Documentation for

Environmental/Low Flow Computation Spreadsheet

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Introduction

Instream flow requirements have historically been expressed in terms of some minimum flow. Examples include establishment of the minimum flow permitted water users or dams are required to release or pass, the non-depletable flow, or other appropriate instream flow limit. Minimum flows are also commonly been used in establishing waste load allocations and for a variety of other regulatory and management purposes.

The most commonly used minimum flow has been the 7Q10 flow, or the 7-day averaged low flow that would be expected to occur at a frequency less than or equal to every 10 years. The 7Q10 flow is most often used as a "reasonable worst case" in a variety of regulatory and management contexts (e.g. analysis of chronic toxicity, an indicator of drought conditions, in the regulation of withdrawals, and for numerous other purposes as described by Pyrce 2004). In addition to the 7Q10 flow, other 7QX flows have been used for other purposes, such as the 7Q1, 7Q2, 7Q5, 7Q20 and 7Q25 flow as tabulated by Pyrce (2004) in Table 1. In addition to yearly minima, minimum flows during specific periods of the year are often important, such as in establishing environmental flow requirements (Martin 2013).

The computation of minimum flows is most commonly based on an analysis of the historical record of daily flows. This spreadsheet was developed to aid in the evaluation of daily flow records for the establishment of minimum and environmental flows. It consists of a series of worksheets and underlying Visual Basic code for the analysis of daily flow data. The worksheets in light green are the computational worksheets, while the others are used in computations only and are only of interest to code evaluators/developers.

Table 1. 7Q Flow Uses Source (From: Pyrce 2004)

7Q Flow	Uses	Source
7Q1	known as the "dry weather flow"	Smakhtin (2001)
	used for abstraction licensing	Smakhtin (2001),Smakhtin and Toulouse (1998)
	used to remove the effect of minor river regulation	Matalas (1963)
7Q2	one of the most widely used design low flow indices	Smakhtin (2001), Smakhtin and Toulouse (1998)
	habitat maintenance flow (represents a period of stress on the system that causes some reduction in populations)	Ontario Ministry of Natural Resources (1994)
	criteria for developing permits for wasteload allocations	Tortorelli (2002)
	used as an instream flow	Caissie and El-Jabi (2003)
	some use as a specific design application for stormwater holding facilities based on stormwater modelling	Odom (2004, personal communication)
	not defined	Beran and Gustard (1977), Hayes (1991), Ries and Friesz (2000)
7Q5	critical low flow for low quality fishery waters (a stream classified for the beneficial use of warmwater semi-permanent fish life propagation or warmwater marginal fish life propagation)	South Dakota Department of Environment and Natural Resources (1998)
7Q20	used as a systems extinction flow (causes significant stress on the system)	Ontario Ministry of Natural Resources (1994)
	used as an indicator of the minimum flow needed to maintain the ecosystem	Ontario Ministry of Natural Resources et al. (2002)
	limiting condition for sewage treatment and wastewater disposal for a receiving water body	Ontario Ministry of the Environment (2000)
	indicator of potential mortality of aquatic life for larger streams	Imhof and Brown (2003)
	• summer design low flow for effluent wastewater discharge and drought flow periods and volumes	Cusimano (1992)
	• flow for sustainable yield/carrying capacity for eco-tourism	Shrivastava (2003)
7Q25	• critical low flow for high quality fishery waters (surface waters designated for the beneficial use of coldwater permanent fish life propagation, coldwater marginal fish life propagation, or warmwater permanent fish life propagation)	South Dakota Department of Environment and Natural Resources (1998)

