2.25	1.38	109.10
2004	0.37	0.56	6.06	3.38	16.64	38.92	16.89	10.19	8.09	2.00	1.45	1.08	105.65
2005	1.08	1.67	4.83	2.72	9.14	11.32	10.36	17.48	5.77	2.37	2.07	2.30	71.15
2006	1.03	1.07	6.64	3.13	9.07	16.58	12.66	10.80	4.67	1.57	1.05	1.11	69.38
2007	2.35	1.89	1.50	2.52	2.11	14.88	9.11	10.34	5.94	3.17	2.04	1.28	57.14
2008	1.38	1.49	1.21	2.60	3.55	16.29	15.19	10.32	3.88	2.14	1.98	1.38	61.42
2009	2.02	1.74	4.30	9.80	25.44	23.72	14.74	6.62	2.61	2.08	0.77	0.51	93.26
2010	1.80	1.94	1.32	5.07	7.49	18.49	20.40	8.70	3.17	2.81	1.65	0.37	89.11
2011	0.81	0.97	1.60	5.25	22.15	23.95	35.57	16.03	9.37	3.59	2.03	1.68	187.00
2012	2.02	1.12	2.71	29.76	38.23	24.75	13.33	13.01	6.33	1.93	1.08	1.10	159.45
MED	1.31	1.96	3.94	11.69	20.52	27.13	27.87	16.40	7.49	2.97	1.76	1.36	129.54
MIN	1.11	1.67	2.91	7.45	17.55	23.95	20.40	12.48	5.99	2.63	1.52	1.17	106.93
MAX	0.00	0.00	0.27	1.62	0.44	4.82	7.81	2.40	0.00	0.00	0.00	0.00	54.79
STDEV	4.34	6.32	15.07	66.69	74.18	107.41	175.89	61.45	33.16	17.34	11.46	7.63	433.74
SKEW	0.92	1.36	2.94	11.44	14.81	16.88	24.99	11.47	6.02	2.66	1.81	1.31	75.58
AVE	0.97	1.42	1.73	2.46	1.50	2.15	3.79	1.55	1.70	2.70	2.80	2.36	2.08

Table 5-4 Double mass of the series of Bisri Dam and Qaraoun Site (m^3/s)

Water Year	Bisri Dam Flow m3/s	Qaraoun Flow m3/s	Cumulative Flows at Bisri Dam Site	Cumulative Flows at Qaraoun Dam Site
1952				
1953				
1954				
1955				
1956				
1957				
1958				
1959				
1960				
1961				
1962				
1963				
1964				
1965				
1966				
1967				
1968				
1969	4.04	9.86	4.04	9.86
1970	5.85	12.44	9.89	22.31
1971	3.44	8.34	13.33	30.64
1972	1.88	4.38	15.20	35.02
1973	3.77	8.92	18.97	43.94
1974	2.99	9.23	21.96	53.17
1975	4.16	12.12	26.12	65.30
1976	4.14	12.07	30.26	77.37
1977	7.45	17.10	37.71	94.47
1978	2.23	5.07	39.94	99.54
1979	5.03	13.69	44.97	113.23
1980	7.19	16.78	52.16	130.01
1981	2.59	7.77	54.76	137.78
1982	5.01	12.79	59.77	150.57
1983	4.31	11.08	64.08	161.65
1984	2.86	8.81	66.93	170.46
1985	2.22	4.48	69.15	174.94
1986	4.47	12.72	73.63	187.66
1987	7.88	17.61	81.51	205.27
1988	2.26	5.54	83.77	210.81
1989	2.36	2.24	86.13	213.05
1990	2.22	4.37	88.35	217.42
1991	12.82	22.49	101.17	239.91

Water Year	Bisri Dam Flow m3/s	Qaraoun Flow m3/s	Cumulative Flows at Bisri Dam Site	Cumulative Flows at Qaraoun Dam Site
1992	6.50	15.88	107.67	255.79
1993	2.63	7.94	110.30	263.73
1994	2.77	8.49	113.07	272.22
1995	2.61	7.83	115.67	280.05
1996	2.42	6.86	118.09	286.90
1997	2.86	8.83	120.96	295.74
1998	2.28	3.00	123.24	298.74
1999	2.25	3.34	125.49	302.08
2000	2.37	2.18	127.86	304.26
2001	2.06	5.12	129.92	309.38
2002	13.75	24.08	143.67	333.47
2003	3.46	15.89	147.13	349.36
2004	3.35	12.84	150.48	362.19
2005	2.26	6.98	152.74	369.17
2006	2.20	5.91	154.94	375.09
2007	1.81	3.66	156.75	378.74
2008	1.95	5.79	158.69	384.53
2009	2.96	9.15	161.65	393.68
2010	2.83	8.70	164.48	402.38
2011	5.93	15.09	170.41	417.46
2012	5.06	13.74	175.46	431.20

Table 5-5 Simple mass of the series of the Bisri Dam (m3/s)

Water Year	Flow at Bisri Dam Site (m^3/s)	Cumulative Flows at Bisri Dam Site m^3/s)
1952	5.67	5.67
1953	6.64	12.32
1954	2.24	14.55
1955	4.51	19.06
1956	3.39	22.45
1957	3.56	26.02
1958	2.81	28.83
1959	1.74	30.57
1960	2.91	33.47
1961	3.40	36.88
1962	5.25	42.13
1963	5.11	47.24
1964	4.66	51.90
1965	2.85	54.75
1966	6.87	61.62
1967	5.27	66.89
1968	8.21	75.10
1969	4.04	79.14
1970	5.85	84.99
1971	3.44	88.43
1972	1.88	90.31
1973	3.77	94.08
1974	2.99	97.06
1975	4.16	101.22
1976	4.14	105.36
1977	7.45	112.81
1978	2.23	115.05
1979	5.03	120.07
1980	7.19	127.27
1981	2.59	129.86
1982	5.01	134.87
1983	4.31	139.18
1984	2.86	142.04
1985	2.22	144.26
1986	4.47	148.73
1987	7.88	156.61
1988	2.26	158.87
1989	2.36	161.24
1990	2.22	163.46
1991	12.82	176.28

Water Year	Flow at Bisri Dam Site (m^3/s)	Cumulative Flows at Bisri Dam Site m^3/s)
1992	6.50	182.77
1993	2.63	185.40
1994	2.77	188.17
1995	2.61	190.78
1996	2.42	193.20
1997	2.86	196.06
1998	2.28	198.34
1999	2.25	200.59
2000	2.37	202.96
2001	2.06	205.02
2002	13.75	218.77
2003	3.46	222.23
2004	3.35	225.58
2005	2.26	227.84
2006	2.20	230.04
2007	1.81	231.85
2008	1.95	233.80
2009	2.96	236.76
2010	2.83	239.58
2011	5.93	245.51
2012	5.06	250.57

CHAPTER 6 FLOODS

6.1 Introduction

Flood hydrographs were developed for the purpose of sizing two hydraulic structures: 1) diversion facilities; and 2) spillway. The procedures and assumptions used for computing the flood hydrographs are described in this chapter. By routing these inflow design flood hydrographs through available storage, either cofferdam or reservoir, the designer of each structure will thereby determine the "outflow design hydrograph". The peak of the outflow design hydrograph is the actual discharge for which the structure, tunnel, conduit, or spillway, must be designed.

The inflow flood for spillway design has a peak discharge of 2,300 m^3/s (11 $m^3/s/km^2$) and a volume of 43 Mm^3.

The inflow flood for the design of diversion facilities has a peak discharge of 600 m^3/s and a volume of 11 Mm^3.

6.2 Recall of the Results of the Floods Study Realized As Part of the Feasibility

For the study results diversion flow flood, the study adopts the results of the statistical adjustment of the Gumbel law for the series of maximum annual daily discharge of the Marj Bisri station for T = 25 years, which corresponds to a peak flow of 440 m^3 / s. This quantity corresponds to the quantity of daily volume rather than quantity of the peak flow, which does not meet the objective of the flood study.

The spillway design flood PMP resulting from the application of the methodology points a peak flow of 3110 m^3 / s and a volume of 87 Mm^3 for 48h.

6.3 Historic Storms

6.3.1 Northern Lebanon Storm

One of the most severe storms ever to hit Lebanon occurred on December 17, 1955, in Northern Lebanon. No flood remembered today has caused such catastrophic flooding in the northern coastal town of Tripoli, although historical records from the past describe similar destructive floods in the same general area. Investigations have indicated that such a storm rainfall and resulting flood may have a frequency of occurrence of 100 years. Estimates of peak discharges during this flood have been made at several locations as follows:

River/Location	Drainage Area (km^2)	Peak Discharge	
		m^3/s	$m^3/s/km^2$
Abou Aali at Tripoli	387	1,300	3.4
Abou Aali at Kousba	144	450	3.1
Rachaine at Zghorta	134	800	6.0
Jouait	94	690	7.3
Chmisse	67	410	6.1

6.3.2 Bisri River Storm

The flood of April 13, 1971, was the largest flood to occur at the Bisri gaging station (D.A. = 222 km^2) in a 21-year period of record from September 1952 to August 1973 in addition to 8 years of record from September 2001to August 2009. Although flood records are not available from 1973 to 1982, no larger flood has been known to occur during these ten years. During this flood, some damage occurred to the Aouali hydropower plant several kilometers downstream of the Bisri gage.

The Bisri gaging station was destroyed during this flood, but a record of the early hours of the flood was later recovered from the recorder. This record showed the flood level still rising rapidly at a discharge of 460 m^3/s at the time the gage stopped functioning. Subsequent studies by Mr. Bocquillion, hydraulics professor at ESIB, resulted in an estimated peak, discharge of 620 m^3/s as shown in Figure 6.2. The second and third largest flood peaks occurring in the 21-year record were 360 m^3/s and 228 /s, respectively.

6.3.3 Storms Recorded at the Jezzine Raingage

On occasion, large storm systems can bring large quantities of moisture into Southern Lebanon over a several-day period. Such storms have been recorded at the Jezzine raingage within the Bisri dam drainage area. Several of these storms occurred as follows:

	Day 1 (mm)	Day 2 (mm)	Day 3 (mm)	Total (mm)
February 2 and 3, 1929	108	131	67	307.2
January 20 and 21, 1947	90	94	-	118
January 17, 18, and 19, 1949	102	84	56	242

The result of such storms is to saturate the watershed during the first day of the storm. Therefore, on the second or third day, a much larger percentage of the rainfall contributes to the direct surface runoff, often causing a greater flood with a smaller second day rainfall Second-day rainfall may also come at a time when discharge in the stream is still high from the previous day flood.

6.4 Database Used in the Flood Study

The database used consists of maximum annual instantaneous and maximum annual daily flow data from the Marj Bisri hydrometric station located downstream of the Bisri Dam Site, in addition to maximum annual daily rainfall data from the rainfall stations nearby.

The rainfall and flow data for the years prior 2000 cannot be verified due to the unavailability of archives records by the authorities managing the measurements network. The Engineer used the data in the pre-feasibility study of the Bisri Dam.

6.4.1 Maximum annual flows

The old series flows were recovered from the pre-feasibility study. For the water year (2002 – 2003), the Marj Bisri Station flows were retrieved using the rating curve developed by Dr. Ezio Todini (Refer to Appendix II: Report on Rating Curves) as for the other water years between 2000-2001 and 2012-2013, the data given by the Litani River Authority was used.

Data of the maximum annual daily and instantaneous flow for the Marj Bisri station (220 km^2) is shown in the Table 6.1.

6.4.2 Maximum Annual Daily Rainfall

The Engineer used the maximum annual daily rainfall recorded in the Table 6.2.

The original data in this table was retrieved from the feasibility report for the old data and from Beirut Airport for the new Data. This data was corrected and completed by Dr. Wajdi Najem member of the panel of experts of Bisri Dam.

6.4.3 Flood Hydrograph

There is only one flood hydrograph corresponding to the flood of April 13, 1971; noted and illustrated in the Table 6.3 and Figure 6.2.

6.5 Methodology

The Engineer proposes in this present study the following methods:

- Selection of a reference station. This choice means that the peak flows will be calculated at the station level and transposed towards the watershed of the dam site under study. This implementation will be done using the Francou-Rodier formula.
- Calculation of floods by different methods and choice of project flows.

The Engineer suggests the following approach:

6.5.1 Statistic Method

With samples of instantaneous flows, statistical adjustments will be made to various laws with the updated database.

These adjustments will lead to have peak flows for different return periods. Flows from this method will be used for the reference station whose sample size measure is sufficient to allow extrapolation of flows for the Centennial occurrence.

The transpositions to the Bisri Dam site will be calculated using the method of Francou-Rodier of specific flows.

6.5.2 Gradex Method

The Description of the Gradex method is in the article of P. Guillot and D. Duban (1968). For its application to the Marj Bisri Station, the Engineer will follow the below steps:

- Application of the method to the reference station, using the rainfall stations within the watershed or basin boundary.
- Adjustment the daily flows of the reference station in the Gumbel distribution and estimate Qdmax of T = 2 years at T*, and calculate $R_{oj}(T)$.
- Adjustment of maximum daily rainfall in the Gumbel distribution and estimation of $P_{jmax}(T)$ for T = 2 à 100 ans.
- From the averages of Po and G of rainfall stations used, we estimate the maximum daily rainfall Pjmax (T) of the watershed from T = 2 to 100 years.
- Application of ARF at Pjmax (T) to achieve Pjmax (A, T):

  Curves "A, B, C" illustrating the Area Reduction Factor in the « Design of Small Dams » concern a frontal rain for which the main duration have a duration is 6 hours while its total duration can reach up to 12 hours or even 24 hours and more.

It is therefore appropriate, for each regional analysis associated with one or more sites, to choose wisely the valid ARF curve between the three possible. In the case of this study, curve B is the proposed one.

- Use of the rainfall Gradex (Average Gradex of the rainfall station utilized) from T = T* years for the estimation of $R_{oj}(T)$, Qdmax(T) from T = T* till 100 ans. The observed runoff is calculated using the following formula:

  $R_{oj}(T) = P_{jmax}(A, T) - \phi_s = P_{jmax}(A, T) - [R_{oj}(T^*) - P_{jmax}(A, T^*)]$

- Calculate $Q_p(T)$ by using C_p. Cp are issued from the statistical analysis of the couples Qp, Qdmax of significant floods.
- Calculations Qp (T) allow the estimation of the coefficients of Francou-Rodier Kp (T) at the gauging station.

With :

T	: Return Period (yerars);
T*	:Return Period from which the soil is considered saturated;
P_{jmax}	: Maximum annual punctual daily rainfall (mm/d) ;
ARF	: Areal Reduction Factor
$P_{jmax}(A, T)$	:Maximum Annual daily rainfall over a watershed (mm/d) ;
R_{oj}	: Maximum annual daily runoff (mm/d) ;
ϕ_s	: Infiltration rate for which the soil is saturated;
Qdmax	: Maximum annual daily flow (m³/s) ;
Q_p	: Maximum annual instantaneous flow (m³/s);
C_p	: Peak Coefficient;
K_p	: Coefficient of Francou- Rodier.

6.5.3 Transposition Towards Bisri Dam Site

6.5.3.1 Francou-Rodier Method

The Formula is:

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

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

With:

Q :	Flow (m^3/s) ;
A :	Bassin Area (km²) ;
K_p :	Francou-Rodier Coefficient.

6.5.3.2 *Specific Flows*

The method of Specific Flows allows within a comparable climate, morphology, lithology and Top soil between two watersheds the extrapolation of the flow of a known bassin to a non-gauged one using the following:

$$Q = Q_c \times \frac{A}{A_c}$$

With:

Q : Flow in ungauged Watershed (m^3/s);

A : Ungauged Watershed area (km^2);

Ac : Area of the known Watershed (km^2);

Qc : Flow in known Watershed (m^3/s).

This method requires that the surfaces of the watersheds involved in this transposition are of adjacent sizes.

6.5.4 Hydrograph and Flood Volumes

The Engineer has only one flood hydrograph, thus a comparative analysis of the results of the use of the dimensionless hydrograph and those theoretical, exponential, triangular and USSCS will be made to select the most appropriate representation of the zone flooding.

The peak time could be estimated from empirical formulas.

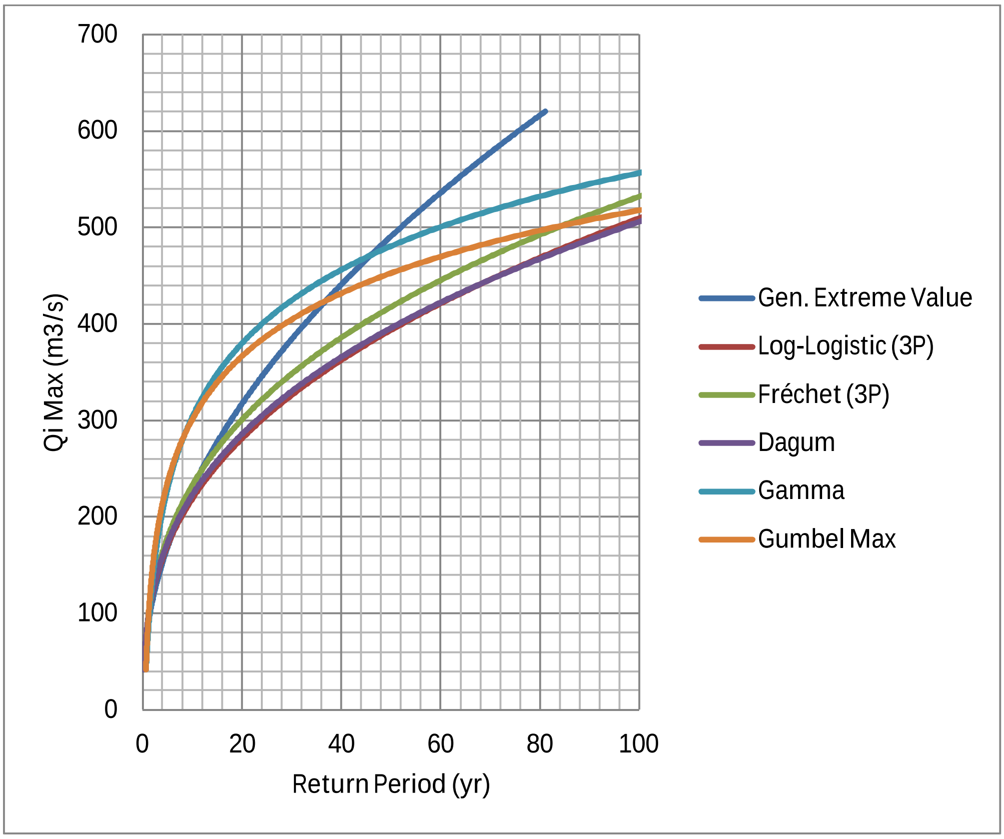
6.6 Methodology Application

The objective is to calculate the peak flows at the Marj Bisri station before transposing to the Bisri dam site.

6.6.1 Statistical Adjustment

Maximum Annual Daily Flows

The adjustment of maximum annual daily flows of Marj Bisri station using different laws is presented in the figure below:

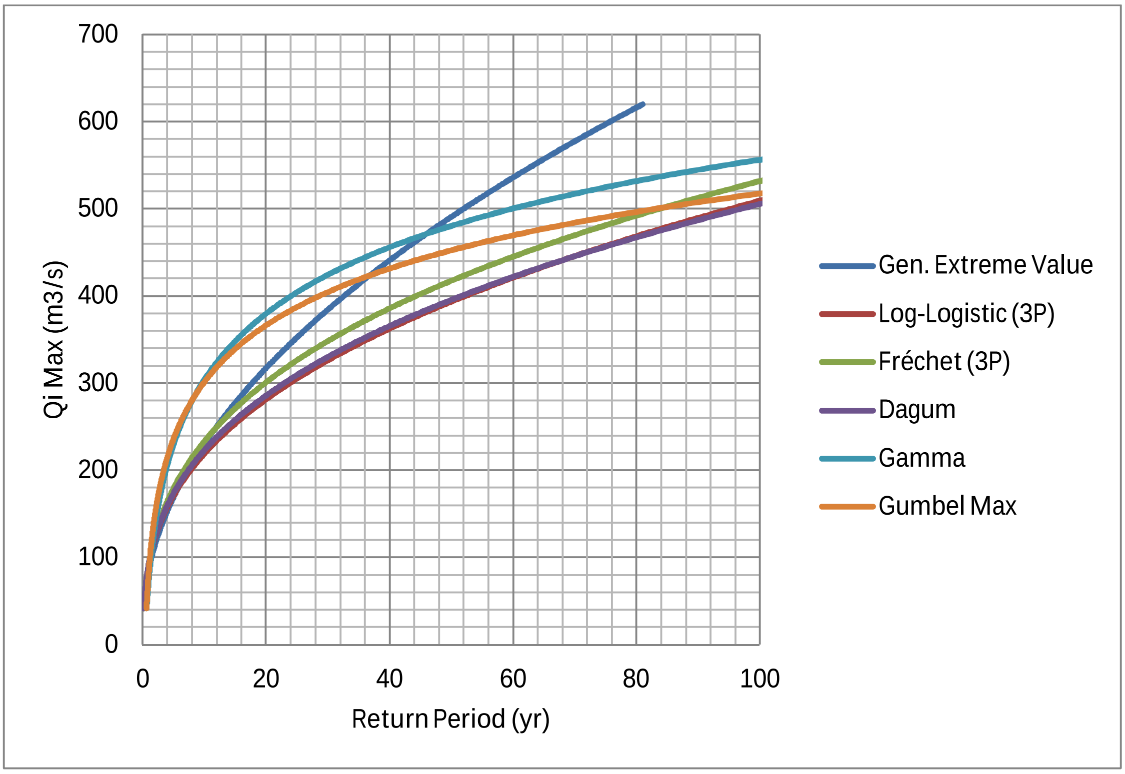


Maximum annual daily flows are summarized below:

Station		Marj Bisri
Qdmax (T)	**2**	72
	5	96
	10	116
	20	140
	50	176
	100	**190**

Maximum Annual Instantaneous Flows

The graph below represents the statistical adjustment using laws of the maximum annual instantaneous flows for the Marj Bisri station:



The following table summarizes the quantities:

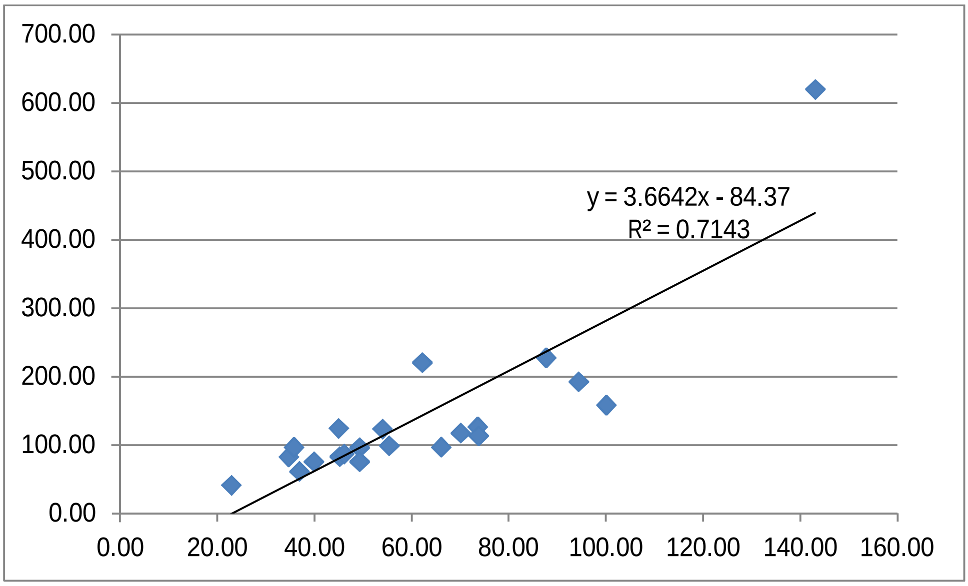
Station		Marj Bisri
Qp (T)	2	115
	5	200
	10	300
	20	370
	50	490
	100	**560**

6.6.2 Gradex Method

Estimation of Peak Coefficient Cp

The peak coefficient Cp is defined as the ratio of the maximum annual peak flow Qp and the maximum annual daily flow Qdmax. It reflects a relationship Qp-Qdmax which allows the calculation of Qp(T) from Qdmax(T).

Table 6.4 and graph below present the observed Cp at Marj Bisri station and illustrate the correlation Qp-Qdmax:



Examination of the table and graph shows that:

- The average value observed is 2.2;
- The average C_p after eliminating highly excessive values is 2 ;
- Average C_p for events of occurrence T ≥ 2 years is 2.4 ;
- The correlation yields to a coefficient of 2.5 ;
- The Engineer proposes the adoption of C_p = 2.5.

Gradex Results

The results of the application of the Gradex Method to Marj Bisri station are summarized in table 6.5.

6.6.3 Adopted Peak Flows at Marj Bisri Station

The adopted Peak flows are given in the table 6.6.

