Estimating flood risk

GG22A: GEOSPHERE & HYDROSPHERE
Hydrology

What is risk?

- Risk = (likelihood of hazard occurring) x (consequences of the hazard)

- Good risk management might aim to:
  - Reduce the likelihood of the hazard occurring
  - Reduce the consequences of the hazard

- This seems very obvious, but good risk management is actually very difficult!

Risk management in practice

- Risk avoidance
  - Don’t invest in property etc. to avoid the liability that goes with it
  - By avoiding risk, you are also avoiding any potential rewards
  - Some level of risk is necessary (*acceptable risk*)
- **Assumes that the risks are known**

Risk management in practice

- Risk reduction
  - Methods to reduce the likelihood and severity of loss

To be effective, *risks must be properly understood*

Risk management in practice

- Risk retention
  - Accepting loss when it occurs
  - Includes “self-insurance”. Common practice in business – setting capital aside
  - All risks that are not avoided or transferred are retained by default:
    - Uninsurable risk
    - Unknown risk

To be effective, *risks must be properly understood*

Risk management in practice

- Risk transfer
  - Causing another party to accept the risk
  - Insurance
    - For the insurance company, over time losses must be less than income from insurance premiums
    - Assumes losses are all economic or can be compensated for financially.

To be effective, *risks must be properly understood* (appropriate cover and premium).

Understanding risk

The Changing Business Risk Environment:

- Physical (Flooding, drought, landslides, hurricanes)
- Political (Instability, water wars? Environmental terrorists?)
- Economic (Changes in supply networks, currency fluctuations)
- Social (Migration, civil unrest)
- Regulatory (Changing tax regimes, regulatory structures)
- Structural and Commercial (emerging liability risks, due diligence, assets and liability management)

These are inter-related, making risk complex

Understanding risk

- In all areas of risk management, risk must be well understood.
- Of course, this means understanding both
  - ***Likelihood*** and
  - ***Consequences***
- Requires good risk assessment

Probabilistic risk assessment

- Commonly used in engineering
- Characterised by:
  - the magnitude (severity) of the possible adverse consequences
  - the likelihood (probability) of occurrence of each consequence
- Attempts to characterise risk precisely

Flood risk: defining probability

- What is the probability of a flood occurring?
- Usually defined using past observations
  - But extreme events are rare: few observations

Flood risk: defining probability

- Annual exceedance probability:
  - The probability that a flood will exceed a given level in any year
- Return periods (or recurrence interval):
  - The average frequency of occurrence of an event of a particular magnitude
    - "1 in 100 year event"
    - The inverse of the exceedance probability – i.e. "1 in 100 year" return period means a 1/100 (or 1%) exceedance probability in <u>any</u> year
  - Problem of perception: a "1 in 100 year" event could occur in consecutive years – no regularity implied

Flood risk: defining probability

- Return period (T_r):

$$T_r = \frac{n+1}{m}$$

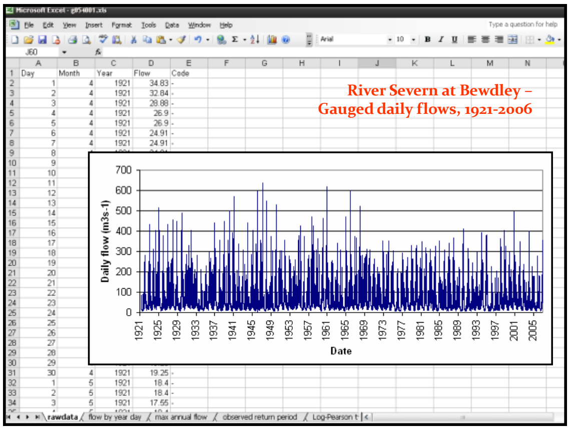
- Annual exceedance probability (p):

$$p = \frac{1}{T_r} = \frac{m}{n+1}$$

- where: $\boldsymbol{n}$ = number of years on record; $\boldsymbol{m}$ = rank of the event being considered