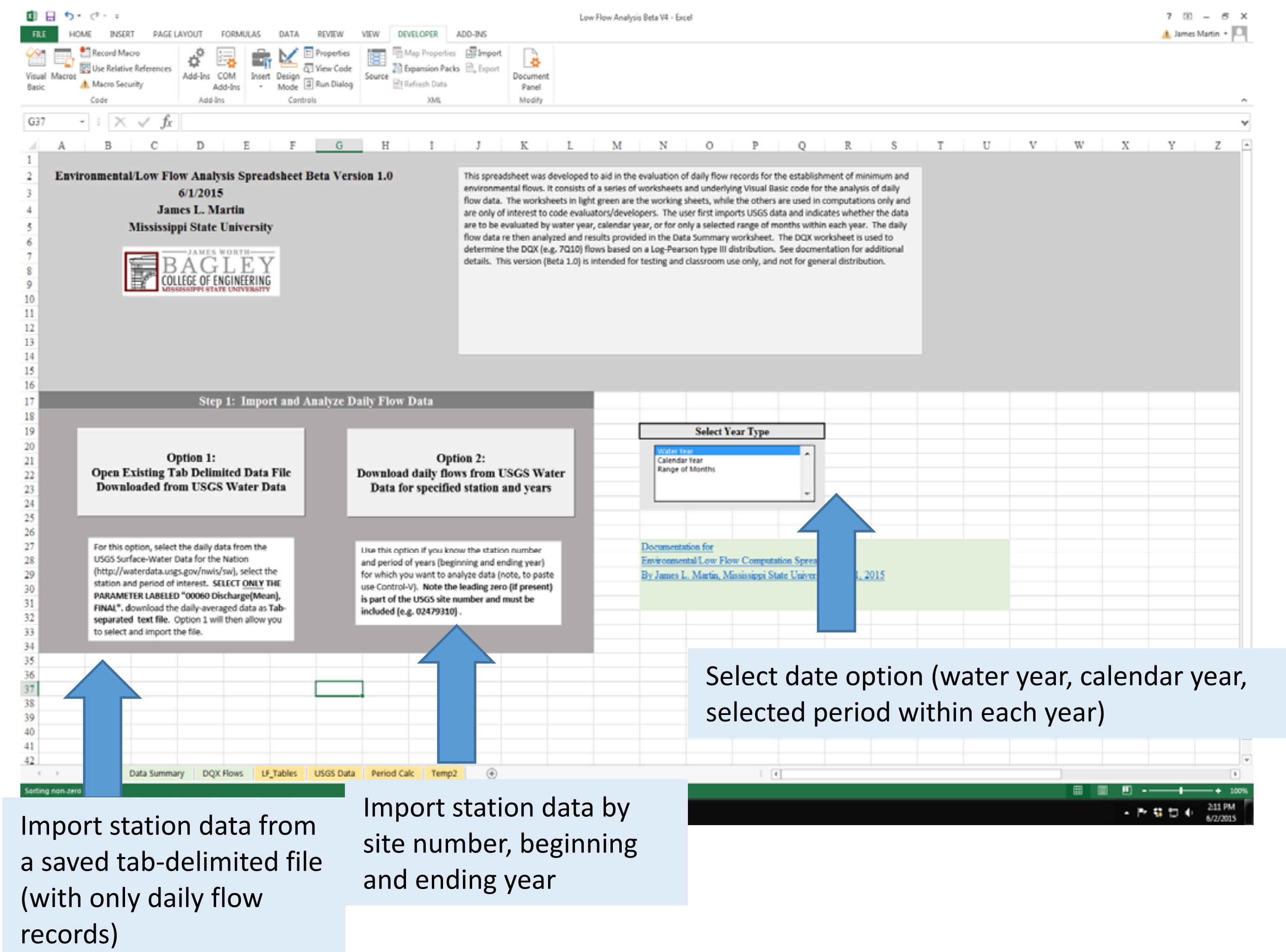
Methodology

Step 1: Getting Flow Records

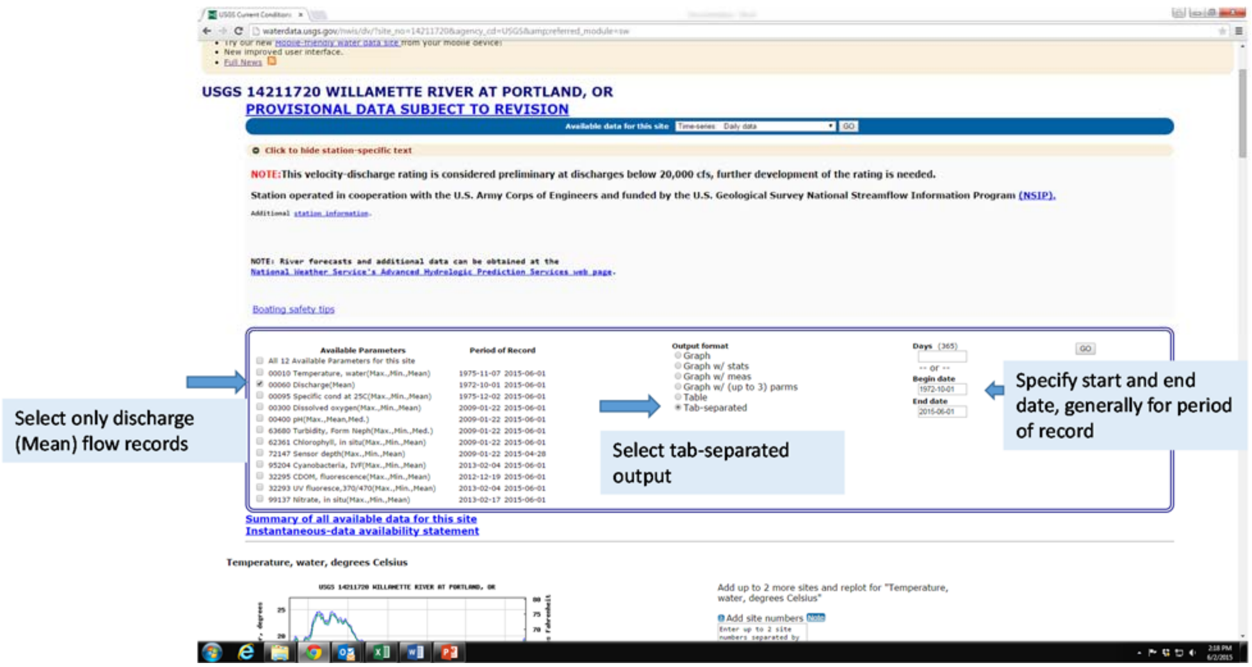
The analysis begins with the selection of USGS gauging station and the importation of flow data. The spreadsheet is based upon the use of daily-averaged flow data. The data can be imported by specifying the site. An alternative is to open a previously saved tab delimited dataset. The USGS data can be downloaded from http://waterdata.usgs.gov/nwis/sw.