6.6.4 Peak Flows Transposition towards the Bisri Dam Site

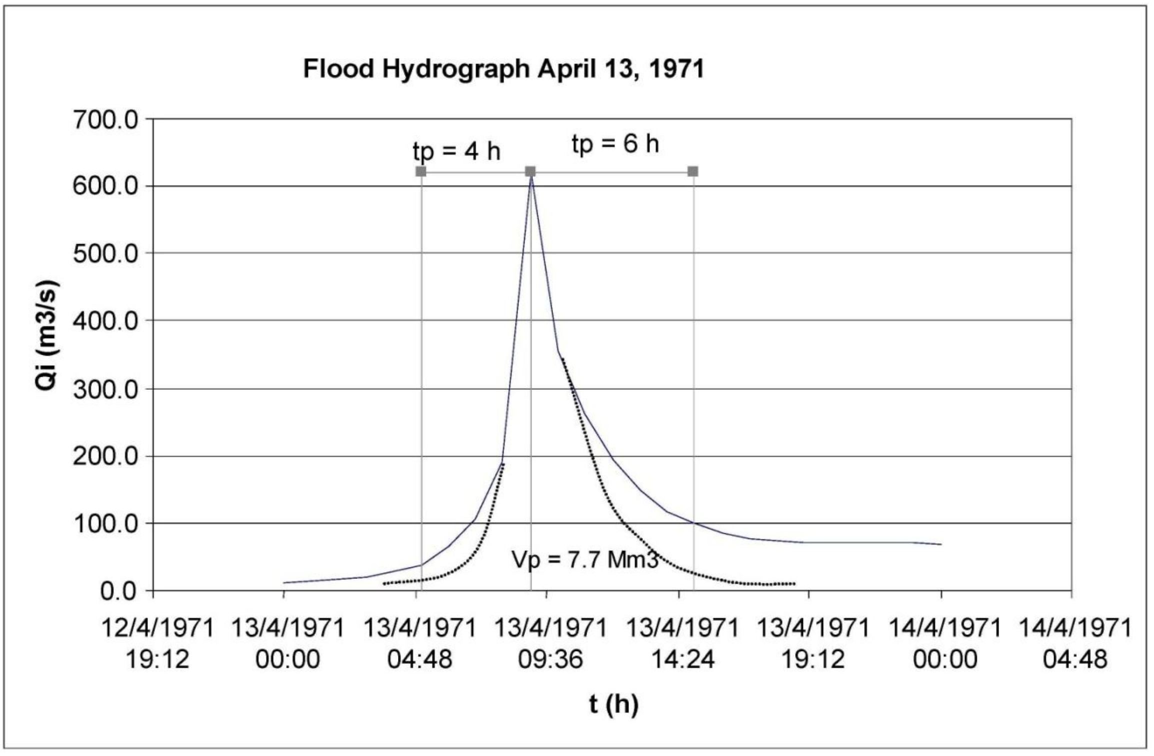
The transposition of peak flows adopted at Marj Bisri station to the Bisri dam site is given in table 6.7.

6.6.5 Flood Hydrographs

The only available flood hydrograph, flood of April 1971, was treated in order to identify the following characteristics:

- The rise or peak time tp is the time interval between the beginning of runoff and peak discharge;
- The base time of the flood tb which corresponds to the total duration of the flood;
- The peak flow Qp representing the maximum annual instantaneous flow reached during the same flood;
- The runoff volume Vp.

The Graph below summarizes the results of this conduct:



We note from the hydrograph of this major flood and the data collected during the field visit, that the area is actually characterized by torrential floods with important peak flows low volumes.

Moreover, the application of different empirical formulas to Marj Bisri station and Bisri site yields the results in table 6.8.

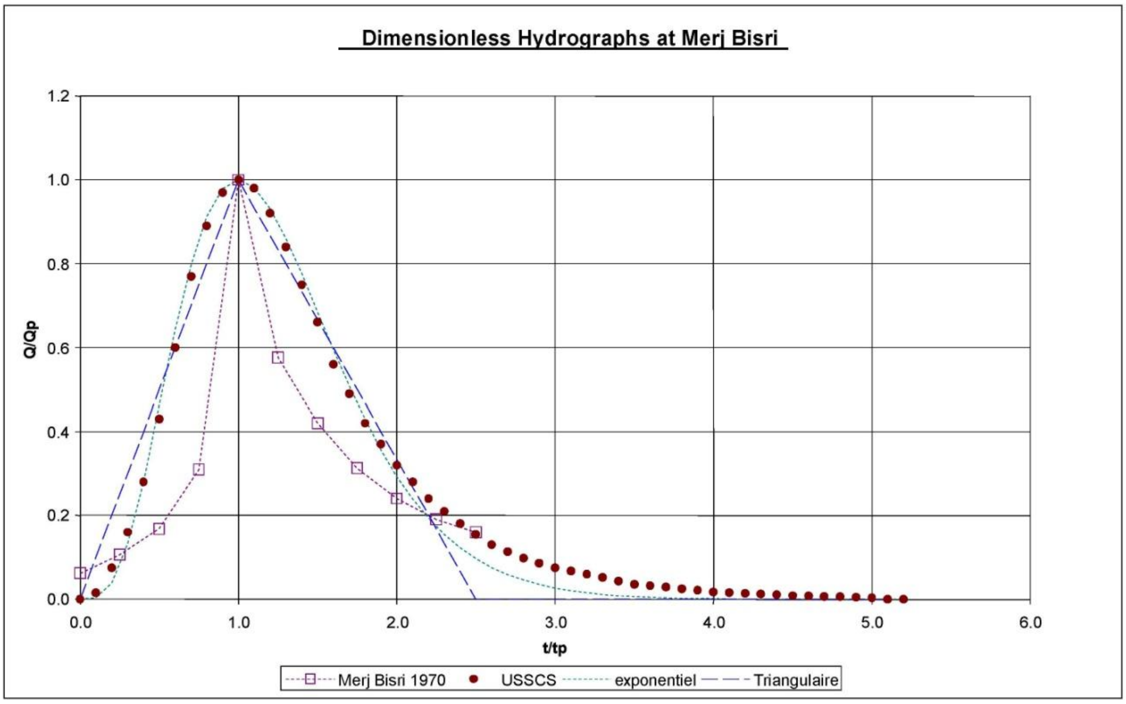
It should be noted that the values of tc calculated using the Giandotti method represent well the flooding type in the area.

To define the typical flood hydrograph of Marj Bisri station, we rendered dimensionless the only flood hydrograph by its rise time and peak flow.

The following figure presents the different rendered dimensionless hydrographs superimposed on three typical dimensionless hydrograph types:

- Triangular hydrograph (tb ≈ 3 tp) ;
- Exponential hydrograph ($Q/Qp = (t/tp)^4 \, e^{(4-4(t/tp))}$)

- USSCS hydrograph



Station	Vpobs (Mm3)	Vtriangular (Mm^3)	Vexp (Mm3)	VUSSCS (Mm3)	Vtriang/ Vflood	VExp/ Vflood	VUSSCS/ Vflood
Marj Bisri	7.7	11.2	11.4	12.1	1.5	1.5	1.6

Given the imprudence of relying on the analysis of a single flood hydrograph and on the other hand, the uncertainty regarding the measurement, processing and storage of data in the area, the Engineer opted for the exponential form to represent the design flood adopted in the previous paragraph.

The table 6.9 gives the adopted flood hydrograph at the Bisri dam site for return periods of 2 years to PMF.

The routing of the PMF will be conducted after determining the spillway characteristics in the final hydraulic calculations.

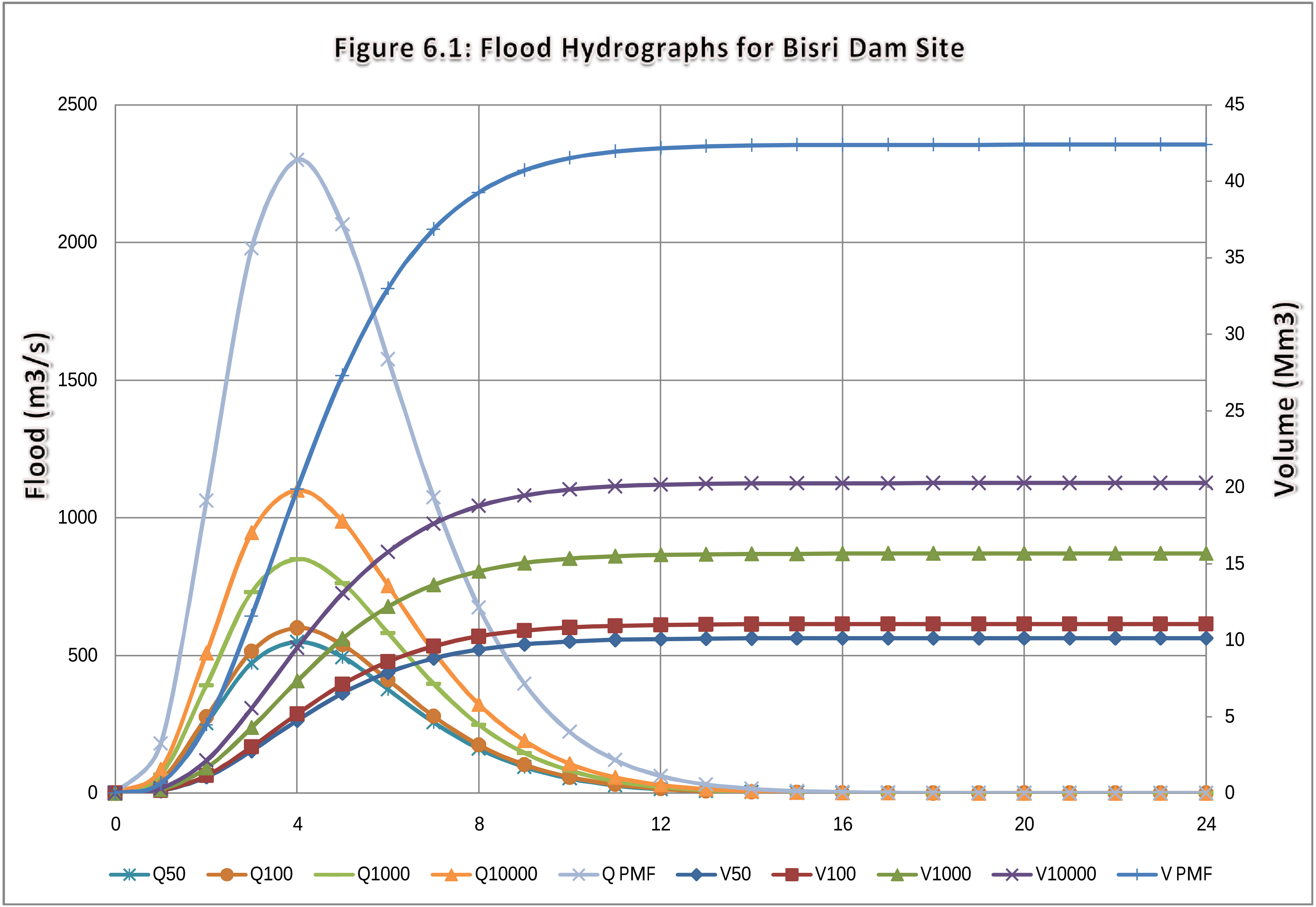


Figure 6.1: Flood Hydrographs for Bisri Dam Site
Flood (m3/s)
Volume (Mm3)
2500
2000
1500
1000
500
0
45
40
35
30
25
20
15
10
5
0
0
4
8
12
16
20
24
Q50
Q100
Q1000
Q10000
Q PMF
V50
V100
V1000
V10000
V PMF

Table 6-1 Maximum Daily and Instantaneous Flows

Water Year	Qp	Qdmax
1952	118.00	70.00
1953	127.00	73.50
1954	83.30	34.60
1955	124.00	53.90
1956	97.60	66.00
1957	96.70	49.20
1958	62.10	36.80
1959	41.90	22.80
1960	99.60	55.30
1961	114.00	73.70
1962	83.70	45.10
1963	76.20	39.80
1964	125.00	44.90
1965	97.40	35.70
1966	221.00	62.10
1967	159.00	100.00
1968	228.00	87.60
1969	193.00	94.30
1970	620.00	143.00
1971	87.50	46.00
1972	76.20	49.20
2001		28.40
2002		106.30
2003		47.10
2004		50.30
2005		14.30
2006		14.20
2007		11.00
2008		13.90
2009		45.20
2010		23.15
2011		38.20
2012		65.90
n	21.00	33.00
AVERAGE	139.58	52.77
MEDIAN	99.60	47.10
MINIMUM	41.90	11.00
MAXIMUM	620.00	143.00
STD. DEV.	120.37	29.54
Cv	1.16	1.79

Table 6-2 Maximum Annual Daily Rainfall Recorded

Water Year	Ain Zhalta 1080 m	Kfar Nabrakh 1020 m	Jdeit Ech Chouf 770 m	Jezzine – 945m	Jezzine – 1070m	Barouk - Fraidis	Deir El Kamar	Jbaa El Chouf
1928				131.00				
1929				74.00				
1930				106.00				
1931				105.00				
1932				51.00				
1933				92.00				
1934				119.00				
1935				106.00				
1936				175.00				
1937								
1938								
1939	93.00			85.00				
1940	80.00			80.00				
1941	52.00			91.00				
1942	74.00		62.00	100.00				
1943	101.00		90.00	104.00				
1944	96.00	102.00	101.00	90.00				
1945	62.00	104.00	87.00	95.00				
1946	111.00	105.00	127.00	94.00				
1947	90.00	102.00	127.00	97.00				
1948	91.00	78.00	59.00	102.00				
1949	66.00	72.00	79.00					
1950	57.00	89.00	86.00	79.00				
1951	70.00	78.00	92.00	96.50				
1952	100.00	114.00	84.00	100.00				
1953	50.80	81.50	80.00	63.00				
1954	42.00	54.00	49.00	42.00				
1955	118.00	137.00	112.00	78.00				
1956	80.40	94.50	99.00	84.00				
1957	62.00	71.50	79.00	81.60				
1958		100.00	105.00					
1959	54.50	63.00	48.00					
1960	80.80	75.00	85.00	72.00				
1961	108.70	91.50	93.00	81.00				
1962	96.00	110.00	123.00	60.00				
1963	65.00	57.00	83.00	72.00				
1964	60.00	123.00	105.00	96.00				
1965	89.00	129.00	88.00	91.00				
1966	86.00	57.00	87.00	87.00				
1967	69.00	116.00	94.00	90.00				
1968	96.00	121.00	99.00	92.00				
1969	84.00	63.00	83.10	91.50				
1970	64.00	60.00	94.70	81.00				
1971								
1972								
1973								
1974								
1975								
1976								
1977				96.00				
1978								

Water Year	Ain Zhalta 1080 m	Kfar Nabrakh 1020 m	Jdeit Ech Chouf 770 m	Jezzine – 945m	Jezzine – 1070m	Barouk - Fraidis	Deir El Kamar	Jbaa El Chouf
1979								
1980								
1981								
1982								
1983								
1984								
1985								
1986								
1987								
1988								
1989								
1990								
1991								
1992								
1993								
1994								
1995								
1996								
1997								
1998							62.70	
1999							51.50	
2000						123.60		53.00
2001						137.90		101.00
2002						75.00	93.10	65.00
2003					109.20	154.60		94.50
2004					100.80		76.60	77.50
2005					66.70	69.50	84.90	73.00
2006					94.00	89.90	82.20	67.00
2007					132.20		70.80	77.00
2008					107.90		93.90	128.00
2009					74.40			77.00
n	31.00	27.00	29.00	39.00	7.00	6.00	8.00	10.00
AVERAGE	79.01	90.67	89.68	90.53	97.89	108.42	76.96	81.30
MEDIAN	80.40	91.50	88.00	91.00	100.80	106.75	79.40	77.00
MINIMUM	42.00	54.00	48.00	42.00	66.70	69.50	51.50	53.00
MAXIMUM	118.00	137.00	127.00	175.00	132.20	154.60	93.90	128.00
STD. DEV.	19.64	24.29	19.66	21.92	22.19	35.23	14.77	21.43
Cv	4.02	3.73	4.56	4.13	4.41	3.08	5.21	3.79

Table 6-3 Bisri Gage Flood, April 13, 1971

t	Qp
0.0	12.0
1.0	13.8
2.0	17.0
3.0	19.8
4.0	28.0
5.0	38.3
6.0	66.0
7.0	104.3
8.0	192.0
9.0	**620.0**
10.0	357.0
11.0	260.5
12.0	194.0
13.0	149.0
14.0	118.0
15.0	99.0
16.0	86.0
17.0	78.0
18.0	74.0
19.0	72.0
20.0	71.0
21.0	70.0
22.0	70.5
23.0	70.0
24.0	68.0

Table 6-4 Observed Cp and Correlation Qp-Qdmax at Marj Bisri

Water Year	Qdmax	Qp	Cp	Rank	F	T	Cp	Cp (T>2years)
1959	22.80	41.90	1.84	1.00	0.02	1.00	1.80	
1958	36.80	62.10	1.69	2.00	0.07	1.10	1.70	
1963	39.80	76.20	1.91	3.00	0.12	1.10	1.90	
1972	49.20	76.20	1.55	4.00	0.17	1.20	1.50	
1954	34.60	83.30	2.41	5.00	0.21	1.30	2.40	
1962	45.10	83.70	1.86	6.00	0.26	1.40	1.90	
1971	46.00	87.50	1.90	7.00	0.31	1.40	1.90	
1957	49.20	96.70	1.97	8.00	0.36	1.60	2.00	
1965	35.70	97.40	2.73	9.00	0.40	1.70	2.70	
1956	66.00	97.60	1.48	10.00	0.45	1.80	1.50	
1960	55.30	99.60	1.80	11.00	0.50	2.00	1.80	
1961	73.70	114.00	1.55	12.00	0.55	2.20	1.50	1.55
1952	70.00	118.00	1.69	13.00	0.60	2.50	1.70	1.69
1955	53.90	124.00	2.30	14.00	0.64	2.80	2.30	2.30
1964	44.90	125.00	2.78	15.00	0.69	3.20	2.80	2.78
1953	73.50	127.00	1.73	16.00	0.74	3.80	1.70	1.73
1967	100.00	159.00	1.59	17.00	0.79	4.70	1.60	1.59
1969	94.30	193.00	2.05	18.00	0.83	6.00	2.00	2.05
1966	62.10	221.00	3.56	19.00	0.88	8.40		3.56
1968	87.60	228.00	2.60	20.00	0.93	14.00	2.60	2.60
1970	143.00	620.00	4.34	21.00	0.98	42.00		4.34
2001	28.40							
2002	360.30							
2003	47.10							
2004	50.30							
2005	14.30							
2006	14.20							
2007	13.90							
2011	60.90							
2012	87.60							
2013	106.30							
n	31.00	21.00	21.00	21.00	21.00	21.00	19.00	10.00
AVERAGE	66.67	139.58	2.16	11.00	0.50	5.01	1.96	2.42
MEDIAN	50.30	99.60	1.90	11.00	0.50	2.00	1.90	2.18
MINIMUM	13.90	41.90	1.48	1.00	0.02	1.00	1.50	1.55
MAXIMUM	360.30	620.00	4.34	21.00	0.98	42.00	2.80	4.34
STD. DEV.	61.84	120.37	0.72	6.20	0.30	9.02	0.41	0.93
Cv	1.08	1.16	3.00	1.77	1.69	0.56	4.81	2.61

Table 6-5 Results of the Guda Method

Station	N	Po	G	A	S	Km	PMP
Ain Zhalta	31	70.17	15.31	79.01	19.64	16.50	403.08
Kfar Nabrakh	27	79.74	18.94	90.67	24.29	15.80	474.40
Jdeidet Ech Chouf	29	80.84	15.33	89.68	19.66	15.80	400.27
Jezzine – 945m	39	80.66	17.09	90.53	21.92	15.50	430.26
Jezzine – 1070m	7	87.90	17.30	97.89	22.19	15.40	439.56
Barouk - Fraidis	6	92.56	27.47	108.42	35.23	15.00	636.91
Deir El Kamar	8	70.31	11.52	76.96	14.77	16.30	317.76
Jbaa El Chouf	10	71.65	16.71	81.30	21.43	16.10	426.38
M		79.23	17.46	89.31	22.39	15.80	441.08

T*	20	
Pjmax(T*)	131.1	
Pjmax(A,T*)	119.3	
Qdmax(T*)	181.1	
Roj(T*)	70.5	
Φs	48.8	Infiltration rate for which the soil is saturated
ARF	0.9	
Cp	2.5	

T	u	Pjmax(T)	Pjmax(A,T)	Roj(T)	Qdmax(T)	Qp(T)	Kp(T)	CN(T)
2	0.37	85.63	77.92	29.10	54.11	135	3.00	78.00
5	1.50	105.42	95.93	47.11	111.17	278	3.60	80.00
10	2.25	118.52	107.85	59.03	148.95	372	3.90	81.00
20	2.97	131.08	119.29	70.47	185.19	463	4.10	82.00
50	3.90	147.35	134.09	85.27	219.10	548	4.20	82.00
100	4.60	159.54	145.18	96.36	247.60	619	4.30	83.00
200	5.30	171.68	156.23	107.41	276.00	690	4.40	83.00
500	6.21	187.71	170.81	122.00	313.46	784	4.50	83.00
1000	6.91	199.82	181.83	133.02	341.78	854	4.60	84.00
2000	7.60	211.92	192.85	144.03	370.08	925	4.60	84.00
5000	8.52	227.92	207.41	158.59	407.49	1019	4.70	84.00
10000	9.21	240.02	218.42	169.60	435.79	1089	4.80	84.00
CMP		441.08	401.38	352.56	905.89	2265	5.50	84.00

Table 6-6 Adopted Peak Flows at Marj Bisri Station

T	Stat Adjustment	Gradex	Adopted
2	115	135	100
5	200	278	250
10	300	372	350
20	370	463	500
50	490	548	550
100	560	619	650
200		690	700
500		784	800
1000		854	900
2000		925	950
5000		1019	1050
10000		1089	1100
CMP		2265	2300

Table 6-7 Transportation of Peak Flows to Bisri Dam Site

Site	**Bisri**	
S (km²)	**215**	
Ref. Station:	**Marj Bisri**	
T	**Qp calculated**	**Qp adopted**
2	131	100
5	269	220
10	361	350
20	448	450
50	530	550
100	**599**	**600**
200	668	700
500	759	800
1000	828	850
2000	896	950
5000	987	1000
10000	**1055**	**1100**
CMP	**2193**	**2300**

Table 6-8 Concentration Time using different methods (hours)

tc	Turraza	Haspers-Java	Ventura	Giandotti	Passini	Kirpich
Marj Bisri	10.6	4.4	9.5	3.7	10.6	3.3
Bisri Dam	10.2	4.2	9.2	3.7	10.2	3.1

Table 6-9 Adopted Flood Hydrograph

t(h)	Q2	Q5	Q10	Q20	Q50	Q100	Q200	Q500	Q1000	Q2000	Q5000	Q10000	CMP
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	8	17	27	35	43	47	55	63	67	75	78	86	180
2	46	102	162	208	254	277	323	369	393	439	462	508	1062
3	86	189	301	387	473	516	602	688	731	817	860	946	1978
4	100	220	350	450	550	600	700	800	850	950	1000	1100	2300
5	90	198	314	404	494	539	629	719	763	853	898	988	2066
6	69	151	240	308	377	411	480	548	582	651	685	754	1576
7	47	103	163	210	257	280	327	374	397	444	467	514	1074
8	29	64	103	132	161	176	205	234	249	278	293	322	674
9	17	38	60	78	95	104	121	138	147	164	173	190	397
10	10	21	34	44	53	58	68	77	82	92	97	107	223
11	5	11	18	23	29	31	37	42	44	50	52	57	120
12	3	6	10	12	15	16	19	22	23	26	27	30	62
13	1	3	5	6	8	8	10	11	12	13	14	15	32
14	1	1	2	3	4	4	5	5	6	6	7	7	16
15	0	1	1	1	2	2	2	3	3	3	3	4	8
16	0	0	1	1	1	1	1	1	1	1	2	2	4
17	0	0	0	0	0	0	1	1	1	1	1	1	2
18	0	0	0	0	0	0	0	0	0	0	0	0	1
19	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0

CHAPTER 7 SEDIMENTATION

In an effort to predict the head volume of Bisri reservoir, this present chapter aims to provide an estimate of average inter-annual sediment yield at the Bisri dam site. This estimate will have an important role in the economic evaluation of the project and in the determination of its life.

Due to the unavailability of data for measured bathymetry of the Qaraoun Dam and sediment transport measures, the Engineer used studies conducted in this region and pertaining to this aspect (the study of Beydoun (Beydoun, 1976) and sediment measures carried by the U.S. Bureau of Reclamation in 1953 (USBR, 1953).

The value of specific degradation reported in previous studies is 1000 t / km / year. The calculation from this value gives the results reported in the table below:

Site	S	L	DS	DSL	DSV	Rhythm Sediment.	Sediment 20 yrs	Sediment 30 yrs	Sediment 50 yrs
	km²	mm	$t/km^2/yr$	g/l	$m^3/km^2/yr$	m^3/yr	Mm^3	Mm^3	Mm^3
Bisri	215	673	1000	1.5	667	143333	3	4	7

with:

DS : Specific Degradation ($t/km^2/yr$);

DSL Ratio of specific degradation over the water height, (concentration (g/ l) ;

DSV : Specific Volume Degradation ($m^3/km^2/yr$).