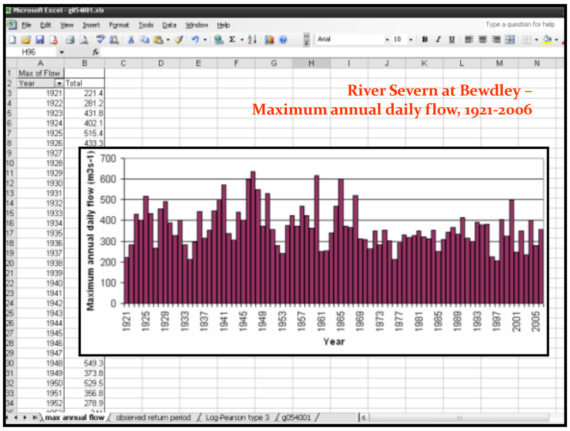
Calculating Return Period (T_r)

1. Gauged data
2. Maximum annual value
3. Rank
4. Calculate return period



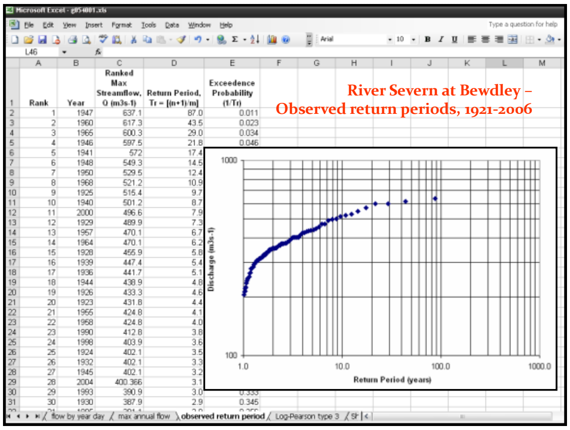
River Severn at Bewdley – Gauged daily flows, 1921-2006

	A	B	C	D	E
1	Day	Month	Year	Flow	Code
2	1	4	1921	34.83	-
3	2	4	1921	32.84	-
4	3	4	1921	28.88	-
5	4	4	1921	26.9	-
6	5	4	1921	26.9	-
7	6	4	1921	24.91	-
8	7	4	1921	24.91	-
9	8				
10	9				
11	10				
12	11				
13	12				
14	13				
15	14				
16	15				
17	16				
18	17				
19	18				
20	19				
21	20				
22	21				
23	22				
24	23				
25	24				
26	25				
27	26				
28	27				
29	28				
30	29				
31	30	4	1921	19.25	-
32	1	5	1921	18.4	-
33	2	5	1921	18.4	-
34	3	5	1921	17.55	-



River Severn at Bewdley – Maximum annual daily flow, 1921-2006

	A	B
1	Max of Flow	
2	Year	Total
3	1921	221.4
4	1922	281.2
5	1923	431.8
6	1924	402.1
7	1925	515.4
8	1926	433.3
9	1927	
10	1928	
11	1929	
12	1930	
13	1931	
14	1932	
15	1933	
16	1934	
17	1935	
18	1936	
19	1937	
20	1938	
21	1939	
22	1940	
23	1941	
24	1942	
25	1943	
26	1944	
27	1945	
28	1946	
29	1947	
30	1948	549.3
31	1949	373.8
32	1950	529.5
33	1951	356.8
34	1952	278.9