The user must also determine the period for the analysis of the flow data, and three options are presently included:

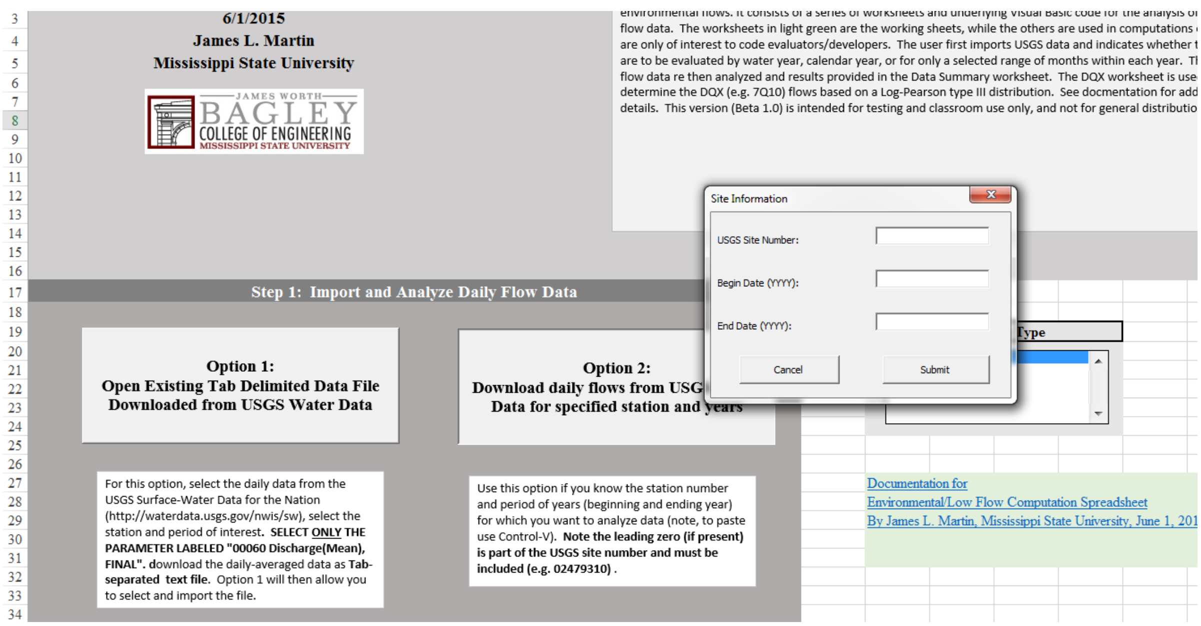
- Water Year: extends from October 1 to September 30 of the following year.
- Calendar year: extends from January 1 to December 31 of the following year
- Month period: begin on day one of a user specified start month to the end of a user specified end month.