The burden of 1.5 g / l of sediment transport seems low. However, in absence of other elements, the Engineer recommends an increase of 20% for the remainder of the study while remaining reassured because during the field visit the river water is not turbid.

Site	Sedimentation 20 years Mm^3	Sedimentation 30 years Mm^3	Sedimentation 50 years Mm^3
Bisri	3	5	9

CHAPTER 8 WATER SUPPLY YIELD

8.1 Introduction

This chapter presents the update of the estimation of the capacity-yield relationship for Bisri Reservoir based on the new available hydrological data. The question "How large does the reservoir capacity need to be to provide for a given controlled release with an acceptable level of reliability" needs to be answered. This section is divided into six main parts: (1) Definition of Terms; (2) Methodology; (3) Shortage Criteria; (4) System Characteristics; (5) Reservoir Capacity-Yield Analyses; and (6) Conclusions based on the analyses.

8.2 Definition of Terms

- *Active Storage*: The active storage of a reservoir is the water stored above the level of the lowest offtake. It is equal to the total volume of stored water less the volume of "dead" storage (the volume below the level of the offtake).
- *Carryover Storage:* The volume of active storage in Bisri Reservoir at the beginning of the wet season.
- *Critical Period:* The period during which a reservoir goes from full condition to an empty condition without spilling in the intervening period. The start of a critical period is a full reservoir; the end of the critical period is when the active storage is zero.
- *Demand:* Demand is the water supply required by a water user.
- *Normal Water Surface Elevation:* The maximum reservoir operating level during normal operating conditions.
- *Operating Rule:* Usually the volume of water released from a reservoir is equal to the volume of water required by the consumers. However, there may be periods when either the reservoir level is so low that the water required cannot be supplied, or when prudence dictates that only part of the water demanded should be released from storage. The way in which releases are controlled is called the operating rule or rule curve.
- *Release:* Release is the volume of controlled water released from a reservoir during a given time interval.
- *Storage:* The storage of a reservoir is total storage which includes dead and active storages.
- *Volumetric Shortage:* The percentage of the volume of water which is required for release to Beirut but cannot be supplied due to lack of water available in the reservoir over the study period.

8.3 BASIC DATA AND ASSUMPTIONS

8.3.1 General

The Bisri Dam Project is intended to store water for municipal and industrial uses within Beirut surrounding areas. The source of water supply for the project is the Bisri River. The headwaters for the Bisri River are located in the Jabal el Barouk Mountains. Both rainfall and snowmelt contribute to the streamflow in the basin. The water supply for the Bisri Project was determined by analyzing streamflow records.

Data required for the operation studies included reservoir evaporation rates, monthly inflow, monthly water demands, installed power capacity, turbine efficiency data, tailwater elevation, and reservoir volume and surface area versus elevation data.

Seepage loss was considered equal to 0.5% of the reservoir volume in determining yield of the Bisri Reservoir, as the geotechnical design of Bisri Dam. Transmission loss between the reservoir and the user was also considered insignificant in the reservoir operation study.

8.3.2 Monthly Inflow

The reservoir operation studies are based on monthly project streamflows at Bisri Dam for 61 years, including 36 years of actual record and 25 years of extended data. The 61 years of project monthly streamflow for the Bisri Dam is developed in Chapter 5.

8.3.3 Monthly Water Demands

Based on the Master Plan of the Awali Water Project, The estimated total demand of the areas supplied from the Bisri system is equal to 5.8 m3/s. This flow covers the following areas:

- Zone A (area situated to the East of Beirut City, extending from Wadi Chahrour Village in the south to Hazmieh Village to the North and ranging in elevation from 40m and rising to approximately 400m above sea level. The main villages included in the project are: Haret El Fghaliye, Haret Es Sitt, Wadi Chahrour, Merdash, Boutchai, Louaize, Baabda, Hadath, Hazmieh, Chiah, Furn El Chebbek): 3.3 m^3/s
- Zone B (The works cover an area situated to the East of Beirut City, extending from Wadi Chahrour Village in the south to Hazmieh Village to the North and ranging in elevation from 40m and rising to approximately 400m above sea level. The main villages included in the project are: Haret El Fghaliye, Haret Es Sitt, Wadi Chahrour, Merdash, Boutchai, Louaize, Baabda, Hadath, Hazmieh, Chiah, Furn El Chebbek): 0.6 m^3/s
- Zone C (coastal area situated to the south of Beirut City, extending from Damour Village in the south to Kfarshima Village to the North and ranging in elevation from sea level and rising to approximately 250m. above sea level. The main villages included in the project are: Damour, Naameh, Choueifet (including Aaramoun and Khaldeh) and Kfarshima): 0.8 m^3/s
- Zone D (The works cover an area situated to the East of Beirut City, extending from Jisr El Basha Village in the south (North of Hazmieh) to Jdeideh Village in the North and ranging in elevation from 50m and rising to approximately 300m above sea level. The main villages included in the project are: Mkalles, Jisr el Bacha, Mar Roukoz, Cap Sur Ville, Sabtiyeh, El-Aamariyeh, Fanar): 1.1 m^3/s

It should be noted that Zone D is divided into two subzones Upper and Lower with respective demands of 0.4 m3/s and 0.7 m3/s. The lower zone will be connected to the Awali system as a back-up source and not as a primary source.

Based on the above, the following basic monthly water demand scenarios were evaluated in the water supply yield analyses:

- 6-month delivery period between June and November at constant releases of 5.1 m^3/s. No release in other months.
- 6-month delivery period between June and November at constant releases of 5.8 m^3/s. No release in other months.

8.3.4 Reservoir Evaporation

Evaporation data from Station Kfar Nabrakh were assumed to represent evaporation from the Bisri Reservoir since this station is the closest evaporation station to the Bisri Reservoir.

The mean monthly measured evaporation rates at Kfar-Nabrakh Station were multiplied by a factor of 0.8 to represent monthly evaporation from the Bisri reservoir surface. Generally, it is the net evaporation from the reservoir surface which is used for the purpose of reservoir operation studies. Net evaporation from Bisri Reservoir was determined by subtracting the mean monthly precipitation at Jdeidet-ech-Chouf, Station No. 516, which is the closest to the Bisri Reservoir, from the monthly evaporation which was determined as described above. The net monthly evaporation values are shown as follows:

Net Reservoir Evaporation in Millimeters											
Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
52	9	-93	-211	-278	-237	-173	-44	18	67	67	70

8.3.5 Reservoir Area, Storage Capacity and Sediment

The area-storage capacity curves for Bisri Reservoir were prepared from a topographic map at a scale of 1:2,000 with a contour interval of 1 meter. For the purposes of reservoir operation studies, the 50-year sediment deposition of 9 Mm3 was used to modify the area-capacity curves and to take the minimum reservoir elevation of 420 m into consideration.

8.4 Methodology

Three series of simulations were performed for the Bisri Reservoir:

- Simulation or Behavior Analyses using the series of 30 years of data (1952 to 1981) referred to as “Old Data”.
- Simulation or Behavior Analyses using the series of 22 years of data (1991 to 2012) referred to as “New Data”.
- Simulation or Behavior Analyses using the series of 61 years of data (1952 to 2012) referred to as “All Data”.

The simulation analysis method requires an unbroken sequence of streamflow data and an assumed starting condition for the storage; the result is often sensitive to both the initial reservoir storage value chosen and the particular period of streamflow data available. The method is flexible and includes such factors as evaporation, seasonal demand, and reservoir restrictions in the computations.

In a simulation analysis, the changes in storage volume of a finite reservoir are calculated using a mass storage equation balancing inflow and outflow from the system. Two assumptions were made: the reservoir is initially full; and the historical data sequence is representative of future river flows.

The three series of simulation analyses were performed for reservoirs with total storage volumes of 125 Mm^3 for a 6 month constant demand of 5.1 or 5.8 m^3/sec in addition to a constant release rate of 0.45 m^3/s during the dry months and 0.3 m^3/s during the wet months into the river for environmental purposes. The active storage used for these analyses included 50 years of reservoir sedimentation. The analyses were performed for the monthly records at the Bisri damsite which included reservoir evaporation losses.

8.5 Shortage Criteria

Water stored in Bisri Reservoir will be used for municipal and industrial purposes for the City of Beirut. If any excess water is available in the early years of the project, the excess amount could probably be used for irrigation. Water shortage is calculated (as a percentage) by dividing the total water shortage (in Mm^3) by total demand for water during the study period. No criteria were established for determining yield for an irrigation purpose since it is not known how much water will be needed for municipal and industrial uses.

8.6 Reservoir Capacity-Yield Analysis

The following section discusses the results of the yield-capacity analyses performed for the Bisri Reservoir. The results are presented in graphical form showing the shortage versus Potable Water Demand of 5.1 m^3/s and 5.8 m^3/s.

8.6.1 Simulation Analyses

Simulation analyses for the 30-year monthly streamflow data (1952 to 1981), for the 22-year monthly streamflow data (1991 to 2012) and for the 61-year monthly streamflow data (1952 to 2012) were performed for a reservoir with a storage volume of 125 Mm^3 for a 6-month constant demand of 5.1 or 5.8 m^3/sec. The results are as follows:

- Figure 8.3 shows the water management results for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as "Old Data" and a potable water demand of 5.1 m^3/s.
- Figure 8.4 shows the water management results for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as "Old Data" and a potable water demand of 5.8 m^3/s.
- Figure 8.5 shows the water management results for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as "New Data" and a potable water demand of 5.1 m^3/s.
- Figure 8.6 shows the water management results for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as "New Data" and a potable water demand of 5.8 m^3/s.
- Figure 8.7 shows the water management results for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as "All Data" and a potable water demand of 5.1 m^3/s.
- Figure 8.8 shows the water management results for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as "All Data" and a potable water demand of 5.1 m^3/s.
- Figure 8.9 shows the water management results presented in graphical form showing the average shortage versus Potable Water Demand of 5.1 m3/s and 5.8 m^3/s.
- Figure 8.10 shows the water management results presented in graphical form showing the zero shortage versus Potable Water Demand of 5.1 m3/s and 5.8 m^3/s.
- Table 8.2 shows a summary of all the simulations results.

8.6.2 Future Operation

In order to estimate the average drop in potable water distribution during dry years, two figures should be observed and analyzed:

- The net volume of the reservoir at the end of the month of May
- The average river flow during the month of May

The examination of the 61 years of available data of the river flow shows that, on average, the total flow in the river during the dry season months extending from the beginning of June till the end of November is equal to about 170% of the flow during the month of May.

The total outflow from the dam during the dry season (Potable Water Demand + Environmental Release in the River) is equal to 104 Mm^3.

In order to insure a permanent potable water distribution of 6 m^3/s during the dry months, the summation of the net volume of the reservoir at the end of the month of May and 170% of the Average river flow during the month of May should exceed 104 Mm^3. Otherwise, the available volume should be distributed equally during the six months taking into consideration the environmental release in the River.

8.7 Power and Energy Capacity Analysis

The following section discusses the results of the power capacity analyses performed for the two proposed hydro-power plants:

- Upstream power plant : Nominal Flow = 0.45 m^3/s
- Downstream Power plant: Nominal Flow = 6 m^3/s

The results are as follows:

- Figure 8.11 shows the Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as “Old Data” and a potable water demand of 5.1 m^3/s.
- Figure 8.12 shows the Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as “Old Data” and a potable water demand of 5.8 m^3/s.
- Figure 8.13 shows the Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as “New Data” and a potable water demand of 5.1 m^3/s.
- Figure 8.14 shows the Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as “New Data” and a potable water demand of 5.8 m^3/s.
- Figure 8.15 shows the Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as “All Data” and a potable water demand of 5.1 m^3/s.
- Figure 8.16 shows the Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as “All Data” and a potable water demand of 5.1 m^3/s.
- Table 8.3 shows a summary of all the simulations results.

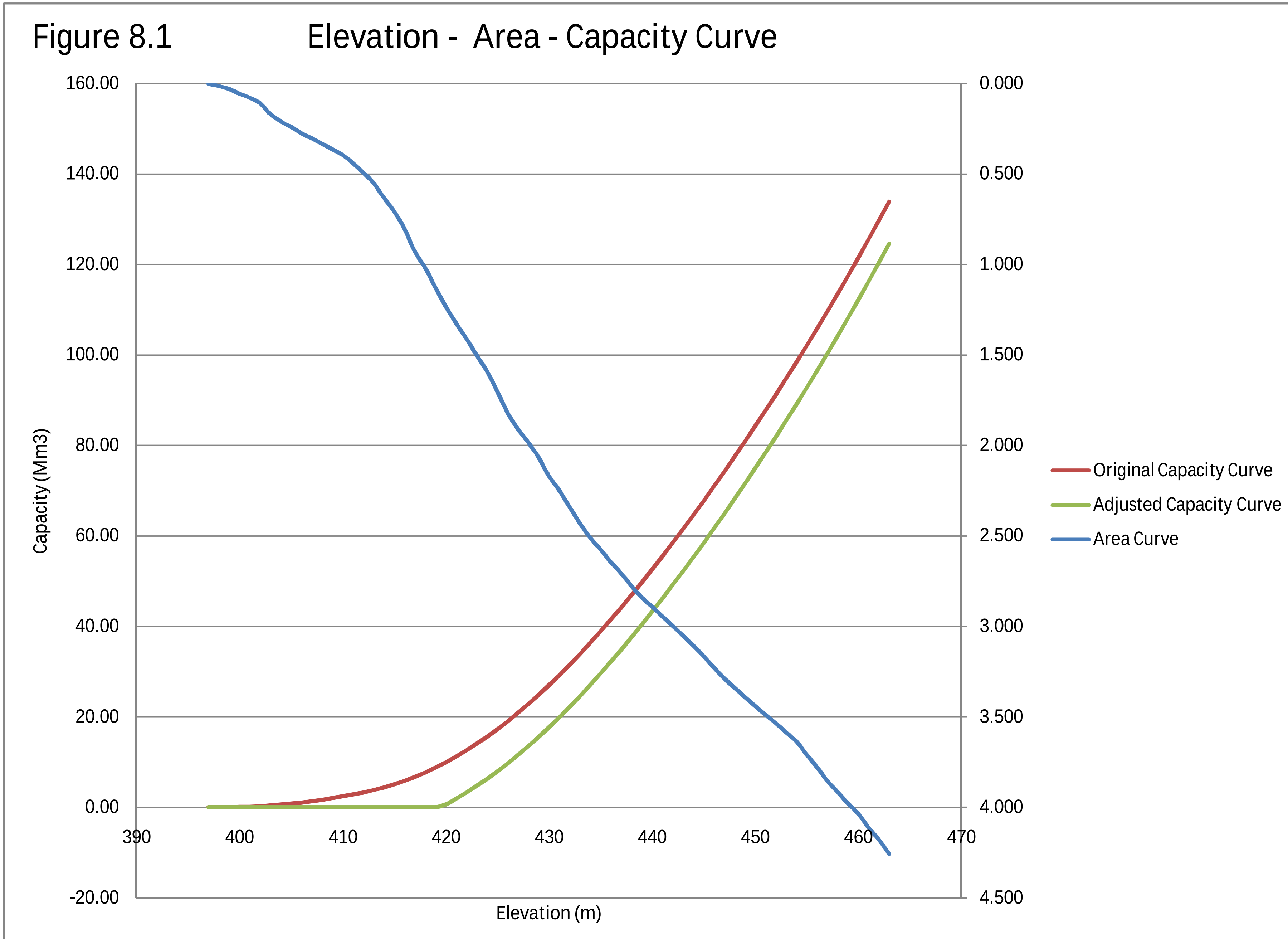


Figure 8.1
Elevation - Area - Capacity Curve
Capacity (Mm3)
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
390
400
410
420
430
440
450
460
470
Elevation (m)
Original Capacity Curve
Adjusted Capacity Curve
Area Curve

Figure 8.2: Monthly Reservoir Evaporation

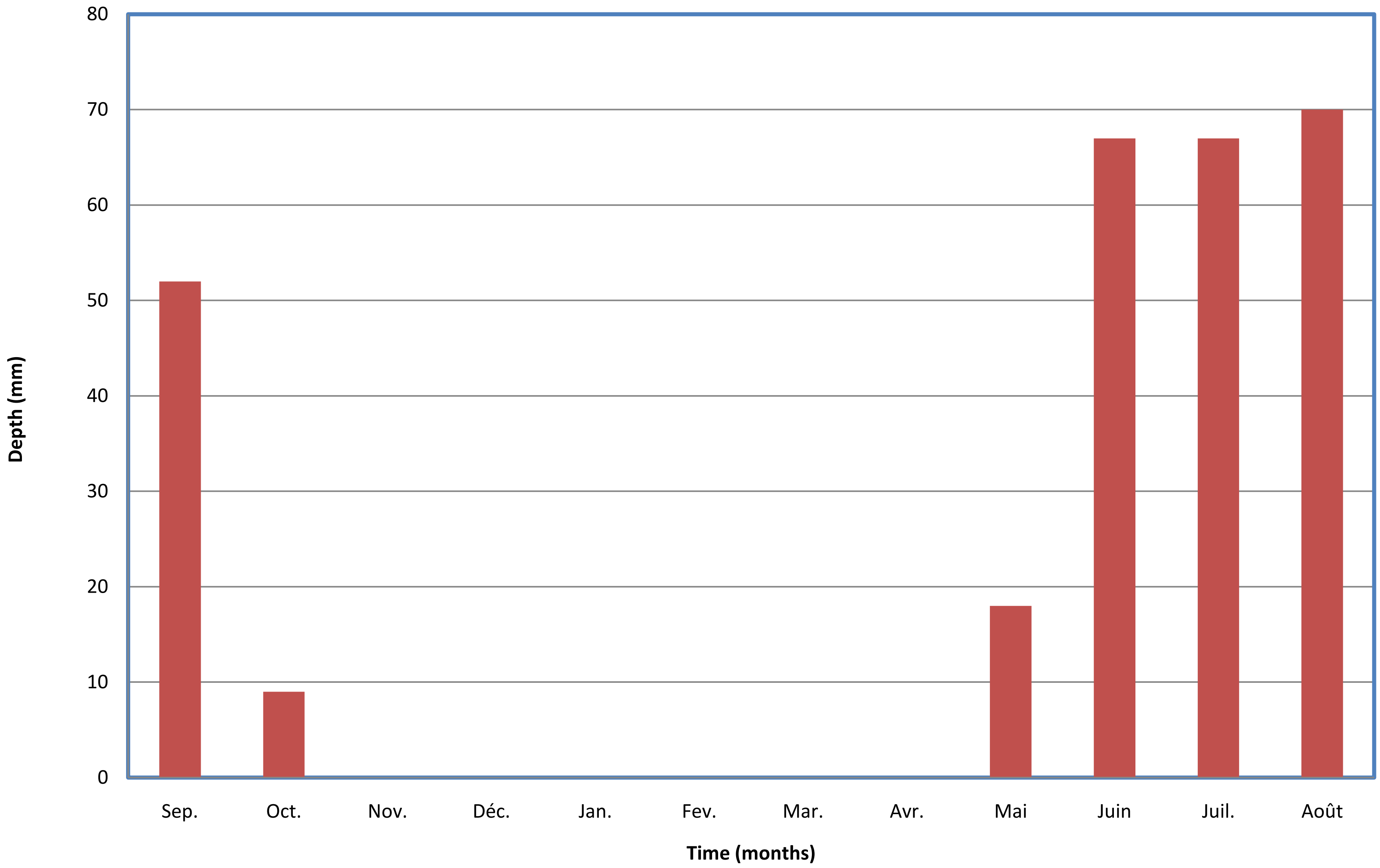


Figure 8.3 Water Management Results for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as "Old Data" and a potable water demand of 5.1 m³/s

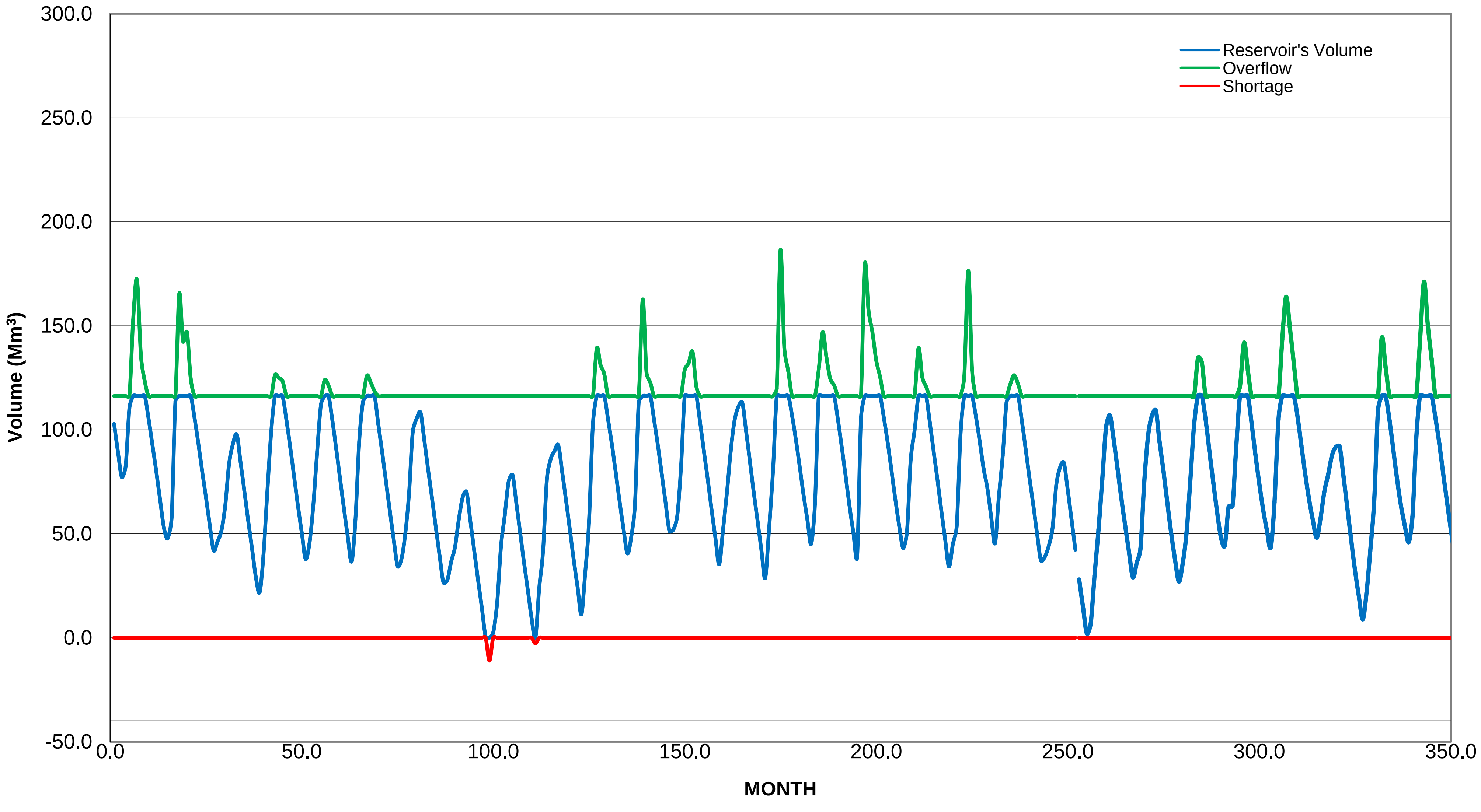


Figure 8.4 Water Management Results for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as "Old Data" and a potable water demand of 5.8 m3/s