River Severn at Bewdley – Observed return periods, 1921-2006

Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)
1	1947	637.1	87.0	0.011
2	1960	617.3	43.5	0.023
3	1965	600.3	29.0	0.034
4	1946	597.5	21.8	0.046
5	1941	572	17.4	
6	1948	549.3	14.5	
7	1950	529.5	12.4	
8	1968	521.2	10.9	
9	1925	515.4	9.7	
10	1940	501.2	8.7	
11	2000	496.6	7.9	
12	1929	489.9	7.3	
13	1957	470.1	6.7	
14	1964	470.1	6.2	
15	1928	455.9	5.8	
16	1939	447.4	5.4	
17	1936	441.7	5.1	
18	1944	438.9	4.8	
19	1926	433.3	4.6	
20	1923	431.8	4.4	
21	1955	424.8	4.1	
22	1958	424.8	4.0	
23	1990	412.8	3.8	
24	1998	403.9	3.6	
25	1924	402.1	3.5	
26	1932	402.1	3.3	
27	1945	402.1	3.2	
28	2004	400.366	3.1	
29	1993	390.9	3.0	0.333
30	1930	387.9	2.9	0.345

Return Periods

- The return period of the maximum flood in our observations will be equal to the number of years of observations plus 1.
  - In our date set, this is 87, giving an annual exceedance probability of 1/87 = 0.012 or 1.2%
- This is likely to be an extremely inaccurate estimate of that event's actual probability
  - The longer the observation record, the more accurate the probability estimates (but the most extreme events will still be inaccurately estimated).

Flood risk: defining probability

- If a flood of a particular size (or greater) occurs on average once every T_r years, then the probability, p, of such an event being **exceeded** in any year is:

$$p = 1/T_r$$

- Then, the probability that there will be NO such flood in any year is $(1 - p)$ and over the next $\boldsymbol{n}$ years is:

$$P_n = (1 - p)^n$$

Flood risk: defining probability

- *If a flood of 5 m or greater occurs on average once every 50 years, what is the probability it will **<u>not</u>** occur for the next 20 years?*
- $T = 50$; $P = 0.02$; $n = 20$

$$P_n = (1 - P)^n$$

$$P_{20} = (1 - 0.02)^{20} = 0.67$$

- Therefore, there is a:
  - 67% chance that a 50-year flood will not occur in the next 20 years
  - 33% chance that ***at least*** one such flood will occur (there may be more than one)

Flood risk: defining probability

- *You are building a bridge and want to be 95% sure that it will not be hit by a 500-year flood. How many years should you expect to have at this level of certainty?*
  - Solve $P_n = (1 - p)^n$ for n using $p = 0.002$ and $P_n = 0.95$:

$$n = \frac{\ln(P_n)}{\ln(1-p)}$$

$$= \frac{\ln(0.95)}{\ln(0.998)} = 25.62\ years$$

Flood risk: defining probability

$$n = \frac{\ln(P_n)}{\ln(1-p)}$$

Tr	*p*	*n* (P_n = 0.50)	*n* (P_n = 0.80)	*n* (P_n = 0.95)	*n* (P_n = 0.99)
1.001	0.999	**0.10**	**0.03**	**0.01**	**0.001**
2	0.5	**1.00**	**0.32**	**0.07**	**0.01**
5	0.2	**3.11**	**1.00**	**0.23**	**0.05**
10	0.1	**6.58**	**2.12**	**0.49**	**0.10**
25	0.04	**16.98**	**5.47**	**1.26**	**0.25**
50	0.02	**34.31**	**11.05**	**2.54**	**0.50**
100	0.01	**68.97**	**22.20**	**5.10**	**1.00**
200	0.005	**138.28**	**44.52**	**10.23**	**2.01**
500	0.002	**346.23**	**111.46**	**25.62**	**5.02**
1000	0.001	**692.80**	**223.03**	**51.27**	**10.05**

Flood risk: defining probability

- *You want to be 95% sure that the bridge will not flood in the next 50 years. What is the return period you must prepare for?*