If the user imports a file they must be careful to ONLY select the discharge (mean) flow records. The output should be saved as a tab-separated text file, the time period (beginning and end dates) should typically be for the period of record.



If the user elects to specify a site number they will prompted for the USGS site number and a beginning and ending year. The site number is generally an 8-10 digit number, and if there is a leading zero it is part of the site number and must be included in the specification.



Once the flow data are selected, they are saved to a worksheet titled “USGS data”. The site number is then used to obtain the site characteristics, which are placed in a table in the Data Summary worksheet (after first being loaded to the sheet “Temp2”). One caution with respect to the continued maintenance of this spreadsheet is that URL’s change, and may have to be updated in the VBA code.

Table 1. Example of Station Information Table

Summary of Station Information	
Site identification number	2479310
Site name	PASCAGOULA RIVER AT GRAHAM FERRY, MS
Site type	ST
Decimal latitude	30.61055556
Decimal longitude	-88.64138889
1996	5
Decimal Latitude-longitude datum	NAD83
Altitude of Gage/land surface	0
Altitude accuracy	0.1
Altitude datum	NGVD29
Hydrologic unit code	3170006
Data type	dv
Parameter code	60
Statistical code	3
Internal database key	19
Additional measurement description	FINAL
Medium group code	wat
Parameter group code	
SRS ID	1645423
Access code	0
Begin date	10/1/1993
End date	9/30/2009
Record count	5479

Once the data are loaded into the spreadsheet, the daily data are parsed (in the worksheet “period calc”) to remove unnecessary records and obtain a time series of daily flows.

Step 2: Statistical evaluation

The second step is to evaluate the statistical distribution of the daily flows. First, all zero or missing flow values are removed. In this version, there is no testing or treatment of outliers and no attempt to fill in missing values.

Once the missing data are removed, the remaining data are evaluated over the period of record and by each year (water year or calendar year) to determine the

- Number of observations
- Mean: the average (1st moment)
- Standard deviation: measure of the spread of the distribution (2nd moment)
- Skewness: measure of the asymmetry of the distribution (third moment)
- Kurtosis: degree of flatness or peakedness of the distribution (4th moment)

$$\bar{x} = average = \frac{\sum x_i}{n}$$

$$\sigma = \text{standard deviation} = \sqrt{\frac{\sum \left(x_i - \bar{x}\right)^2}{n-1}}$$

$$s(x) = Skewness = \left[\sum \frac{\left(x_i - \bar{x}\right)^3}{\sigma^3}\right] \frac{n}{(n-1)(n-2)}$$

$$k(x) = Kurtosis = \left[\sum \frac{\left(x_i - \bar{x}\right)^4}{\sigma^4} \frac{n(n+1)}{(n-1)(n-2)(n-3)}\right] - \frac{3(n-1)^2}{(n-2)(n-3)}$$

An example of a statistical evaluation from the data summary worksheet is provided in Table 2.