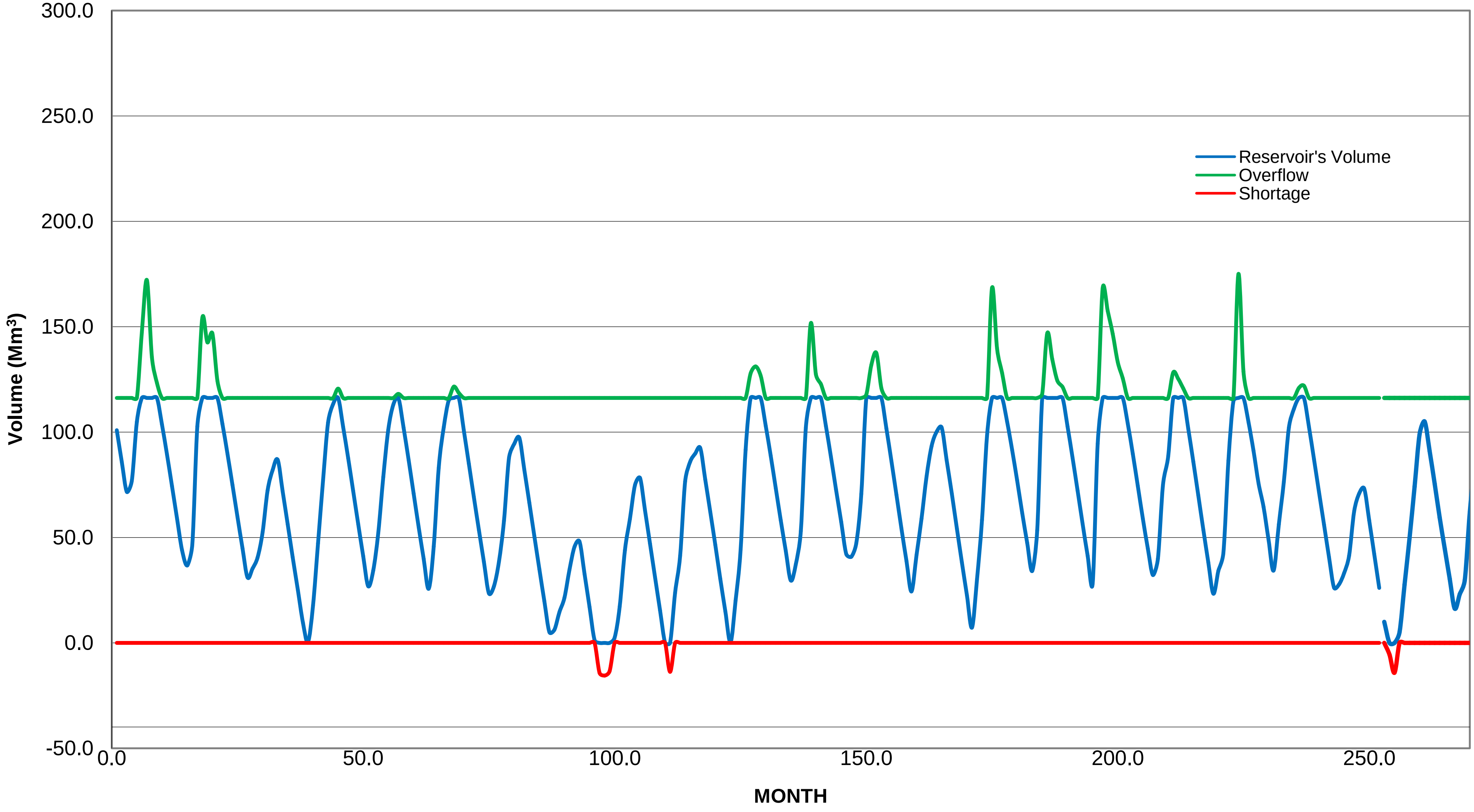


Figure 8.5 Water Management Results for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as “New Data” and a potable water demand of 5.1 m3/s

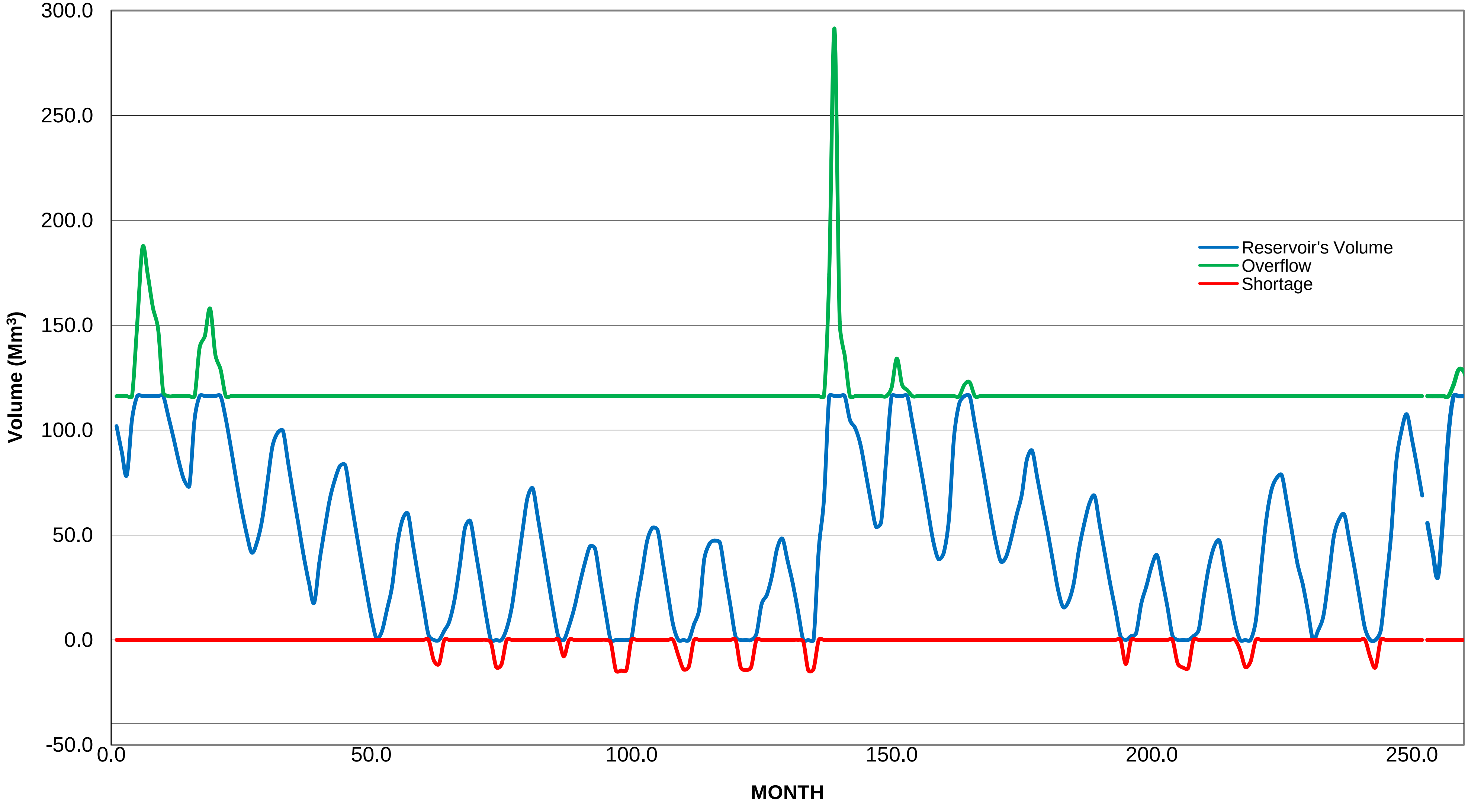


Figure 8.6 Water Management Results for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as “New Data” and a potable water demand of 5.8 m3/s

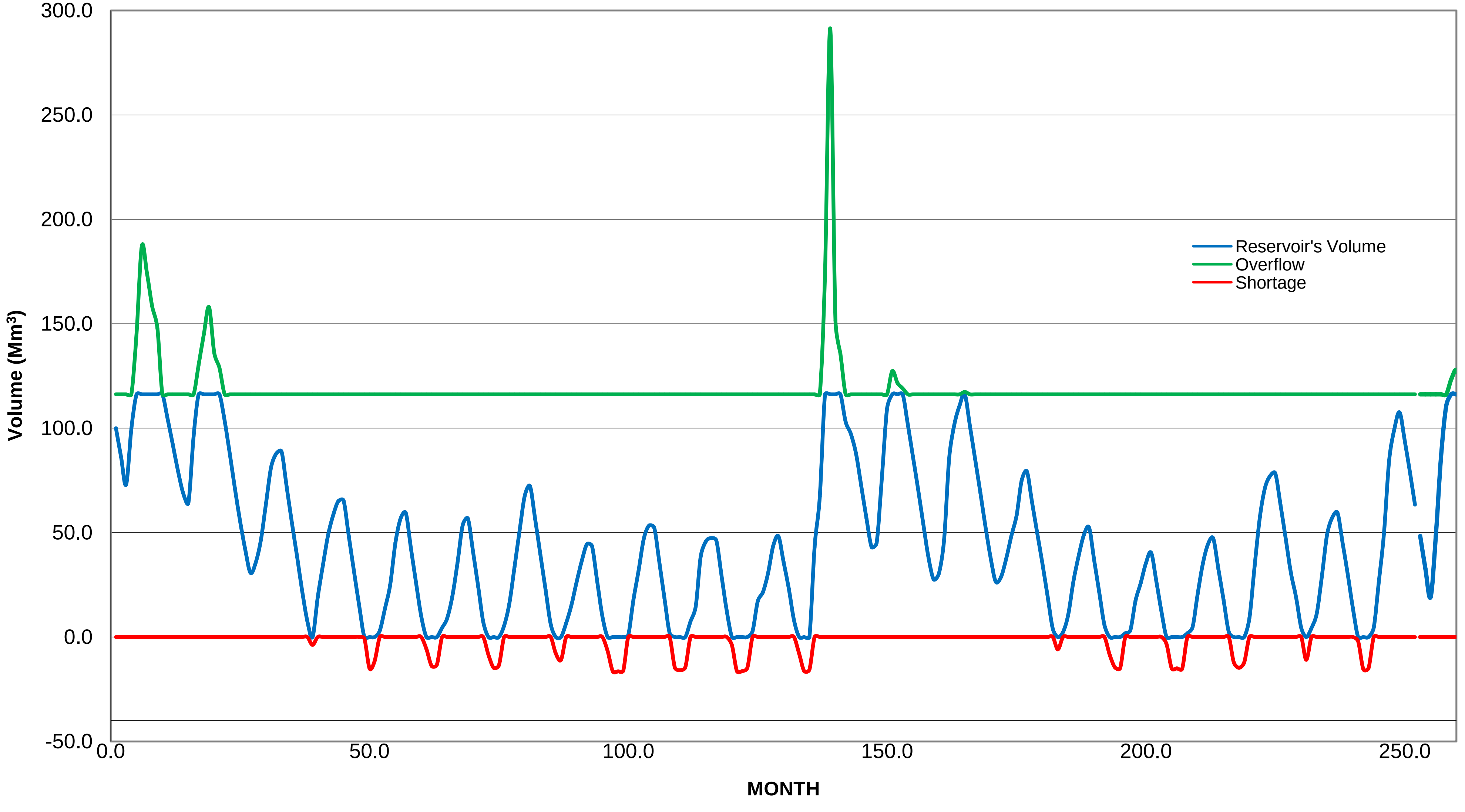


Figure 8.7 Water Management Results for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as “All Data” and a potable water demand of 5.1 m3/s

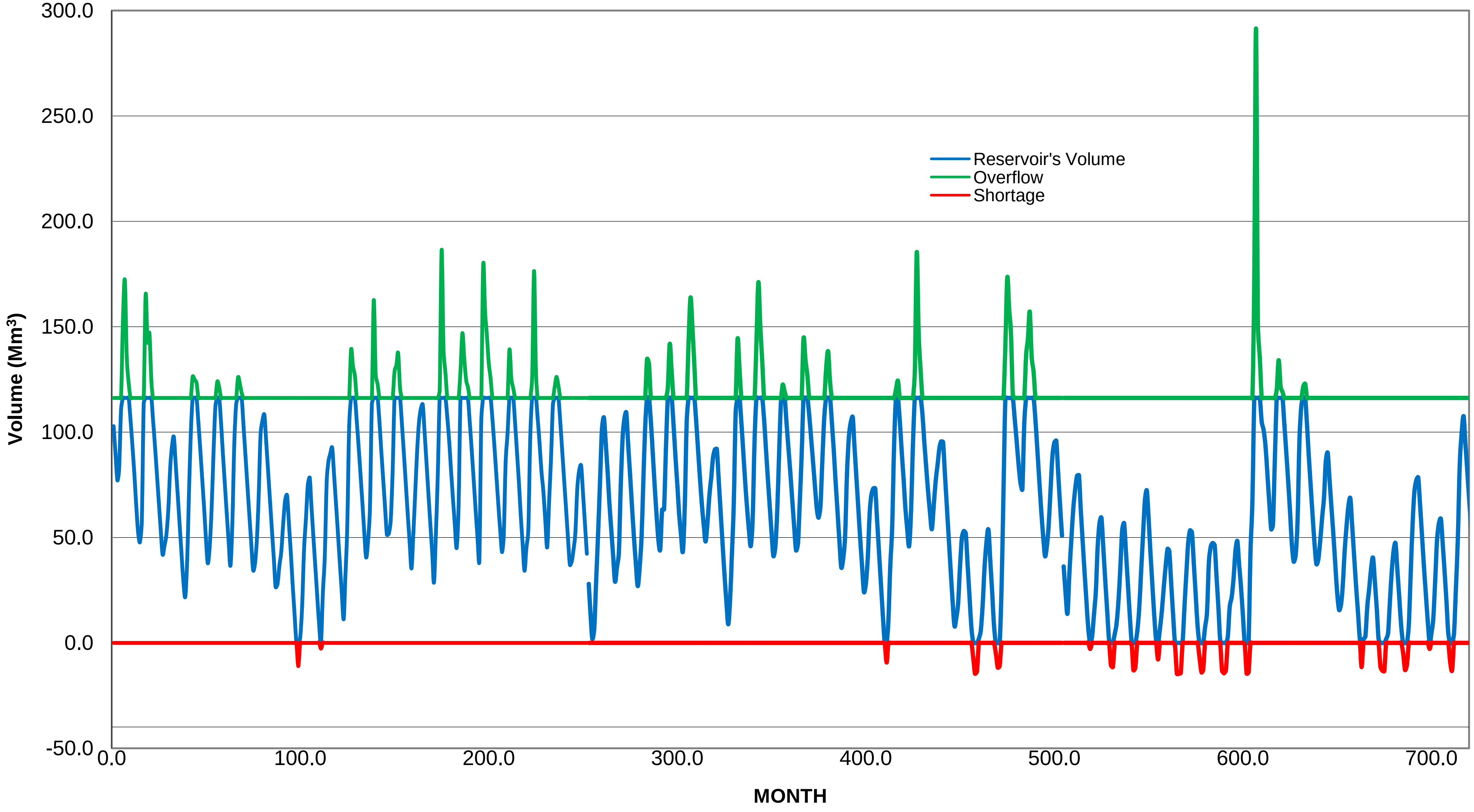


Figure 8.8 Water Management Results for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as “All Data” and a potable water demand of 5.8 m3/s

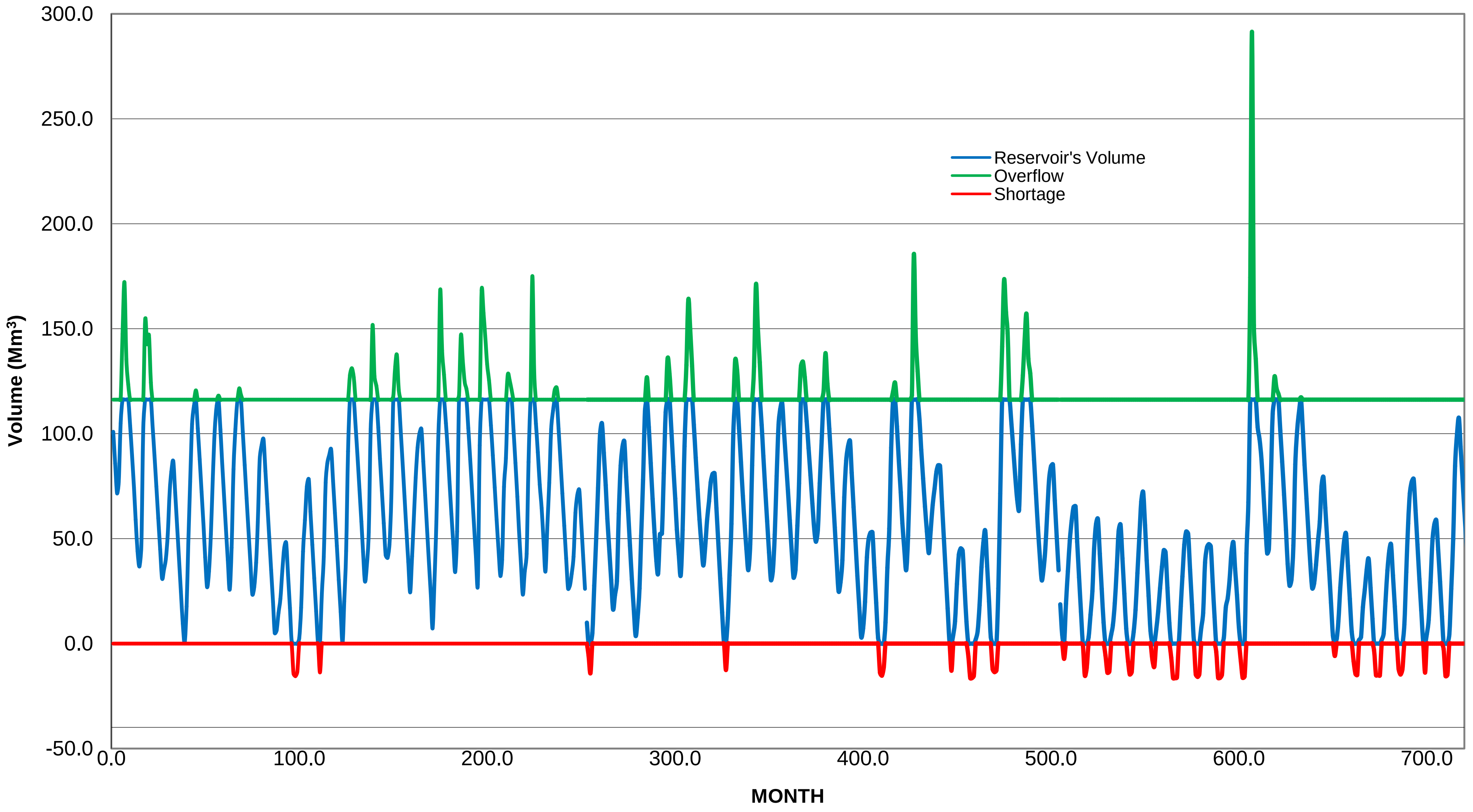


Figure 8.9: Results of the Simulations in term of Average Shortage Percentage

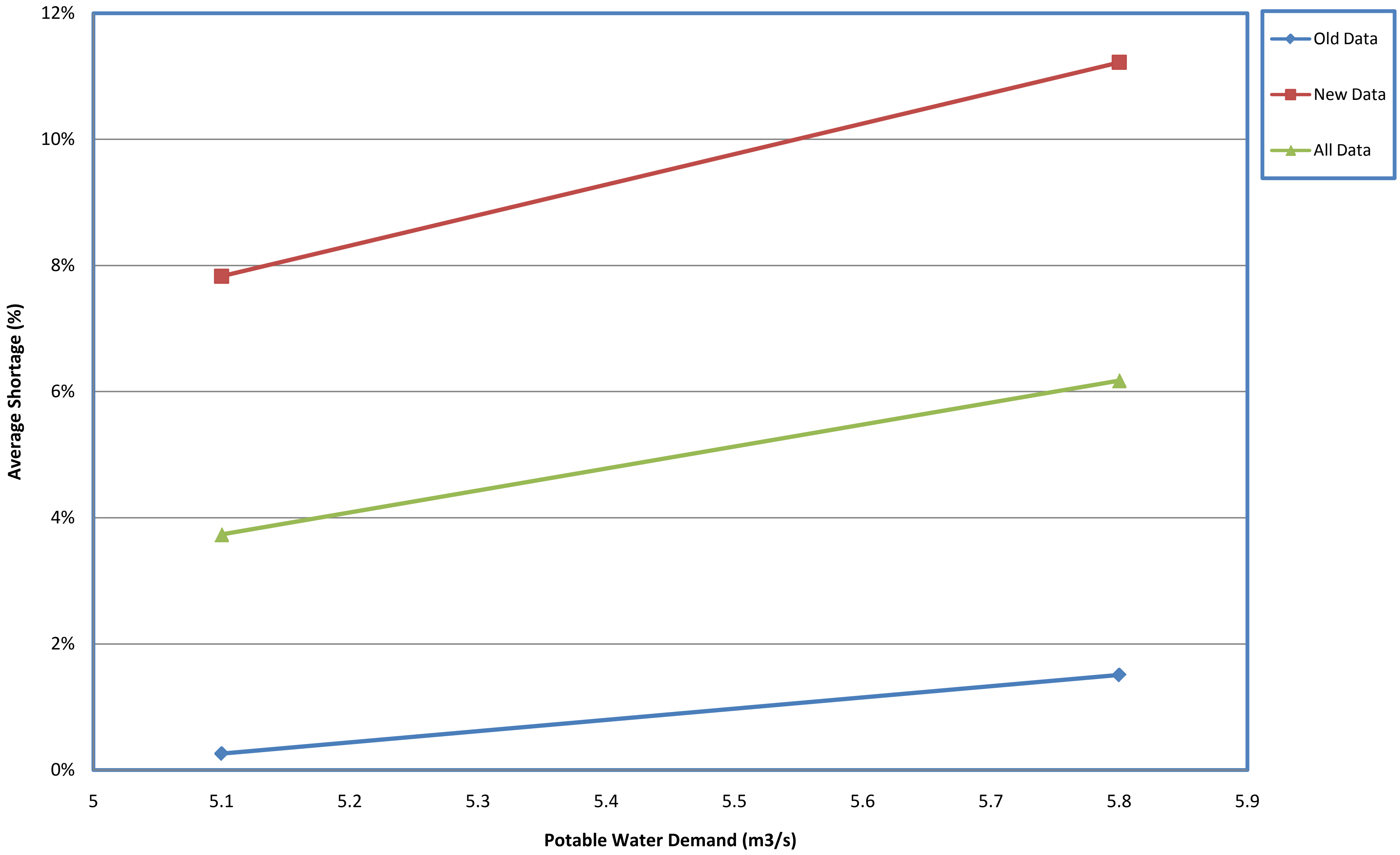


Figure 8.10: Results of the Simulations in term of Zero Shortage Percentage

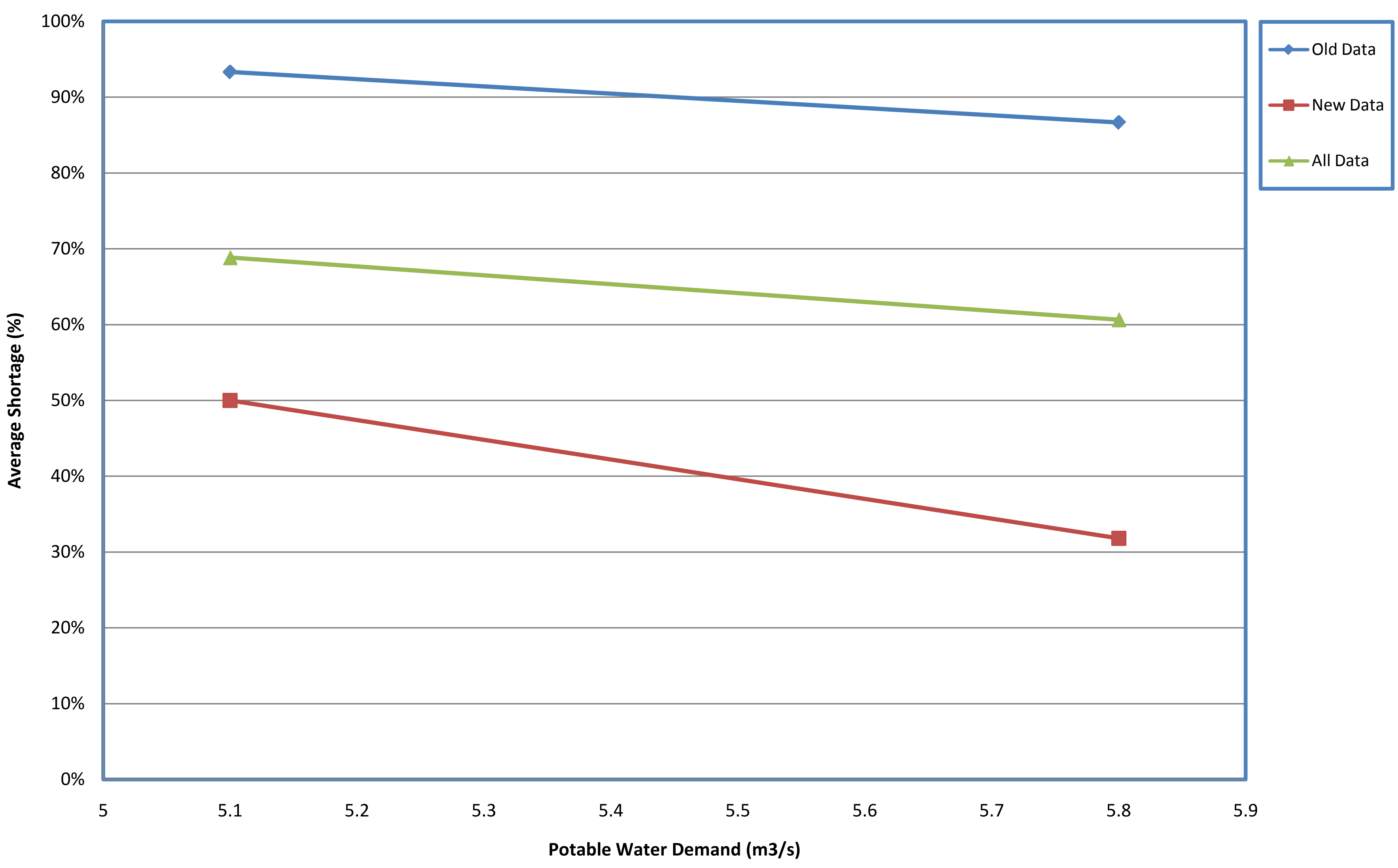


Figure 8.11 Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as “Old Data” and a potable water demand of 5.1 m^3/s.

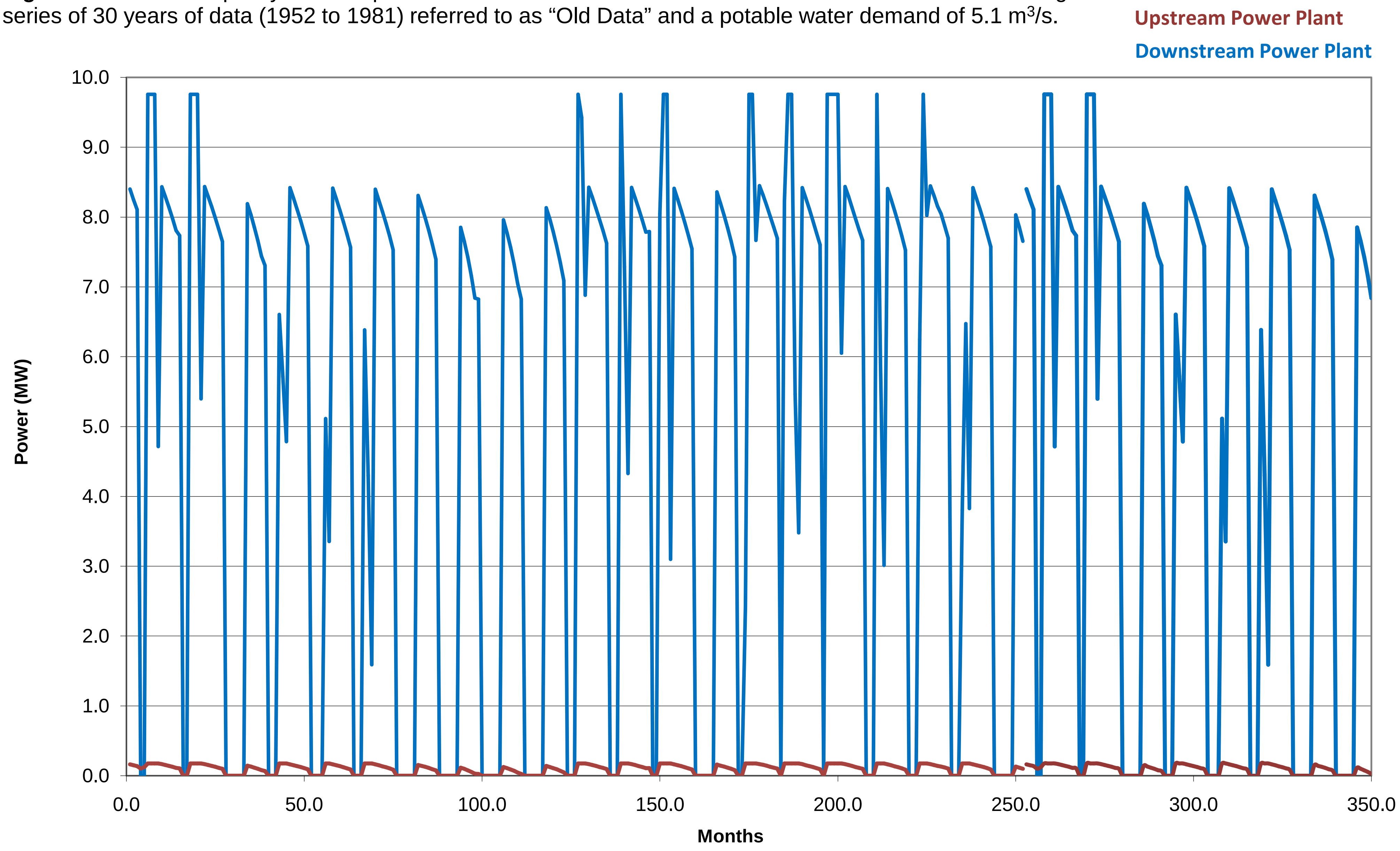


Figure 8.12 Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 30 years of data (1952 to 1981) referred to as “Old Data” and a potable water demand of 5.8 m3/s.

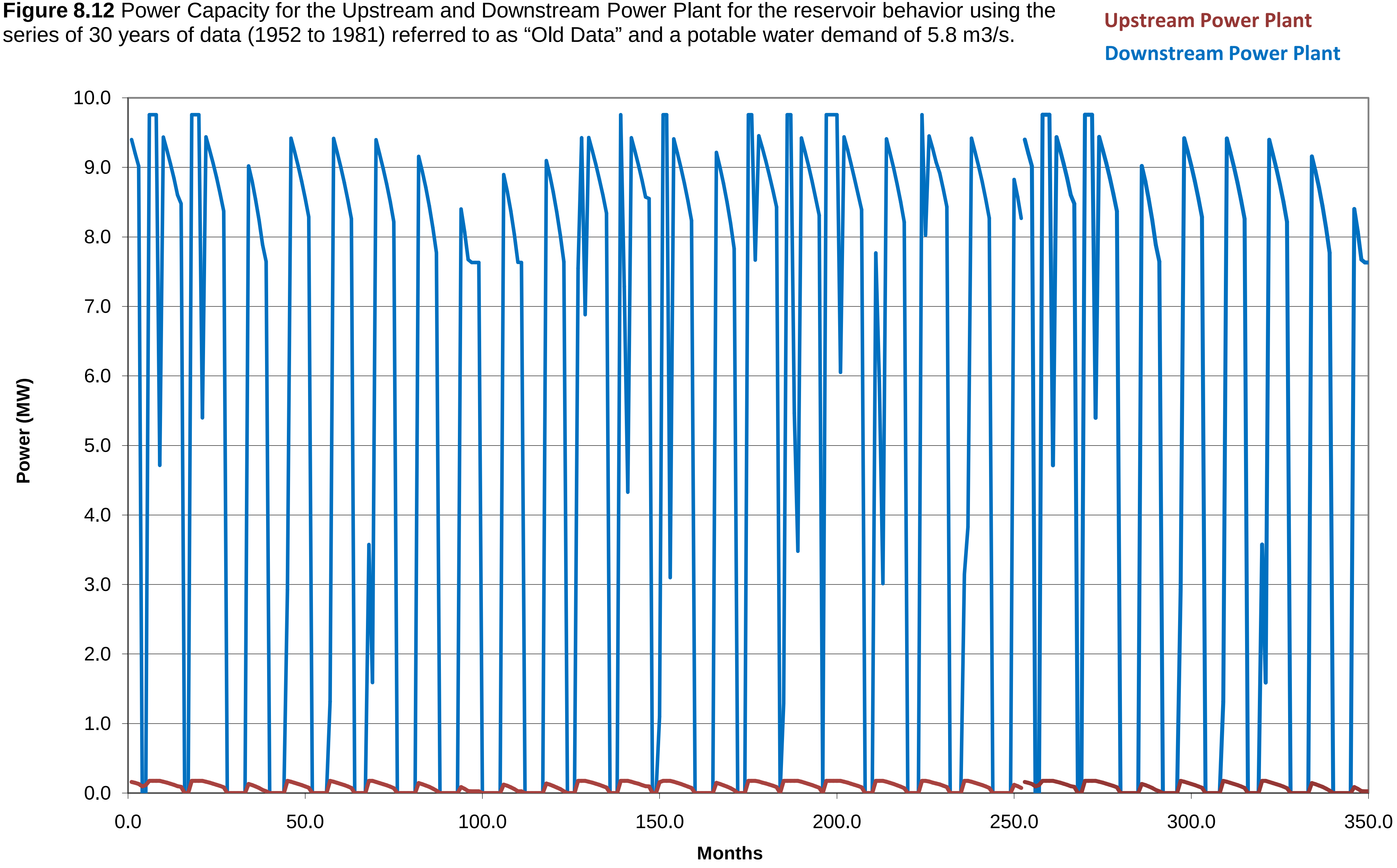


Figure 8.13 Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as “New Data” and a potable water demand of 5.1 m3/s.

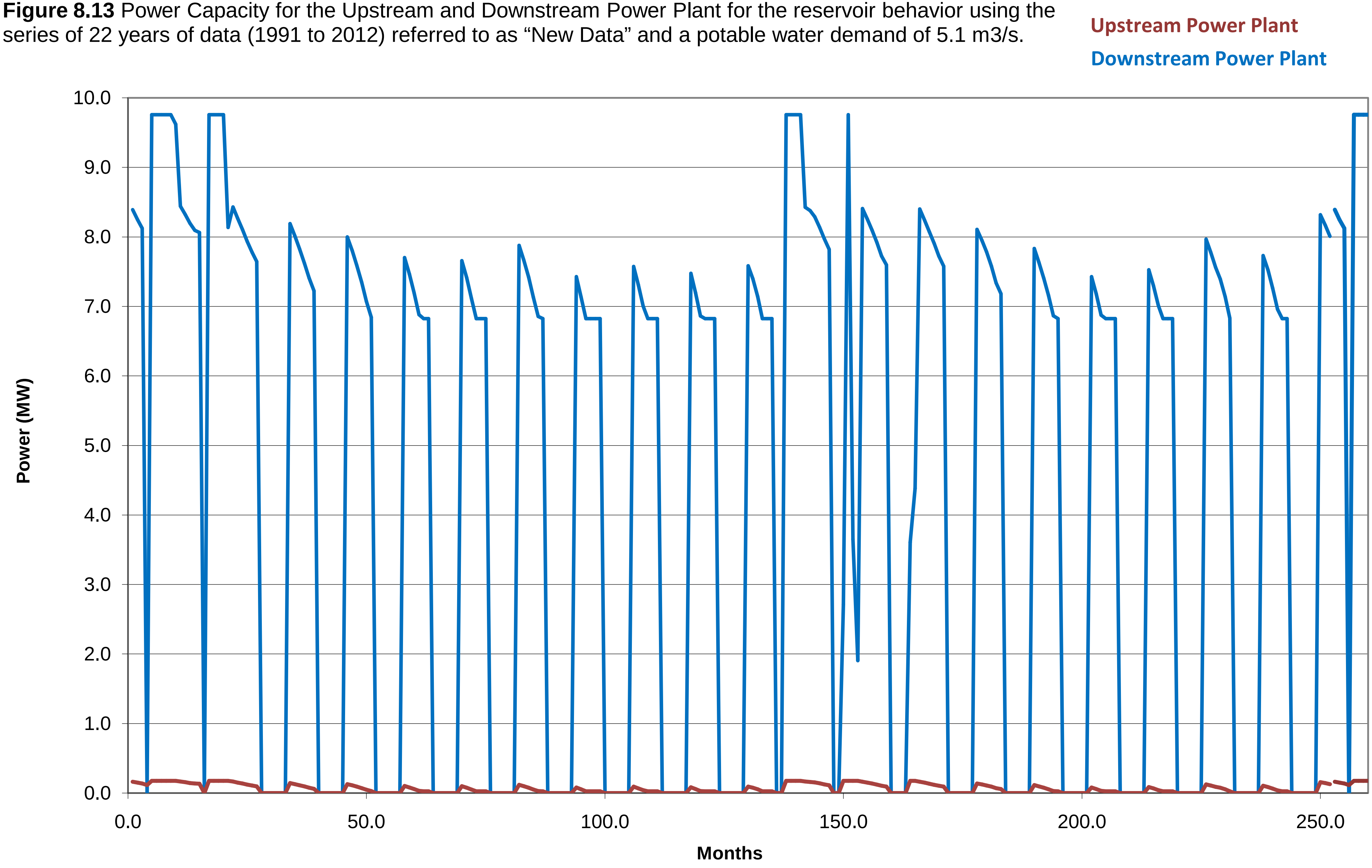


Figure 8.6 Water Management Results for the reservoir behavior using the series of 22 years of data (1991 to 2012) referred to as “New Data” and a potable water demand of 5.8 m3/s

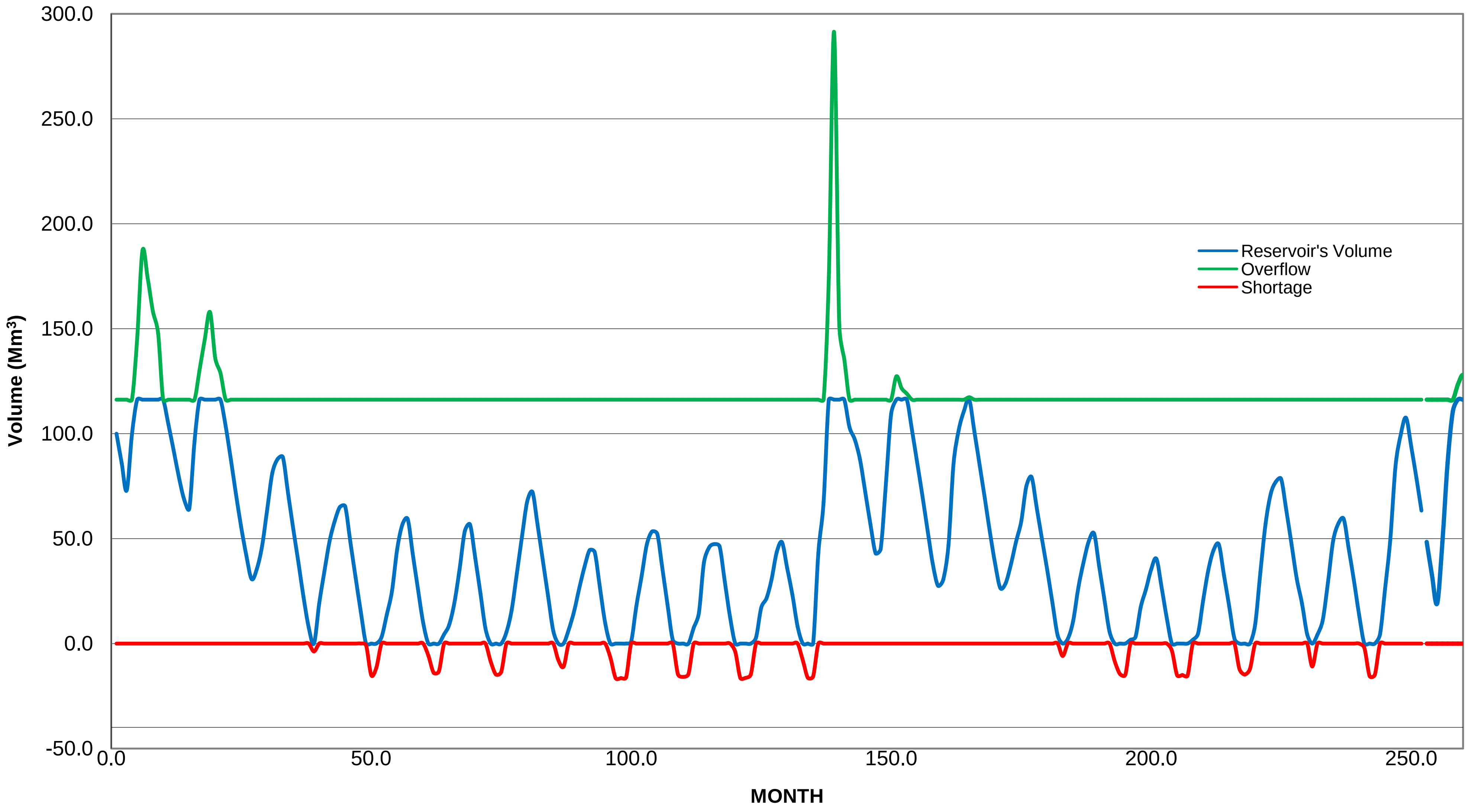


Figure 8.15 Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as “All Data” and a potable water demand of 5.1 m3/s.

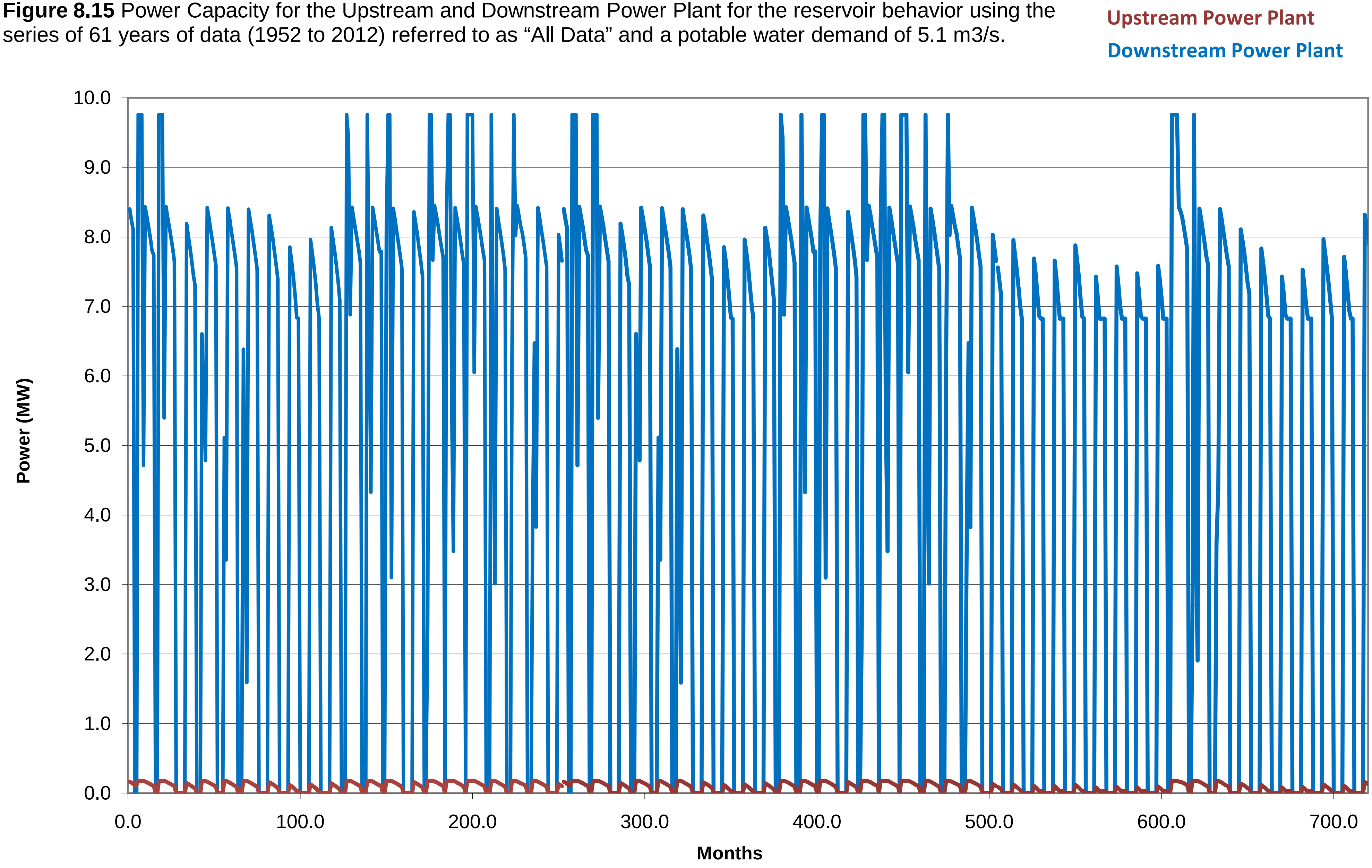


Figure 8.16 Power Capacity for the Upstream and Downstream Power Plant for the reservoir behavior using the series of 61 years of data (1952 to 2012) referred to as “All Data” and a potable water demand of 5.8 m3/s.

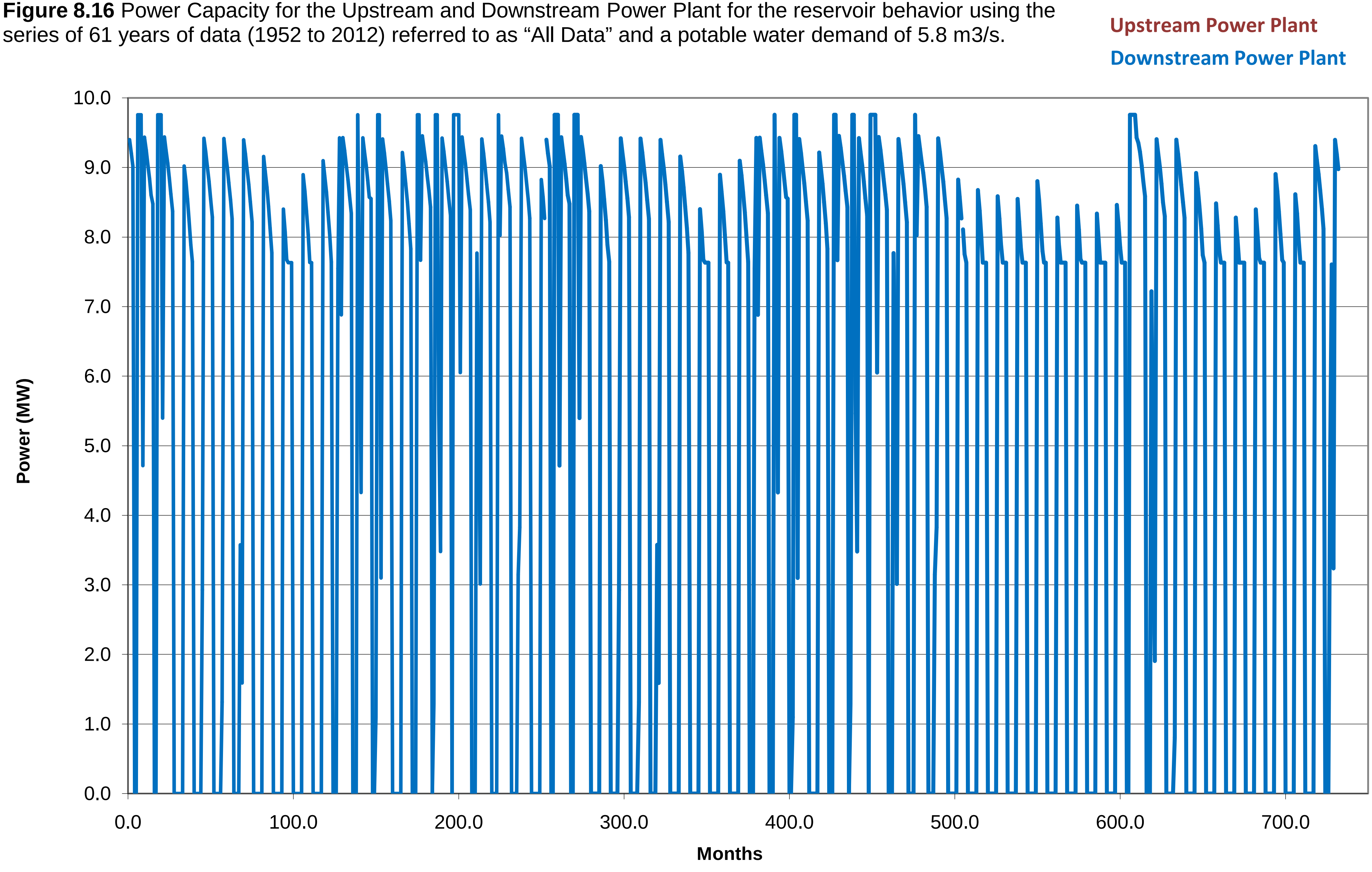


Table 8-1 Reservoir Area-Capacity Relationship

Elevation (m)	Area (Mm^2)	Original Capacity (Mm^3)	Revised Capacity (Mm^3)
397	0.003	0.00	0.00
398	0.015	0.01	0.00
399	0.031	0.03	0.00
400	0.057	0.08	0.00
401	0.080	0.14	0.00
402	0.110	0.24	0.00
403	0.170	0.38	0.00
404	0.210	0.57	0.00
405	0.241	0.79	0.00
406	0.275	1.05	0.00
407	0.304	1.34	0.00
408	0.333	1.66	0.00
409	0.365	2.01	0.00
410	0.396	2.39	0.00
411	0.440	2.81	0.00
412	0.493	3.28	0.00
413	0.549	3.80	0.00
414	0.632	4.39	0.00
415	0.708	5.06	0.00
416	0.802	5.81	0.00
417	0.929	6.68	0.00
418	1.017	7.65	0.00
419	1.128	8.72	0.00
420	1.231	9.90	0.59
421	1.325	11.18	1.87
422	1.410	12.55	3.24
423	1.502	14.00	4.69
424	1.591	15.55	6.24
425	1.702	17.20	7.88
426	1.820	18.96	9.65
427	1.910	20.82	11.51
428	1.983	22.77	13.46
429	2.066	24.79	15.48
430	2.169	26.91	17.60
431	2.247	29.12	19.81
432	2.340	31.41	22.10
433	2.429	33.80	24.48
434	2.509	36.27	26.95
435	2.574	38.81	29.50
436	2.644	41.42	32.10
437	2.707	44.09	34.78
438	2.775	46.83	37.52
439	2.840	49.64	40.33
440	2.890	52.51	43.19
441	2.945	55.42	46.11
442	2.997	58.39	49.08
443	3.050	61.42	52.11
444	3.106	64.50	55.18
445	3.164	67.63	58.32
446	3.227	70.83	61.51
447	3.287	74.08	64.77

Elevation (m)	Area (Mm^2)	Original Capacity (Mm^3)	Revised Capacity (Mm^3)
448	3.339	77.40	68.08
449	3.390	80.76	71.45
450	3.439	84.18	74.86
451	3.488	87.64	78.33
452	3.535	91.15	81.84
453	3.585	94.71	85.40
454	3.635	98.32	89.01
455	3.709	101.99	92.68
456	3.777	105.74	96.42
457	3.854	109.55	100.24
458	3.915	113.44	104.12
459	3.978	117.38	108.07
460	4.035	121.39	112.08
461	4.113	125.46	116.15
462	4.178	129.61	120.30
463	4.258	133.83	124.51

Table 8.2: Summary of Water Management Simulations Results

Data	01- Old Data	02- Old Data	03- New Data	04- New Data	05- All Data	06- All Data
Number of Years of Data	30	30	22	22	61	61
Demand (m^3/s)	5.1	5.8	5.1	5.8	5.1	5.8
Reservoir Storage (Mm^3)	125	125	125	125	125	125
Annual Potable Water shortage (%)						
Average	0.3%	1.5%	7.8%	11.2%	3.7%	6.2%
Minimum	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Maximum	6.3%	21.9%	24.8%	24.9%	24.8%	24.9%
Percentage of years of % shortage						
0	93%	87%	50%	32%	69%	61%
0% < 5%	3%	0%	0%	9%	7%	3%
5% < 10%	3%	10%	9%	5%	7%	10%
10% < 20%	0%	0%	27%	27%	11%	11%
20% < 30%	0%	3%	14%	27%	7%	15%
Annual Potable Water Volume (Mm^3)						
Average	92.3	102.0	85.3	91.9	89.0	97.2
Maximum	92.5	103.6	92.5	103.6	92.5	103.6
Minimum	86.7	80.9	69.5	77.8	69.5	77.8
Annual overflow (Mm^3)						
Average	44.4	36.2	12.0	11.2	35.8	30.7
Minimum	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	161.1	150.1	288.3	288.3	288.3	288.3

Table 8.3: Summary of Power Simulations Results

Data	01- Old Data	02- Old Data	03- New Data	04- New Data	05- All Data	06- All Data
Number of Years of Data	30	30	22	22	61	61
Demand (m^3/s)	5.1	5.8	5.1	5.8	5.1	5.8
Reservoir Storage (Mm^3)	125	125	125	125	125	125
Upstream Hypropower Plant Annual Energy (MWh/yr)						
Average	810	714	511	455	667	592
Maximum	1324	1302	1406	1391	1324	1302
Minimum	312	261	179	167	179	167
Upstream Hypropower Plant Power (MW)						
Average	0.09	0.08	0.06	0.06	0.08	0.07
Maximum	0.18	0.18	0.18	0.18	0.18	0.18
Downstream Hypropower Plant Annual Energy (MWh/yr)						
Average	46124	47592	38457	41177	42433	44450
Minimum	67149	70913	71946	75427	69273	71636
Maximum	31767	34911	30244	33667	30244	33667
Downstream Hypropower Plant Power (MW)						
Average	5.23	5.38	4.56	4.90	4.96	5.17
Maximum	9.76	9.76	9.76	9.76	9.76	9.76

CHAPTER 9 EFFECTS OF CLIMATE CHANGE AND CONCLUSIONS CONCERNING THE HYDROLOGIC ANALYSIS

9.1 Introduction

It is a proven fact that on a geologic scale (large periods of time, thousand years and more) climate changes do occur (e.g. North Africa experienced much more rainfall during the Roman Empire than today). Such changes are gradual and unfold over centuries or so. So even if hydrologic stationary is not real, one can assume that climate change is reasonably slow and that the statistical approach based on a few dozen years of data is quite valid (on a human/historical scale) to statistically envision events in the near future (within half a century or so).