Table 2. Example of statistical evaluation for daily flow records

Analysis for all daily flows for period of record and by year							
Year	Number of daily flows	Maximum Daily Flow	Minimum Daily Flow	Mean Annual Flow	Standard deviation of daily flows	Skewness Coefficient	Kurtosis Coefficient
All Flows	1380	68700	1060	6237.43	8687.08	4.17	-3.01
1993	0	0	999999	0.00	0.00	0.00	0.00
1994	92	30200	2240	6577.50	6796.06	2.15	-3.10
1995	92	8560	1440	3064.02	1546.41	1.74	-3.10
1996	92	9060	1900	3402.50	1576.07	1.80	-3.10
1997	92	23500	1990	6094.67	4624.03	1.78	-3.10
1998	92	67700	1920	4978.26	7870.72	6.74	43.72
1999	92	7800	1350	2550.54	1246.29	2.11	-3.09
2000	92	2550	1060	1379.13	265.15	1.85	-3.09
2001	92	46500	2840	9675.54	9507.81	2.46	-3.10
2002	92	43900	1780	4666.52	6510.33	4.84	12.21
2003	92	68700	4700	17491.09	16400.12	1.99	-3.10
2004	92	37000	2520	9145.43	9372.75	2.08	-3.10
2005	92	68500	2930	11858.70	14309.50	2.73	-3.10
2006	0	0	999999	0.00	0.00	0.00	0.00
2007	92	10000	1390	3197.07	1777.08	1.76	-3.10
2008	92	30600	1290	5884.46	6925.45	2.45	-3.10
2009	92	11700	2080	3595.98	2223.41	2.31	-2.63
2010	0	0	999999	0.00	0.00	0.00	0.00
2011	0	0	999999	0.00	0.00	0.00	0.00
2012	0	0	999999	0.00	0.00	0.00	0.00
2013	0	0	999999	0.00	0.00	0.00	0.00
2014	0	0	999999	0.00	0.00	0.00	0.00
2015	0	0	999999	0.00	0.00	0.00	0.00

In addition to the above statistics, the flow data for the period of record are sorted (using a bubble sort) in descending order, ranked (from 1 to N where N is the number of observations), and assigned a probability of occurrence using the Weibull plotting position

$$P = \frac{rank}{N+1}$$

after which a probability plot for all daily flows for the period of record is developed, as illustrated.

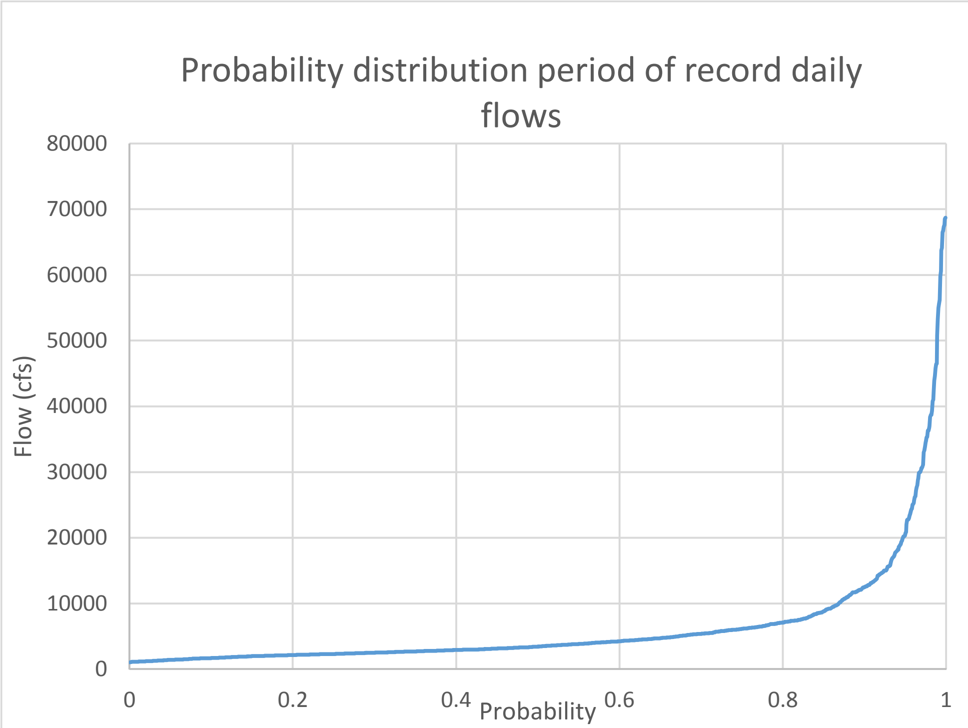


Figure 1. Example probability (duration) plot for period of record daily flows

Step 3: Computation of DQX flows

The next section of the spreadsheet and VBA code compute and output the DQX flows (e.g. 7Q10), where D is the averaging period and X is the recurrence interval (e.g. 10 years, or P=probability=1/10). First the user specifies the D averaging period and the minimum number of observations required for that period (water year, calendar year or period of moths) to be included in the analysis.

D-Day averaging and minima

A D-day average is taken here to mean a running average of daily flows over the entire period of record, such that a window for D-days duration is moved sequentially through the record in 1 day increments (e.g. for D=3 days, the average of days 1,2,3 and then 2,3,4, etc.). The parsed (zero values removed) daily flows are then averaged each D-day period.