Human-induced climate change is on the other hand a possibly faster phenomenon that is already impacting precipitations worldwide. But for lack of data, it remains difficult to predict how rainfall patterns and the resulting flows will evolve in different parts of the world.

Some hydrologists and meteorologists try to identify cycles in the pattern of rainfalls. Cyclical patterns have also been mentioned when discussing weather events such as El Nino, possibly linked to solar activity. So far no clear correlation (if it exists) has been proven.

In this report, the main climate change impacts will be mentioned and the results of some local studies, concerning these impacts on the hydrologic and water resources aspects will be exposed.

9.2 Main Climate Change Impacts

As a global meteorological process, change in climate conditions has become a serious topic that many researchers work on. However, data availability is still the major problem to analyze this process and the significance of predicted climatic changes is still uncertain.

Normally, climatic variability originates two major meteorological elements:

- Precipitation deficiency over an extended period of time including volume, intensity and timing
- Increase in temperature, wind velocity and sunshine, and decrease in relative humidity and cloud cover

Most of the attention is actually given to the impact of climate change on the increase in temperature from global warming. However, the most severe impacts of climate change are expected from changes in runoff and in particular the extremes: droughts and floods. In fact, the impact of temperature rise is particularly strong on those mechanisms with thermal thresholds, such as the melting of snow and ice.

In Lebanon, very little studies and analysis concerning the climate changes and its impact on the hydrology and water resources have been done in the last years. The overall figure of climatic elements in Lebanon has not been well demonstrated due to the lack of sequential and complete data. Therefore, it is still early to give absolute conclusions in this respect.

9.3 Previous Studies and Analysis

9.3.1 Study No. 1- Hydrological impact simulations of climate change on Lebanese coastal rivers- Antoine Hreiche, Wajdi Najem & Claude Bocquillon

The hydrological consequences of climatic changes on Lebanese catchments were analyzed by means of different scenarios of rainfall variability and temperature increase. A climate–runoff model was used to determine the impact of a temperature increase of 2 degrees on the flow characteristics of a watershed affected by seasonal snow cover.

The catchment area analyzed in this study is Nahr Ibrahim basin. This watershed was chosen because it is a typical Lebanese watershed where measurement data exist at the spring outlets as well as at the catchment outlet. The snowmelt contributes up to about two thirds of the total yearly discharge.

9.3.1.1 Main Results of This Study

- Potential Impact of Precipitation Change

  Runoff coefficient: An average amplifying effect of 2 is demonstrated for Lebanese catchments, i.e. a variation in the annual rainfall will involve a double variation in the annual discharges.

  Daily Distributions: Some scenarios, which increase the duration of the rainy spells, accelerate the rainfall mechanisms and decrease the rainy season, lead to more severe drought.

- Hydrological Impact of Potential Climate Warming

  Simulation of hydrological variables: this study shows that an increase of 2°C decreases the snow width by approximately 50% and the drought occurs 15 days to one month earlier. The snowmelt floods of April–May are often replaced by rainfall floods in February–March.

  Potential impact on the mean daily discharge and the discharge distribution

  The 50 years of generated data allow the discharge distribution to be defined in the two cases: the reference simulation and the scenario of an increase of 2°C. It is noticed that the modifications in the time of flow occurrence did not modify their probability distribution.

9.3.1.2 Main Conclusions of This Study

The modifications of the hydrological regimes are: droughts are predicted to occur 15 days to one month earlier; snowmelt floods are often replaced by rainfall floods; and the peak flow occurs two months earlier.

9.3.2 Study No. 2- Analyzing Climatic and Hydrologic Trends in Lebanon-A-Shaban

This study presents illustrations on climatic and hydrologic trends in Lebanon. They were built in combination between data from ground measures and from satellite images. It established a complete figure on precipitation (rainfall and snow) and temperature trends.

9.3.2.1 Main Results of This Study

1- Precipitation

The resulting trends of rainfall since 1967 up to 2009, reveals a relatively small decline in rainfall amount, within a limit of less than 50 mm. However, there is an obvious decline in snow amount, the overall trend of snow cover area decline is accompanied with a decrease in time residence of snow due to higher melting rate, thus it decreased from 110 to 85 days.

2- Temperature

As it is obvious, there is a change in average annual temperature since 1963 towards an ascending trend, thus remarkable temperature increase existed and result an ascending trend of about 1.8 between 1963 and 2009.

3- Rivers and Springs

It is showed a clear decline in the amount of discharging water in rivers and springs, the decline in water discharge is almost doubled in some sources. The diverse in the percentage of discharge decrease is mainly due to the geologic setting of the replishment areas, as well as the human impact.

9.3.2.2 Main Conclusions of This Study

The amount of water from rainfall has not been remarkably changed over more than forty years. The areal extent of snow cover has been reduced, but it was accompanied with faster melting rate, which can be the reason for the reduction of snow cover. This is well evidenced with the illustration built for temperature and shows an increase about 1.8 degrees between 1963 and 2009.

Water resources are abruptly decreased, which is obviously noticed in the amount of water whether in rivers or springs. However, it is unanticipated that the decrease, in some instances, reaches to 50%. This can be attributed to the increase in population size, as well as the unwise use of water rather to be a result of climate change.

9.4 Conclusions Concerning the Hydrologic Analysis of Bisri Dam

Based on the limited previous studies related to the climate change and its effects on the on the hydrologic and water resources in Lebanon, it can be concluded that climate change can have effects on the following elements of Bisri Hydrology:

- The discharge of Bisri River
- The floods of Bisri River

9.4.1 Bisri Discharge and Reservoirs Capacity

Concerning the Bisri River discharge, the registered measurements confirm that the average flow in the last 20 years is less by around 5% than the total average yearly volume of the previous 59 Years. Therefore, and seen the decline in the amount of discharging flows in the river, it is reasonable to select a reservoir capacity insuring a reasonable amount of water supply shortage on the longest series as well as on the last years, considered as drought years. In our case, for a reservoir capacity of 125 Mm^3, the average shortage for the 59 years of data is about 10% and for the last 20 years of data, the shortage increases to 19%.

It worth to mention that any less capacity chosen for the dam would result a higher deficiency in the supplied water especially in case of dry years scenario.

9.4.2 Floods

Concerning the floods, it can be concluded, from the study of a similar watershed partially supplied by snow, that the scenario of temperature increase will lead to the replacement of the floods of April–May by rainfall floods in February–March, without any indication about modification in the flood flows, which can have no effects on the adoption of the flood flow calculated using the traditional methods.

APPENDICES

APPENDIX I FINAL REPORT ON MISSING VALUES PATCHING BY PR EZIO TODINI (WORLD BANK), MARCH 7TH 2014

FINAL REPORT ON MISSING VALUES PATCHING

by Ezio Todini

March 7th, 2014

Introduction

From a detailed analysis of the rating curves used by LITANI in the period 2001-2013, it must be acknowledged that the monthly water volume figures published by LITANI in the corresponding period of time are highly questionable and uncertain, particularly on medium and high flow values. This is because several rating curves are obtained by fitting low observed values and then extrapolated far beyond the measurement range.
Therefore, it was decided to recompute only the monthly values for the year 2002-2003 using the revised rating curve, which is justified by the lack of fit of the originally developed rating curve over the measurement values as well as by the excessively large values estimated in correspondence of highest water levels. On the other hand this modification leads to a relatively minor change in the yearly volume of 2002-2003 by about 11%.
All the other water years will be taken at face value, although the hydrology report will discuss the potential effects caused by the extremely high uncertainty in the adopted rating curves.

Alternative approaches to patching missing data

After correcting the 2002-2003 water year using the values and extending the records to the year 2012-2013, several alternative approaches were implemented on the data transferred to the Bisri Dam site.

The different approaches were then compared on the basis of how well they could meet the scope of the patching, namely to obtain a basic record aimed at: (i) designing the reservoir size; (ii) finding appropriate operating rules; (iii) assessing their performances by means of relevant indicators; (iv) establishing the risk of failure and the resilience of the reservoir viz-a-viz climatic cyclo-stationarities or more in general non-stationarities.

For any given demand, the size of a reservoir is dominated by the mean, the variance of the inflow discharge record. Moreover, the reservoir size is also a function of the “Range”, namely the difference between the maximum positive and the maximum negative deviation of the cumulated flows from the cumulated mean. Therefore, this additional element, which is important when dealing with non-stationary processes, was also taken into consideration for the selection of the most appropriate record to be used in the Bisri reservoir design.

Accordingly the approaches were compared on the basis of how well they approached (i) the expected mean, (ii) the expected standard deviation of the patched years and the expected “Rescaled Range”.

In order to define the expected mean, the Qaraoun record was divided into two parts:

1) a first record q_{Qc} containing the contemporary observations available for Marj Bisri, which were rescaled to the catchment closed at Bisri Dam (namely by multiplying them by the ratio of the catchment areas 215/222) q_{BDc}.
2) A second record q_{Qm} containing the observations to be used as the basis for patching the missing data q_{BDm} into Bisri Dam record.

By assuming a certain regional climatological pattern, the expected mean EM_{BDm} and the expected standard deviation ES_{BDm} of the missing data q_{BDm} at Bisri Dam can be defined as follows:

$$EM_{BDm} = \frac{M_{BDc}M_{Qm}}{M_{Qc}} = \frac{9.74 \times 25.52}{26.02} = 9.55$$

$$ES_{BDm} = \frac{S_{BDc}S_{Qm}}{S_{Qc}} = \frac{16.07 \times 32.24}{32.85} = 15.77$$

Furthermore, assuming once again similar climatological conditions between the two locations, from the 44 years of observations at Qaraoun the expected rescaled range for a 61 years record could be established as:

$$E(R_{BD}/S_{BD})_{732} = E\left(R_Q/S_Q\right)_{732} = \left(R_Q/S_Q\right)_{528} \times \frac{732^{0.58}}{528^{0.58}} = 37.49 \times \frac{732^{0.58}}{528^{0.58}} = 45.29$$

as discussed in Appendix A.

The approaches compared in this report are:

1) Non-Linear Regression on yearly values and monthly disaggregation according to the Qaraoun monthly values (Y-NR) (the same approach taken by the consultant but using the update record for 2003);
2) Linear Regression on yearly values and monthly disaggregation according to the Qaraoun monthly values (Y-LR);
3) Piecewise Linear Regression on yearly values and monthly disaggregation according to the Qaraoun monthly values (Y-LR_X);
4) Non-Linear Regression based on monthly values (M-NR);
5) Linear Regression based on monthly values (M-LR);
6) Kalman Filter based patching technique proposed by Geoff Pegram (PATCHS);
7) Rescaling Qaraoun record by means of expected mean and standard deviation (M&V)

$$q_{BDm} = \frac{\left(q_{Qm} - M_{Qm}\right)}{S_{Qm}} ES_{BDm} + EM_{BDm}$$

where EM_{BDm} and ES_{BDm} are the previously defined values;
8) Rescaling Qaraoun record by imposing expected mean and standard deviation (M&V_X)

$$q^*_{BDm} = \frac{(q_{Qm} - M_{Qm})}{S_{Qm}} ES^*_{BDm} + EM^*_{BDm}$$

where EM^*_{BDm} and ES^*_{BDm} are values different from EM_{BDm} and ES_{BDm} but specifically estimated in such a way that q^*_{BDm} will be an EM_{BDm} mean and $(ES_{BDm})^2$ variance variable after setting the negative values to zero.

The reason for implementing approach 3 (Y-LR_X) is due to the fact that the linear regression tends to over depress the flow volumes at Bisri Dam when the flow volume at Qaraoun is smaller than 260 Mm^3.
The reason for implementing approach 8 (M&V_X) is due to the fact that several methods produce a large number of negative values, which must then be set to zero, thus distorting (overestimating) the mean and (underestimating) the variance.

The final results of the comparison are synthesized in Table 1 and in Figure 1 where the values are given in the form of ratio to the expected ones.

Table 1 – Comparison of mean, standard deviation and coefficient of variation for the patched data using the alternative approaches.

	EXPECTED	Y - NR	Y - LR	Y – LR_X	M - NR	M - LR	PATCHS	M&V	M&V_X
MEAN	9.55	9.73	9.51	10.01	9.54	9.72	10.26	10.32	9.55
STD	15.77	12.11	13.14	13.08	12.39	13.15	12.98	15.21	15.77
CV	1.65	1.25	1.38	1.31	1.30	1.35	1.26	1.47	1.65

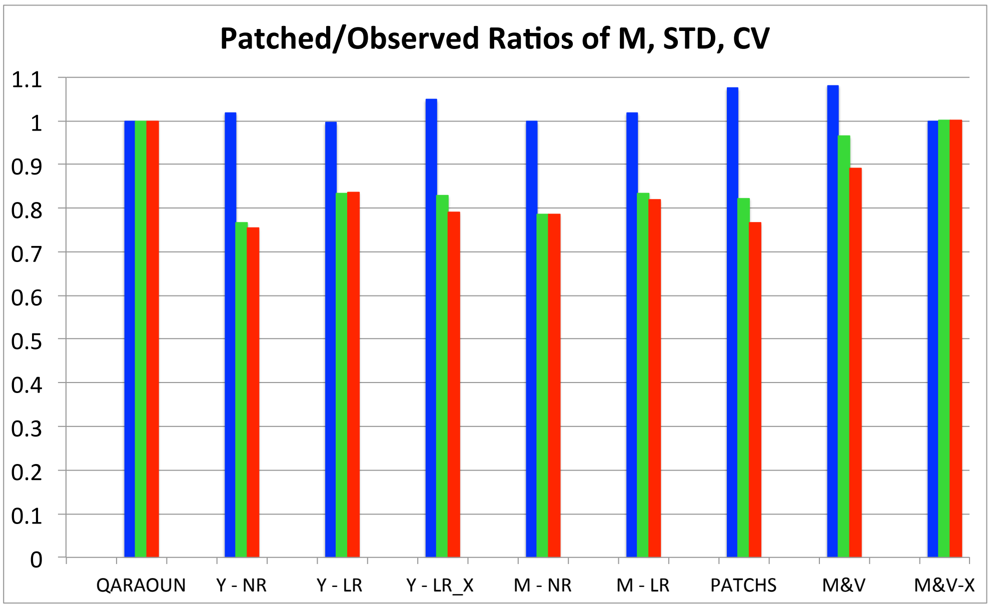


Figure 1 – Comparison of the different approaches in terms of mean (blue), standard deviation (green) and coefficient of variation (red) (ratios to the expected values)

It must be understood that:

1) A mean of the reconstructed values smaller (ratio < 1) is preferable to a than higher one to be on the safe side in order to avoid overestimating the potential availability of water. Nonetheless, one must realize that the effect of a small error in the mean will not strongly affect the overall record.
2) Most of the overestimation of the mean is due to the setting of negative values to zero.
3) The standard deviation of the reconstructed values will always be smaller than the observed due to the fact that the in-filled values correspond to the "expected values", which implies loosing part of the natural variability. The higher the ratio the better.

Both the Pegram's approach (PATCHS) and the M&V tend to strongly overestimate the mean due to the large number of negatives set to zero, while the non-linear regression at a monthly level (M-NR) tends to show a reduced standard deviation.

Apart from that all the approaches seem more or less acceptable

The second type of comparison is based on the Rescaled Range applied to the full record (1952-2013) of 61 years. Table 2 shows the results, while Figure 2 shows the ratios of the different values with the expected one.

Table 2 – Comparison of the rescaled range and exponent values obtained using the alternative approaches and the expected one.

	EXPECTED (61 YEARS)	Y - NR	Y - LR	Y – LR_X	M - NR	M - LR	PATCHS	M&V	M&V_X
R/S	45.29	40.07	45.43	46.58	40.76	42.36	43.78	45.41	43.72
h	0.58	0.56	0.58	0.58	0.56	0.57	0.57	0.58	0.58

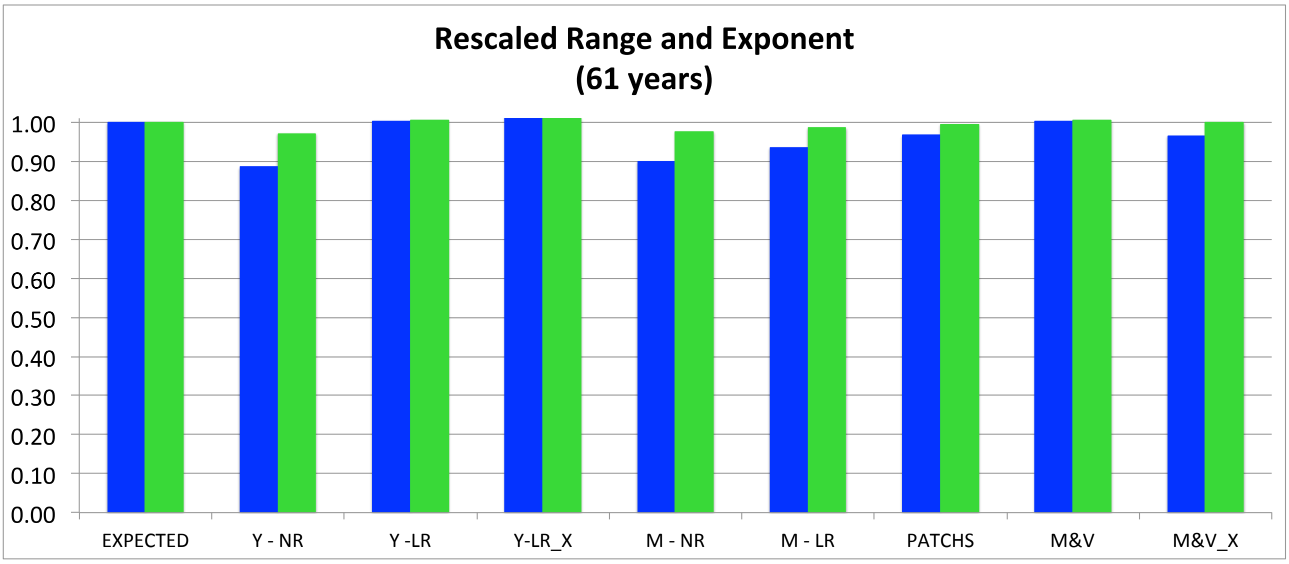


Figure 2 – Comparison of the different approaches in terms of rescaled range (ratios to the expected values)

As can be seen from Table 2 and Figure 2, there are three approaches which results are quite close to the expected values, namely the yearly linear regression (Y-LR) the mean and variance (M&V) and the piecewise linear regression (Y-LR_X).

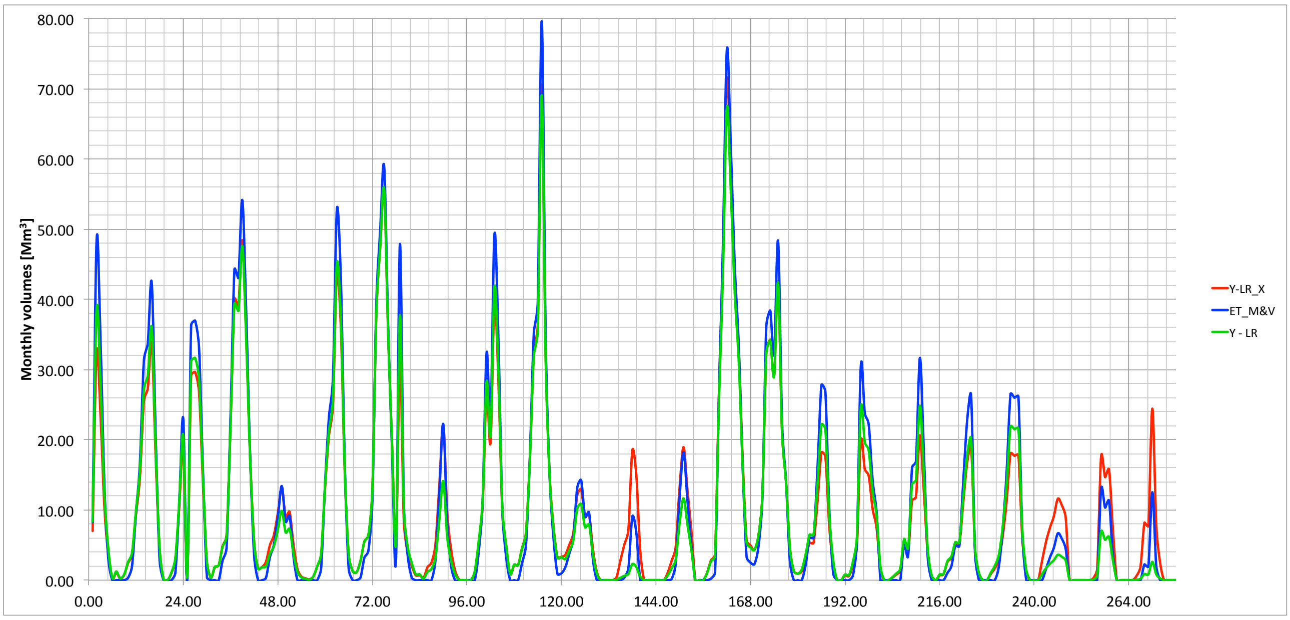
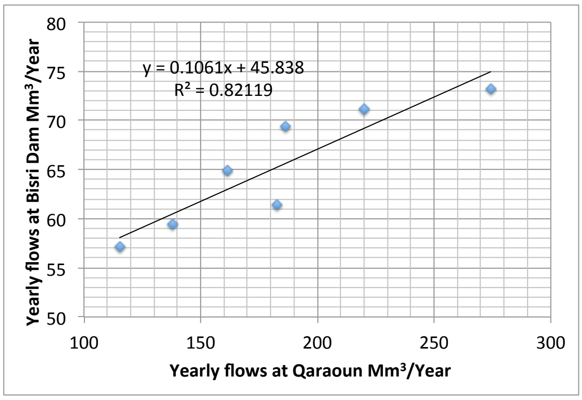


Figure 3 – Comparison of the different approaches in terms of reconstructed values

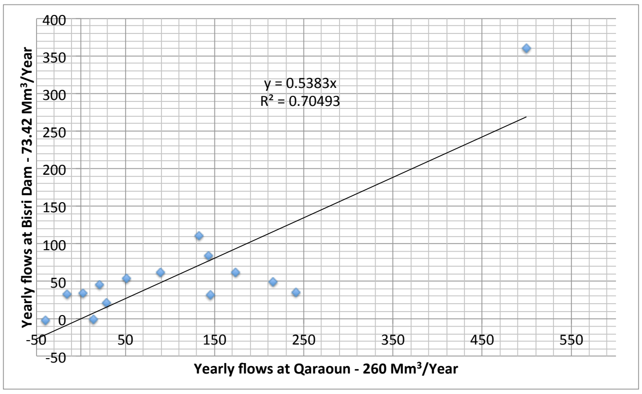
From Figure 3, where the three series of reconstructed values are plotted, one can observe that

- (M&V) tends to largely increase the number of zeroes in the record
- (Y-LR) tends to generate years with almost null flow

Therefore, as a conclusion of this comparative study, it is suggested the use the piecewise yearly linear regression (Y-LR).