The second step is to determine a date (and then period) associated with each D-day average. The average is referenced to the middle day of the interval, such as (Zaidmen et al. 2002)

$$m = \left(\frac{D}{2} + 1\right), where\ D\ is\ even$$

$$m = \left(\frac{D+1}{2}\right), where\ D\ is\ odd$$

Where m is the index day. The index day (m) is then associated with the year in which that day falls for the purposes of determining yearly values (e.g. minima).

Missing Data and Outliers

In this present spreadsheet, all missing or zero data are excluded and there is no attempt to identify or treat outliers.

Statistical Evaluation

Once all of the D-day averages are determined, the D-day averaged values are evaluated using the statistical methods described above and then tabulated. An example of the tabulated values (from the DQX worksheet) is illustrated below:

Table 3. Example of statistics for the D-Day (in this case 7 day) averaged flows

Beginning with 1st day of month			7 and ending on the last day of month				9
Analysis of D-Day Average flows for period of record and by year							
Month Range	Number of flows	Maximum Flow	Minimum Flow	Mean	Standard deviation	Skewness Coefficient	Kurtosis Coefficient
All D-Day	1374	63243	1137	6232.52	8020.51	3.84	-3.01
1993	92	25986	2470	6576.65	6431.97	1.92	-3.10
1994	92	7104	1581	2988.35	1361.36	1.56	-3.10
1995	92	16457	2080	4001.86	2608.28	2.88	2.94
1996	92	17443	2034	5503.90	3504.98	1.00	-3.10
1997	92	20096	2117	5025.19	4251.77	2.76	-2.96
1998	92	5663	1420	2485.70	1067.60	1.58	-3.10
1999	92	5823	1137	1526.49	737.08	4.31	10.31
2000	92	38186	3046	9631.93	8554.02	2.14	-3.10
2001	92	50629	1929	5930.64	9142.14	3.60	3.53
2002	92	63243	5457	17095.90	14891.52	2.01	-3.10
2003	92	35371	2847	8213.23	8112.61	2.44	-3.10
2004	92	56414	3349	11830.37	12620.30	2.37	-3.10
2005	1	2921	2921	0.00	0.00	0.00	0.00
2006	91	7591	1460	3190.88	1621.76	1.14	-3.10
2007	92	26900	1469	5891.01	6406.06	2.16	-3.10
2008	86	10160	2216	3414.95	1842.49	2.55	-0.87
2009	0	0	999999	0.00	0.00	0.00	0.00

Estimation of the DQX flows

The DQX flows are determined using a log-Pearson Type III frequency analysis. The methodology is based on the “Log-Pearson Frequency Analysis Spreadsheet, Version 2.5, 6/2014” developed by S.E. Yochum, Hydrologist, and distributed by the NRCS. This spreadsheet, as described in Chapter 5 of “Part 654 Stream Restoration Design National Engineering Handbook” was designed to compute high flows (e.g. 100 year return period storm flows), rather than a low flow analysis. For the analysis of low flows, the tables of k values used in Yochum's spreadsheet were replaced by those from Table 1 of "Tables of Percentage Points of the Pearson Type III Distribution, Technical Release 38, USDA NCRS T-38, 1998.

The methodology was first based on developed a yearly list of yearly minimum flows from Table 3 above, excluding those years for which the number of D-day average records were less than the user specified value. The values were then converted to natural log values and statistics recomputed for the log values.

The appropriate k values for the low-flow distribution were interpolated for the computed skewness coefficient (of the ln(DQ) flows) and a specified range of probabilities (14 values ranging from P=0.01 to 0.95) from the NCRS T-38 values (see sheet LF_values). The

$$DQX = \exp(\bar{x} + \sigma k)$$

where

$\bar{x}$ = the mean of the natural log values,

σ = the standard deviation of the natural log values, and

k the percentage points of the Pearson Type III Distribution (interpolated).

Following Yochum (2014), the resulting DQX flow (cfs) was rounded to three significant figures. Note that unlike Yochum (2014), for this analysis there was no correction for outliers. In addition, there was no correction for generalized skew.