(a)



(b)

Figure 4 – The piecewise regression model. (a) Linear Regression for values of Qaraoun yearly flows lower than 260 Mm^3/year; (b) Linear Regression for values of Qaraoun yearly flows larger than 260 Mm^3/year

The chosen model is the following:

$$\begin{cases} q_{BD} = 45.838 + 0.1061\, q_Q & \forall\, q_Q \leq 260 \\ q_{BD} = 73.424 + \ 0.5383\, (q_Q - 260) & \forall\, q_Q > 260 \end{cases}$$

where:

q_{BD} is the yearly flow at Bisri Dam in Mm^3/year

q_Q is the yearly flow at Qaraoun in Mm^3/year

The monthly values are then rescaled according to the Qaraoun monthly percentage for each specific year.

APPENDIX A - The Hurst Phenomenon and the Rescaled Range

Given a long record of river flow, the minimum capacity required to sustain the specified demand from a dam without interruption can be determined as the difference between the largest positive and the largest negative departure of the cumulated flow from the cumulated mean. This quantity is called the "range" and represents the required storage capacity ignoring all evaporation and other losses.
A long record is likely to contain a more severe drought sequences than a short record, and given that the greater the variability of the flow in the river the greater will be the storage capacity required to meet the specified demand, the range R will grow both as a function of the standard deviation and of the length of the record.

In other words:

$$R_n = S_n \times n^h$$

where:
R_n is the range in a record of n observations;
S_n is the standard deviation in a record of n observations;
h is the exponent;

Theoretically, for a stationary process h should have a value of 0.5 for normally (or log-normally) distributed sequences of independent random values.

Hurst, an English engineer working on the long Nile records of yearly maximum levels observed at Roda Nilometer found a specific anomaly, today known as the Hurst phenomenon, for which the exponent h resulted in a value of 0.75 much larger than 0.5, which gave an indication that the long time natural processes could not be fully considered as stationary.

In this report the application of the range and in particular of the rescaled range (R_n/S_n), is not performed on a yearly basis for assessing non-stationarity of long time spells, but rather on a monthly basis for its connection to the reservoir size.

If $y_1, y_2, \dots, y_n$ is a set of n flow observations (such as for example the flow at Qaraoun or at Bisri Dam site), its mean can be defined as:

$$\bar{y}_n = \sum_{i=1}^{n} y_i$$

while the cumulated flow can be defined as:

$$Y_n = \sum_{i=1}^{n} y_i$$

The largest positive and negative departures of Y_n from the cumulated mean are then defined as:

$$D_n^+ = \max_{1 \le i \le n} (Y_i - i\bar{y}_i)$$

$$D_n^- = \min_{1 \le i \le n} (Y_i - i\bar{y}_i)$$

from which the range is estimated as:

$$R_n = D_n^+ - D_n^-$$

In most of hydrological approaches one uses the rescaled (or readjusted) range defined as:

$$R_n/S_n \simeq n^h$$

Using the 528 (44 x 12) monthly values available for Qaraoun, the following result was obtained:

Table A1 – Estimated values for the 1969-2013 Qaraoun flow record

n	528
D_n^+	709.60
D_n^-	-509.04
R_n	1218.64
S_n	32.50
R_n/S_n	37.49
h	0.58

Using the estimated exponent $h = 0.58$ it was then possible to estimate the rescaled range for the full record of 732 = 61 x 12 values, which gave:

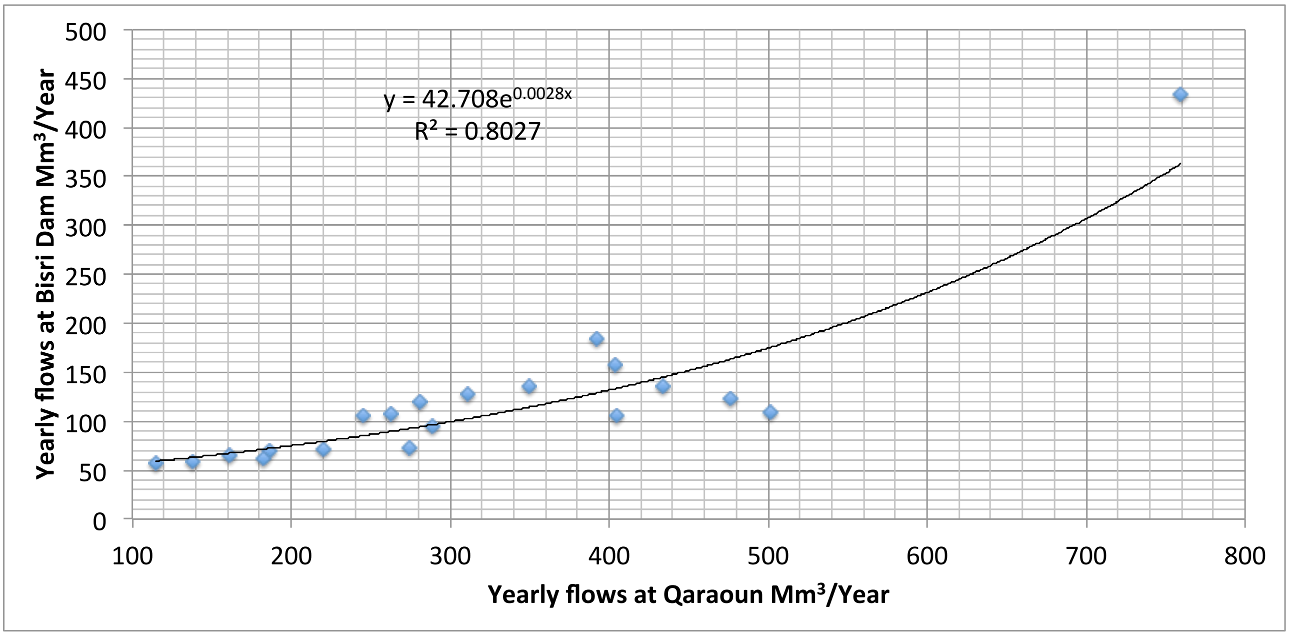
$$R_{732}/S_{732} = R_{528}/S_{528} \times \left(\frac{732}{528}\right)^{0.58} = 45.29$$

APPENDIX B - The in-filled monthly flows at Bisri Dam using the Piecewise Linear Regression on the yearly values (Y-LR_X)

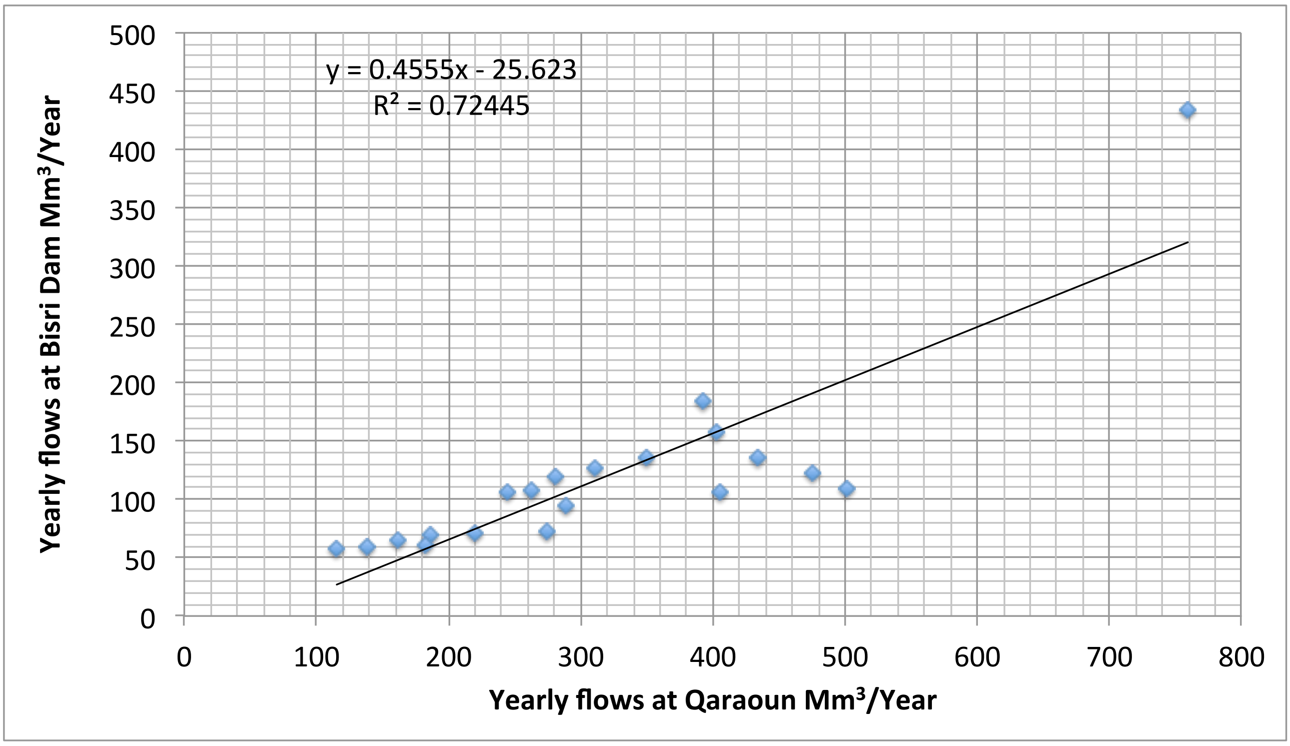
YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
1952-1953	2.03	1.91	2.35	5.83	28.16	43.10	56.62	20.48	8.61	4.74	3.07	2.10
1953-1954	1.69	1.72	9.23	10.43	56.21	51.97	27.11	31.90	9.68	5.02	3.17	2.25
1954-1955	1.90	1.87	2.63	4.62	5.55	12.23	20.48	10.70	6.19	2.09	1.52	1.19
1955-1956	1.11	1.23	7.35	17.99	30.07	30.13	28.02	9.94	8.72	3.64	2.49	1.50
1956-1957	1.33	1.49	2.19	7.86	18.10	26.89	23.17	12.98	6.51	3.23	1.94	1.25
1957-1958	1.10	1.66	2.20	20.46	37.70	19.54	13.45	7.72	3.83	1.92	1.48	1.30
1958-1959	1.36	1.56	1.53	3.81	12.07	19.73	30.43	7.76	4.18	2.04	1.49	1.15
1959-1960	1.15	1.37	1.79	1.82	8.98	7.32	13.78	11.77	3.59	1.53	1.11	1.04
1960-1961	0.86	0.93	3.01	3.21	15.28	27.31	15.49	16.99	4.63	1.75	1.12	1.04
1961-1962	0.99	1.16	2.70	24.59	17.78	35.68	9.95	4.95	4.01	2.19	1.71	1.39
1962-1963	0.69	1.29	1.62	20.50	24.47	47.89	36.87	16.15	12.06	4.22	2.92	1.87
1963-1964	1.67	2.30	2.38	8.17	15.99	49.51	50.17	12.48	8.01	3.95	2.61	1.86
1964-1965	1.53	1.59	15.07	6.88	23.56	47.60	16.34	22.56	6.12	2.89	1.73	1.17
1965-1966	0.86	1.53	1.94	17.70	17.59	20.24	15.06	7.88	3.52	1.76	1.04	0.56
1966-1967	0.77	1.17	1.04	23.52	28.46	40.29	70.91	24.66	13.36	6.13	3.90	2.58
1967-1968	1.80	2.50	3.07	19.74	64.93	31.15	19.05	9.54	6.70	3.75	2.36	1.65
1968-1969	1.18	1.69	3.26	66.69	74.18	41.74	31.07	18.22	10.72	5.07	2.98	1.91
1969-1970	1.59	2.50	3.93	8.13	35.08	14.10	40.49	10.26	5.99	2.76	1.66	1.00
1970-1971	0.77	1.19	1.64	11.35	8.82	44.10	28.92	61.45	13.96	5.91	3.58	1.85
1971-1972	1.38	1.40	2.13	22.59	20.69	25.98	9.22	10.68	7.03	3.51	1.89	1.56
1972-1973	1.53	1.18	2.08	2.06	5.60	8.73	21.45	9.49	3.60	1.90	0.97	0.79
1973-1974	0.68	0.98	2.33	5.78	23.26	22.58	24.81	25.95	7.32	3.17	1.68	1.05
1974-1975	2.26	2.33	2.26	7.39	7.06	32.48	23.44	10.25	3.68	0.28	1.05	0.22
1975-1976	0.76	2.44	3.68	9.32	14.64	25.42	27.32	33.69	17.52	4.30	0.15	0.00
1976-1977	1.02	2.98	10.61	19.26	0.44	29.15	29.66	26.83	13.81	2.51	0.33	1.78
1977-1978	2.16	4.90	6.43	22.24	40.04	39.00	48.38	34.44	17.18	5.44	1.66	1.87
1978-1979	2.63	4.99	6.40	9.50	13.12	9.03	9.70	4.99	1.57	0.51	0.27	0.12
1979-1980	0.50	1.92	3.65	13.14	20.63	24.89	43.79	36.07	15.33	3.57	1.27	1.11
1980-1981	2.81	5.54	6.42	12.76	37.84	47.52	55.62	35.29	19.32	5.24	2.64	1.19
1981-1982	1.88	1.78	3.28	4.81	17.55	28.27	25.11	8.55	4.43	3.39	3.51	3.51
1982-1983	2.38	2.28	3.60	4.15	21.40	20.49	56.36	19.39	12.23	7.07	4.45	4.20
1983-1984	3.64	4.54	11.10	6.93	23.21	21.38	25.03	23.73	9.30	3.53	1.80	1.71
1984-1985	0.95	0.92	2.19	5.19	11.68	31.02	18.70	8.34	3.85	2.03	0.72	0.69
1985-1986	0.34	1.85	2.50	4.99	13.43	22.13	9.73	4.35	1.38	0.13	0.00	0.00
1986-1987	0.00	1.19	5.33	10.87	26.89	19.63	39.74	28.34	9.79	4.66	0.86	2.12
1987-1988	2.18	4.60	6.82	17.66	32.69	36.45	70.60	32.06	15.15	7.57	3.26	3.35
1988-1989	3.61	5.05	6.67	12.09	12.93	8.99	9.47	4.42	1.14	0.00	0.00	0.00
1989-1990	0.00	0.45	2.87	5.13	7.17	18.48	15.01	4.22	0.00	0.00	0.00	0.00
1990-1991	0.00	0.00	1.10	2.81	4.69	13.20	18.94	12.76	6.93	0.00	0.00	0.00
1991-1992	1.11	2.89	3.69	27.07	46.09	71.34	58.63	43.34	33.16	17.34	5.69	4.93
1992-1993	4.34	6.32	12.00	32.35	34.26	29.15	42.44	21.12	14.15	4.62	1.30	0.93
1993-1994	1.24	3.04	5.32	5.32	11.17	18.17	17.59	7.61	2.29	0.00	0.00	0.67
1994-1995	0.61	2.14	4.90	19.78	15.84	14.86	10.14	7.44	1.48	0.00	0.00	0.35

1995-1996	0.79	1.34	4.87	3.79	11.29	11.88	20.63	12.61	3.62	0.55	0.00	0.67
1996-1997	0.86	2.58	3.21	5.12	5.06	11.04	16.73	18.96	4.29	0.95	0.00	0.00
1997-1998	0.87	1.68	2.91	6.17	11.17	18.03	17.70	17.82	5.87	1.23	0.00	0.00
1998-1999	0.00	2.72	5.44	7.45	9.10	11.59	10.70	8.93	0.00	0.00	0.00	0.00
1999-2000	0.00	0.00	0.27	1.62	17.65	14.67	15.75	7.09	0.00	0.00	0.00	0.00
2000-2001	0.00	0.62	1.93	8.20	7.73	24.44	7.81	2.40	0.00	0.00	0.00	0.00
2001-2002	0.14	0.16	1.67	3.61	14.95	4.82	9.41	13.99	5.88	4.53	4.09	1.60
2002-2003	0.37	0.11	0.74	43.82	24.49	107.41	175.89	36.76	20.83	4.22	11.46	7.63
2003-2004	1.72	1.32	2.64	2.61	31.34	33.52	18.66	6.72	4.31	2.63	2.25	1.38
2004-2005	0.37	0.56	6.06	3.38	16.64	38.92	16.89	10.19	8.09	2.00	1.45	1.08
2005-2006	1.08	1.67	4.83	2.72	9.14	11.32	10.36	17.48	5.77	2.37	2.07	2.30
2006-2007	1.03	1.07	6.64	3.13	9.07	16.58	12.66	10.80	4.67	1.57	1.05	1.11
2007-2008	2.35	1.89	1.50	2.52	2.11	14.88	9.11	10.34	5.94	3.17	2.04	1.28
2008-2009	1.38	1.49	1.21	2.60	3.55	16.29	15.19	10.32	3.88	2.14	1.98	1.38
2009-2010	2.02	1.74	4.30	9.80	25.44	23.72	14.74	6.62	2.61	2.08	0.77	0.51
2010-2011	1.80	1.94	1.32	5.07	7.49	18.49	20.40	8.70	3.17	2.81	1.65	0.37
2011-2012	0.81	0.97	1.60	5.25	22.15	23.95	35.57	16.03	9.37	3.59	2.03	1.68
2012-2013	2.02	1.12	2.71	29.76	38.23	24.75	13.33	13.01	6.33	1.93	1.08	1.10

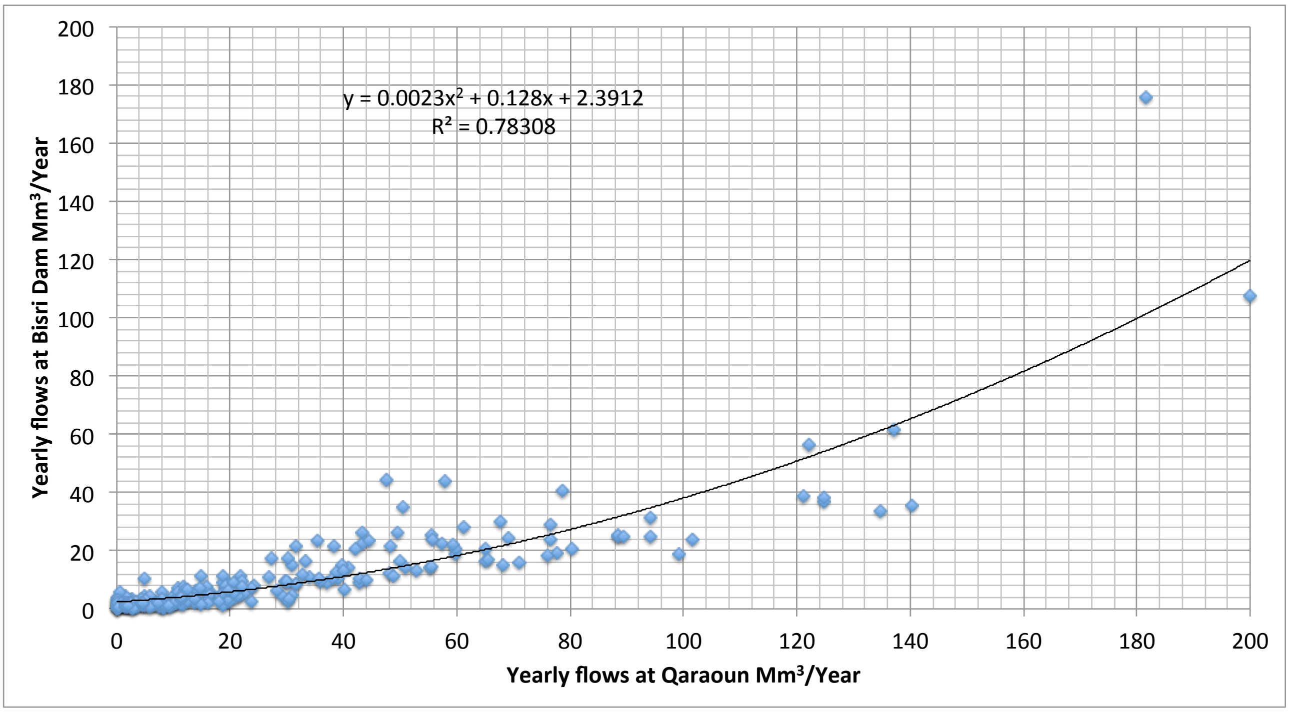
APPENDIX C – The additional regression models



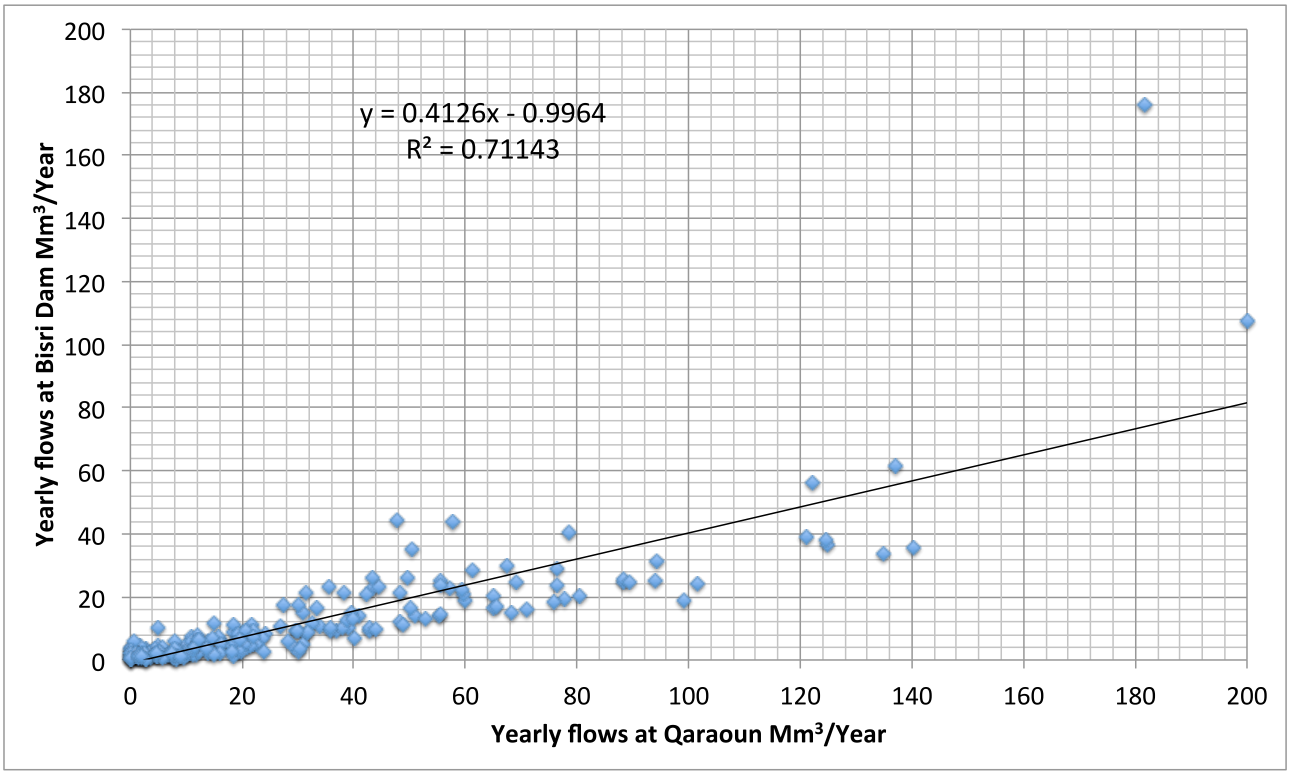
Non-Linear Regression on yearly values (Y-NR)



Linear Regression on yearly values (Y-NR)



Non-Linear Regression on monthly values (M-NR)



Linear Regression on monthly values (M-LR)

APPENDIX II REPORT ON RATING CURVES BY PR EZIO TODINI (WORLD BANK) ADDRESSED TO PR WAJDI NAJEM (PANEL OF EXPERTS OF BISRI DAM)

Dear Prof. Najem,
I am writing to you, as a member of the Panel of Experts, in order to urgently get from you some advice for completing the Bisri dam hydrological study and update the hydrological report.