Once the DQX flows were determined, again based on Yochum's (2014) spreadsheet, the 95% confidence intervals were determined.

$$X_{CI,U} = \bar{x} + \sigma K_{CI,U}$$
$$X_{CI,L} = \bar{x} + \sigma K_{CI,L}$$

Where $X_{CI,U}$ and $X_{CI,L}$ are the logarithmic upper and lower confidence limits, and

$$K_{CI,U} = \frac{k + \sqrt{k^2 - ab}}{a}$$
$$K_{CI,L} = \frac{k - \sqrt{k^2 - ab}}{a}$$
$$a = 1 - \frac{z_c^2}{2(n-1)}$$
$$b = k^2 - \frac{z_c^2}{n}$$

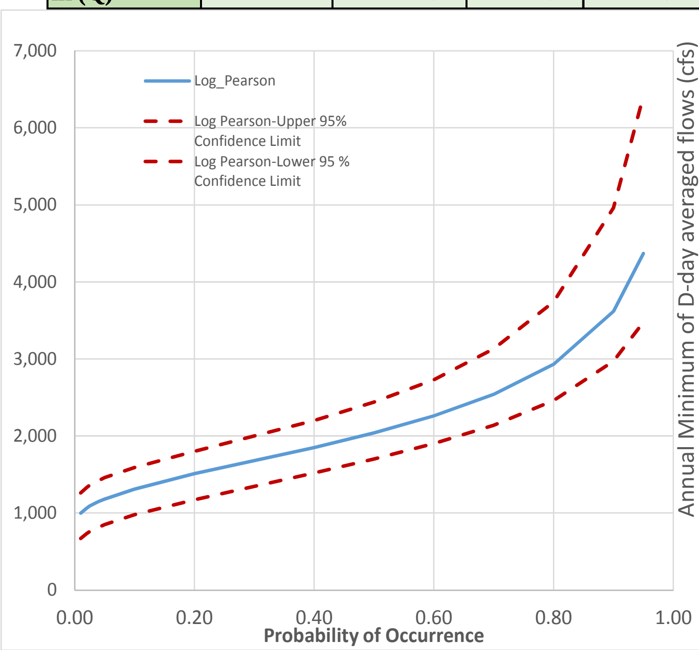
where

n=record length

z_c = standard normal deviate, which for the 95% confidence interval = 1.64485.

An example of the computed probability distribution is provided below.

	Corrected Yearly Minimums (considering specified Minimum days)				
	Analyses of	7 Day Moving Average Flows			
	Number of Years of D-Day flows	Mean	Standard deviation	Skewness Coefficient	Kurtosis Coefficient
	15	2307.43	1078.62	1.90	-3.77
ln (Q)	15	7.66	0.40	0.71	-1.56



For 7 (D) Day Averaged Flows				
			95 % Confidence Interval	
Return Period (X, years)	Probability	DQX Flow (cfs)	Upper (cfs)	Lower (cfs)
100	0.01	998	1,260	670
50	0.02	1,060	1,330	734
40	0.03	1,090	1,360	758
25	0.04	1,150	1,420	816
20	0.05	1,180	1,460	849
10	0.10	1,310	1,590	977
5	0.20	1,510	1,800	1,170
2.5	0.40	1,850	2,200	1,520
2	0.50	2,040	2,440	1,700
1.666667	0.60	2,260	2,730	1,900
1.428571	0.70	2,540	3,130	2,140
1.25	0.80	2,930	3,740	2,460
1.111111	0.90	3,620	4,960	2,970
1.052632	0.95	4,370	6,420	3,480

References

Martin, James. L. 2013. Hydro-Environmental Science. CRC Press.

NRCS. 1998. “Part 654 Stream Restoration Design National Engineering Handbook, Chapter 5 Stream Hydrology, USDA Natural Resources Conservation Service

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Pyrce R.S. 2004. "Hydrological Low Flow Indices and their Uses," WSC Report No.04-2004, watershed science Centre, Peterborough, Ontario, pp. 37.

Zaidman, M.D., V. Keller and A.R. Young. “Low Flow Frequency Analysis, Guidelines for Best Practice,” Technical Report W6-064/TR1, Center for Ecology and Hydrology, Oxfordshire, England

World Meteorological Organization. 2008. “Manual on low-flow estimation and prediction,” Operational Hydrology Report No. 50, WMO-No. 1029