As you might remember, after my visit in Beirut, I was given a drawing of the 2002-2003 rating curve at Marj Bisri, which I considered incorrectly fitted to the observed values (Figures 1 and 2) with large potential overestimation of the high flows (Figure 2).

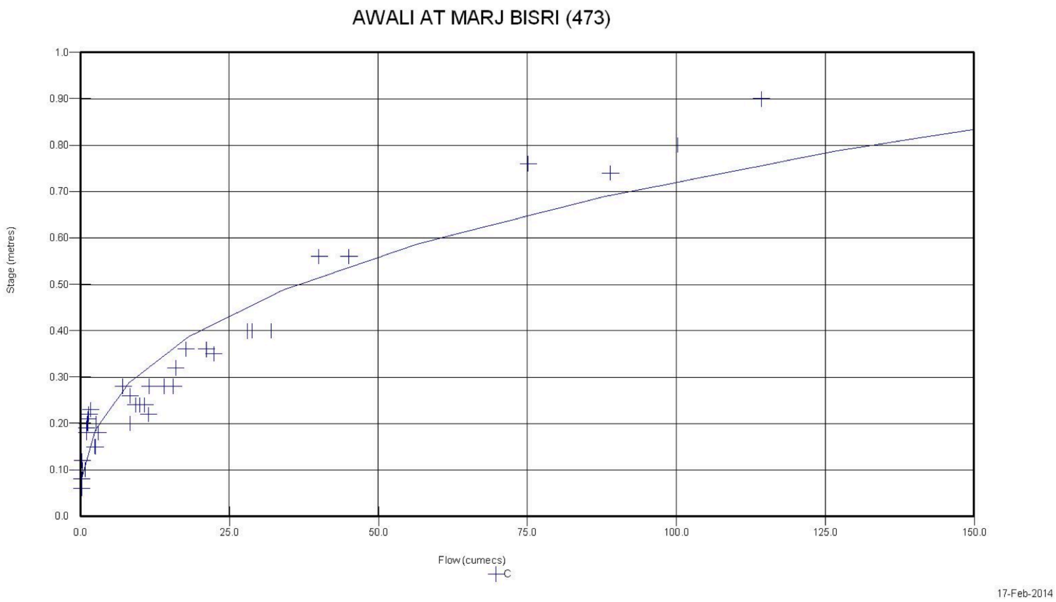


Figure 1 – The rating curve at Marj Bisri which validity extends from 01/09/2002 to 31/08/2003

To overcome the problem, I proposed to use an alternative equation, which better fitted the observed values (Figure 2).

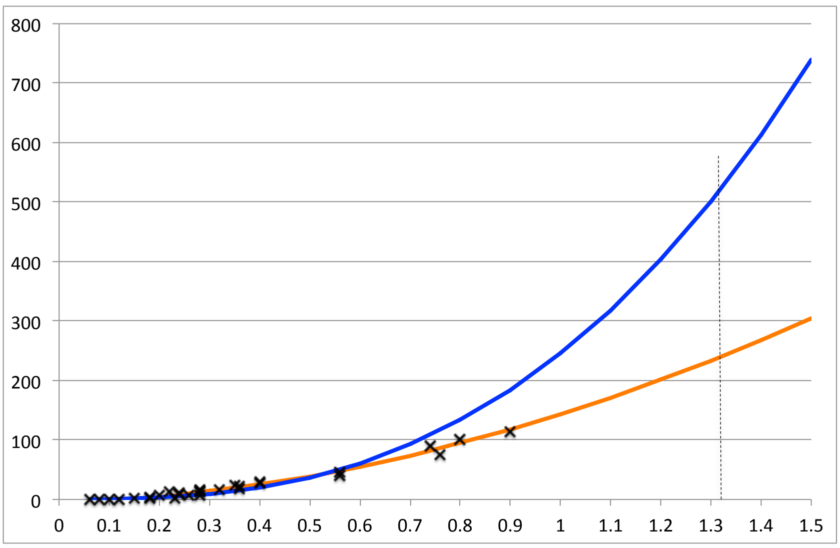


Figure 2 – Comparison of the two rating curves. The original one (solid blue) and the new one (red solid line). Note the large difference of discharge corresponding to the March 2003 reading (1.32 m) (dashed vertical line). Please note that in this figure the abscissas correspond to the water stage and the ordinates to the discharge.

Only recently I obtained all the other rating curves in graphical and numerical form together with their validity (time period and water stage range).

In general, in a less stable river bed cross section, one should expect variations similar to the ones shown in Figure 3. Namely variations in the lower end of the curve, due to gravel and sand deposition or erosion, which tend to disappear at higher flows.

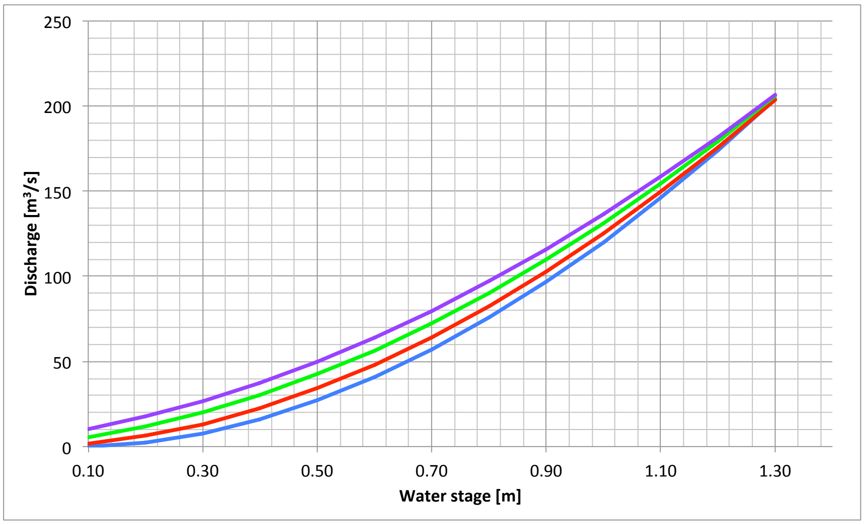


Figure 3 – Expected variations of rating curves in time due to erosion and/or deposition of sand and gravels.

Marj Bisri gauging station is installed in a stable concrete cross section under a bridge (Figure 4), which has never worked under pressure during the recording period. I am mentioning this because if the bridge worked as a pressurized pipe differences in the upper values could be expected. Consequently, one may expect variations in the lower end of the rating curve, but hardly on the upper end, unless the bottom slope of the river downstream the bridge can be classified as “mild” (much smaller than 1/1000).

Figure 4 – The Marj Bisri gauging station

I have plotted all the available rating curves together in Figure 5, in order to appreciate their extremely high variability, which increases with the water stage. This variability, as previously mentioned, is not justified by type of cross section where the measurements are taken.

The observed variations can only be attributed to three causes:

1) errors in the velocity measurements
2) the formation of a loop in the rating curve
3) extrapolation out of the measurement range

Giving credit to LITANI technicians I do not expect large errors in the velocity measurements as well as I do not expect that they performed the velocity measurements during a flood (with the potential loop rating curve formation), although I expect the local slope to be sufficiently high to reduce the size of the loop. Therefore, the major expected effect is, in my opinion, due to the extrapolation far from the measurement range. The measurements being mostly concentrated between zero and 10 m³/s with few values around 30 m³/s and only one around 115 m³/s (2002-2003).

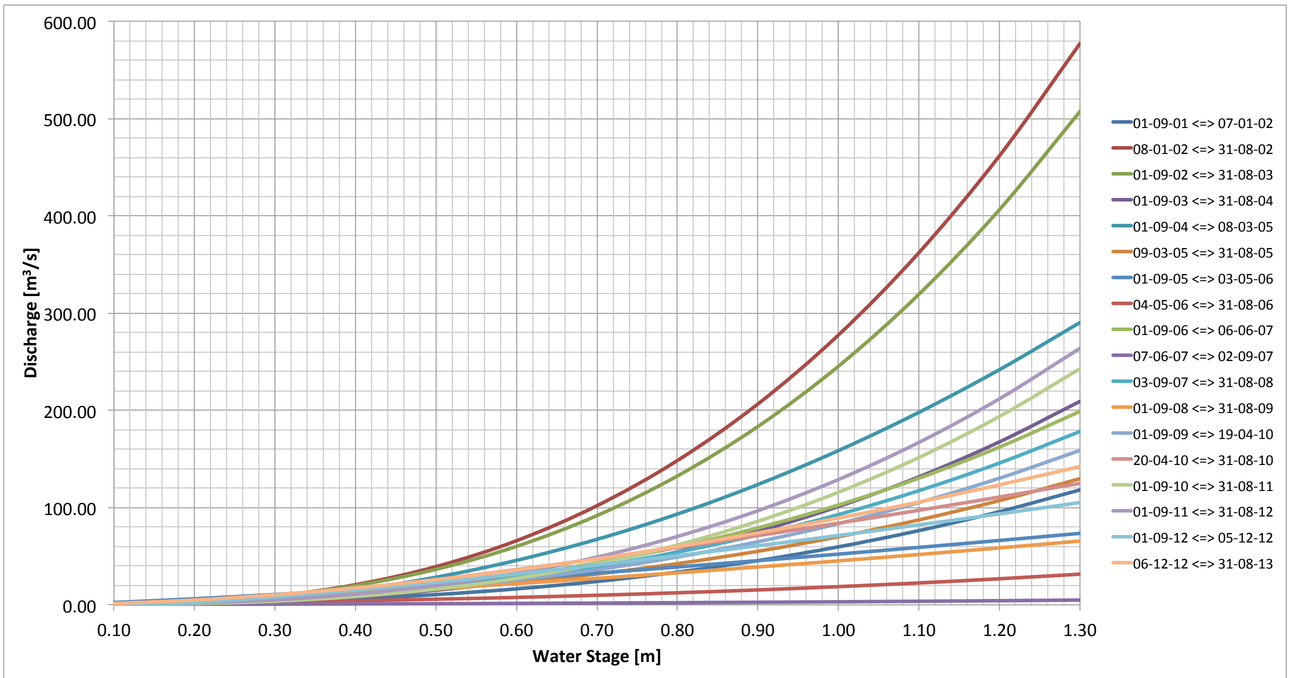


Figure 5 – A comparative plot of all the rating curves developed by LITANI and used in the estimation of flows at Marj Bisri in the period 2001-2013.

This is for instance the case of the two uppermost rating curves in figure 5 (the light green and brown). The light green, relevant to the period 01/09/2002-31/08/2003 has already been discussed (Figure 1 and 2). Similarly it is easy to notice that also the brown rating curve relevant to the period 08/01/2002-31/08/2002 cannot be accepted at face value given that it was adjusted on few low observations (see Figure 6)

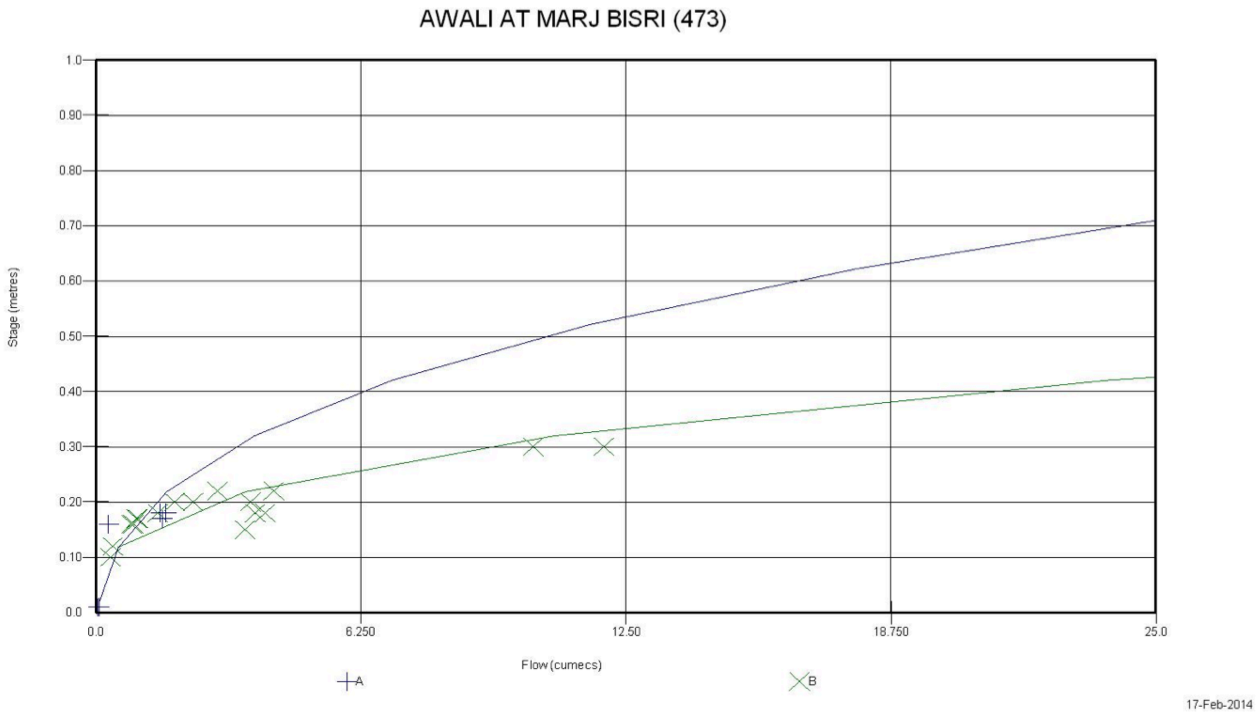


Figure 6 – The two rating curves developed for the water year 2001-2002. The first one (the black one) with validity 01/09/2001-07/01/2002 is adjusted on few observations smaller than 3 m^3/s, while the second one (the green one, corresponding to the brown curve of Figure 5), which validity extends from 07/01/2002 to 31/08/2002, is adjusted on observed discharges smaller than 12 m^3/s. Moreover, both curves are based on water level observations below 0.3 m. As discussed in a previous report (and also clear from the Figure 4) around 0.3 m there is a discontinuity in the rating curve due to the presence of a threshold (the end of the bridge concrete bottom coverage)

In this comparison, there is another issue that does not appear to be satisfactorily, namely the curvature of the rating curves, encapsulated into the value of the exponent of the equations. For bottom slopes larger than 1/1000, as one would expect for Marj Bisri, the friction slope is close to the bottom slope and the flood waves move according to the “kinematic wave” flow pattern. In the kinematic wave flow, for rectangular cross sections similar to the one in Marj Bisri, the rating curve can be described as:

$$Q = \frac{B^{5/3} J^{1/2}}{n(2y+B)^{2/3}}\ y^{5/3} \qquad (1)$$

where:
Q is the discharge in [$m^3\ s^{-1}$]
y is the water stage in [m]
J is the friction slope
n is the Manning’s friction coefficient in [$s\ m^{-1/3}$]
B is the bottom width in [m]

If the bottom slope S_0 is relatively high (>1/1000) it is possible to assume that the friction slope coincides with the bottom slope, namely $J \cong S_0$, to give:

$$Q = \frac{B^{5/3} S_0^{1/2}}{n(2y+B)^{2/3}}\, y^{5/3} \tag{2}$$

From Eq. 2 it is possible to notice that for a rectangular cross section the exponent is expected to be smaller (in general) or at most equal to 5/3, when $y \ll B$ so that $2y + B \cong B$. Larger values of the exponent may be also expected when the cross section is not perfectly rectangular, as in the hypothesis, as well as in the presence of mild bottom slopes when the friction slope increases with y, Q, namely $J = J(y, Q)$ and becomes larger than the bottom slope $J > S_0$.

Therefore, given that (1) the cross section at Marj Bisri can be significantly assimilated to a rectangular cross section, and (2) the slope (as for the information I received) is not smaller than 1/1000, one should extrapolate the rating curves using equations having an exponent not far from 2/3 and very unlikely around 2.8 (as in the case of most of the LITANI developed rating curves).

To show what this means, I have adjusted Eq. 2 to the Marj Bisri cross section, which from the Fig. 4 seems slightly wider than the 20 m (4 x 5) of rectangular channels under the bridge. Assuming a bottom width of 23 m, a roughness coefficient of 0.015 s $m^{-1/3}$ (rough concrete surface) and a bottom slope of 1/100, the curvature needed to fit the observations in Fig. 2 is 1.95, which is not to far from 1.667 (2/3). **Please note that the assumptions on the actual cross section width along the vertical of the gauge and on the bottom slope can easily be incorrect given le limited available information. Nonetheless, what really matters is the curvature of the rating curve (namely the value of the exponent), which is of the uttermost importance when extrapolating beyond the range of the measurements. The resulting curvature is much smaller than the one, around 2.8 assumed in 12 rating curves out of 18.**

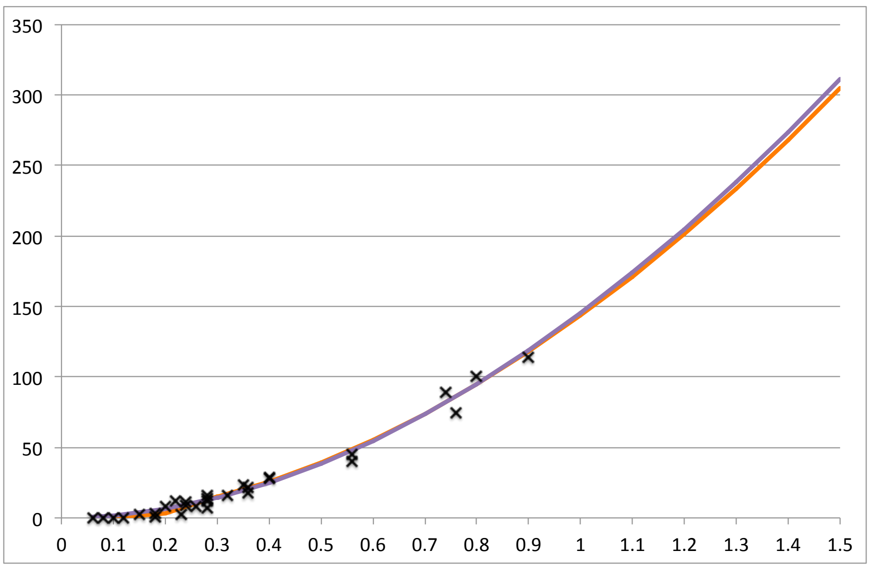


Figure 7 – The grey line represents the result from Eq. 2, while the red line represents the regression equation fitted to the observations as in Fig. 2

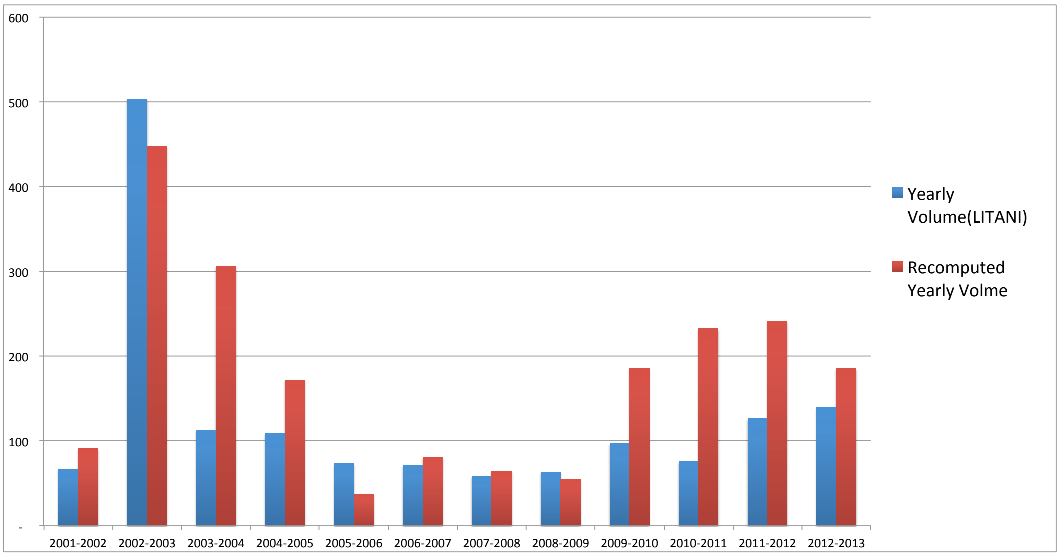


Figure 8 – Yearly volumes in Mm^3 computed by LITANI (in blue) and re-computed using the modified 2002-2003 rating curve

Conclusions

Given all the above considerations, it must be acknowledged that the monthly water volume figures prublished by LITANI in the period 2001-2013 are highly questionable and uncertain, particularly on medium and high flow values. This is because several rating curves are obtained by fitting low observed values and then extrapolated far beyond the measurement range.
One could decide to use a single rating curve (namely the 2002-2003 rating curve fitted to the observations as in Figures 2 and 7) for all the years, but the result would also be hard to justify, due to the significant variations in the resulting volumes from the ones published by LITANI. As can be seen from Figure 8 apart from 2002-2003 and 2005-2006, in most of the other years the re-estimated volume is larger than what previously estimated.
Moreover, at this point in time in the project, the change of basic data would mean a large amount of work to be requested to the Consultant, which I do not think appropriate.

Therefore, bearing in mind that more available water than what estimated by LITANI may be expected (as per Figure 8), to be on the safe side, my suggestion is **to recompute only the monthly values for the year 2002-2003 using the revised rating curve**. This is justified mainly by the lack of fit of the measurement values (Figures 1 and 2) as well as by the excessively large values estimated in correspondence of highest water levels. On the other hand this modification leads to a relatively minor change in the yearly volume of about 11%
All the other water years will be taken at face value, although the hydrology report will discuss the potential effects caused by the extremely high uncertainty in the adopted rating curves.

APPENDIX – RATING CURVES

Rating	Type	From	To	Stage range
A	Power	01-Sep-2001	07-Jan-2002	0.0 -10.0

Q = 47.57638168 (h + 0.084)^2.8

Rating	Type	From	To	Stage range
B	Power	08-Jan-2002	31-Aug-2002	0.0 -10.00

Q = 291.62478638 (h - 0.018) ^ 2.747

Rating	Type	From	To	Stage range
C	Power	01-Sep-2002	31-Aug-2003	0.0 -10.0

Q = 236.60668945 (h + 0.013)^2.8

Rating	Type	From	To	Stage range
D	Power	01-Sep-2003	31-Aug-2004	0.0 - 10.0

Q = 97.79440308 (h + 0.012)^2.8

Rating	Type	From	To	Stage range
E	Power	01-Sep-2004	08-Mar-2005	0.0 - 10.0

Q = 203.36956787 (h - 0.113)^2.074

Rating	Type	From	To	Stage range
F	Power	09-Mar-2005	31-Aug-2005	0.0 - 10.0

Q = 40.31083298 (h + 0.218) ^2.8

Rating	Type	From	To	Stage range
G	Power	01-Sep-2005	03-May-2006	0.0 - 10.0

Q = 52.56432343 (h - 0.006) ^1.3

Rating	Type	From	To	Stage range
H	Power	04-May-2006	31-Aug-2006	0.0 - 10.0

Q = 6.45376825 (h + 0.463) ^2.8

Rating	Type	From	To	Stage range
I	Power	01-Sep-2006	06-Jun-2007	0.0 - 10.0

Q = 73.45562744 (h + 0.127) ^2.8

Rating	Type	From	To	Stage range
J	Power	07-Jun-2007	02-Sep-2007	0.0 - 10.0

Q = 0.68843657 (h + 0.72) ^2.8

Rating	Type	From	To	Stage range
K	Power	03-Sep-2007	31-Aug-2008	0.0 - 10.0

Q = 63.71121979 (h + 0.144) ^2.8

Rating	Type	From	To	Stage range
L	Power	01-Sep-2008	31-Aug-2009	0.0 – 0.28

Q = 45.731987 (h - 0.008) ^1.407

Rating	Type	From	To	Stage range
M	Power	01-Sep-2009	19-Apr-2010	0.0 – 2.00

Q = 54.8168335 (h + 0.162) ^2.8

Rating	Type	From	To	Stage range
N	Power	20-Apr-2010	31-Aug-2010	0.0 – 2.00

Q = 105.35637665 (h - 0.16) ^1.3

Rating	Type	From	To	Stage range
O	Power	01-Sep-2010	31-Aug-2011	0.0 – 2.00

Q = 118.71948242 (h - 0.009) ^2.8

Rating	Type	From	To	Stage range
P	Power	01-Sep-2011	31-Aug-2012	0.0 – 0.76

Q = 118.92578125 (h + 0.029) ^2.8

Rating	Type	From	To	Stage range
Q	Power	01-Sep-2012	05-Dec-2012	0.0 – 0.18

Q = 86.50099945 (h - 0.138) ^1.3

Rating	Type	From	To	Stage range
R	Power	06-Dec-2012	31-Aug-2013	0.0 – 0.7

Q = 90.14857483 (h - 0.006) ^1.768