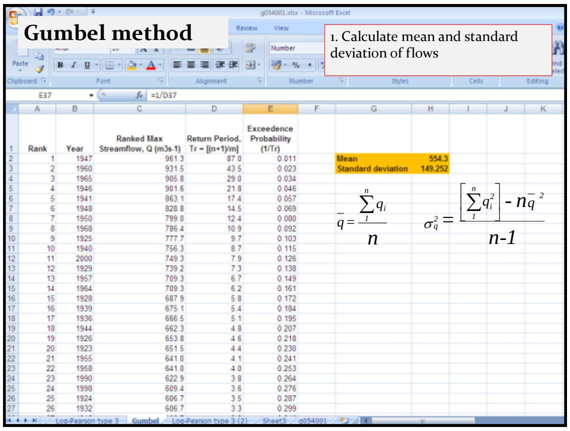
$$T_r = \frac{1}{1 - P_n^{(1/n)}}$$

$$= \frac{1}{1 - 0.95^{0.02}} = 975.28$$

Therefore, to have a high degree of certainty over an extended period of time you must prepare for an extreme event.

Extrapolating Return Periods

- In order to estimate the levels of more extreme events, we need to fit a *probability density function* (pdf) to the observed data.
- Numerous different methods –
  - Normal, Log Normal
  - Gumbel extreme value type 1
  - Log-Pearson Type III
    - This is the recommended technique for flood frequency analysis in the United States (US Water Advisory Committee 1982)



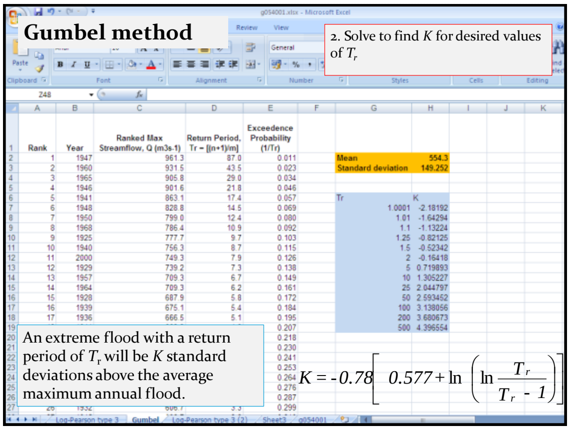
Gumbel method

1. Calculate mean and standard deviation of flows

Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)
1	1947	961.3	87.0	0.011
2	1960	931.5	43.5	0.023
3	1965	905.8	29.0	0.034
4	1946	901.6	21.8	0.046
5	1941	863.1	17.4	0.057
6	1948	828.8	14.5	0.069
7	1950	799.0	12.4	0.080
8	1968	786.4	10.9	0.092
9	1925	777.7	9.7	0.103
10	1940	756.3	8.7	0.115
11	2000	749.3	7.9	0.126
12	1929	739.2	7.3	0.138
13	1957	709.3	6.7	0.149
14	1964	709.3	6.2	0.161
15	1928	687.9	5.8	0.172
16	1939	675.1	5.4	0.184
17	1936	666.5	5.1	0.195
18	1944	662.3	4.8	0.207
19	1926	653.8	4.6	0.218
20	1923	651.5	4.4	0.230
21	1955	641.0	4.1	0.241
22	1958	641.0	4.0	0.253
23	1990	622.9	3.8	0.264
24	1998	609.4	3.6	0.276
25	1924	606.7	3.5	0.287
26	1932	606.7	3.3	0.299

Mean	554.3
Standard deviation	149.252

$$\bar{q} = \frac{\sum_{1}^{n} q_i}{n} \qquad \sigma_q^2 = \frac{\left[\sum_{1}^{n} q_i^2\right] - n\bar{q}^2}{n-1}$$



Gumbel method

2. Solve to find K for desired values of T_r

Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)
1	1947	961.3	87.0	0.011
2	1960	931.5	43.5	0.023
3	1965	905.8	29.0	0.034
4	1946	901.6	21.8	0.046
5	1941	863.1	17.4	0.057
6	1948	828.8	14.5	0.069
7	1950	799.0	12.4	0.080
8	1968	786.4	10.9	0.092
9	1925	777.7	9.7	0.103
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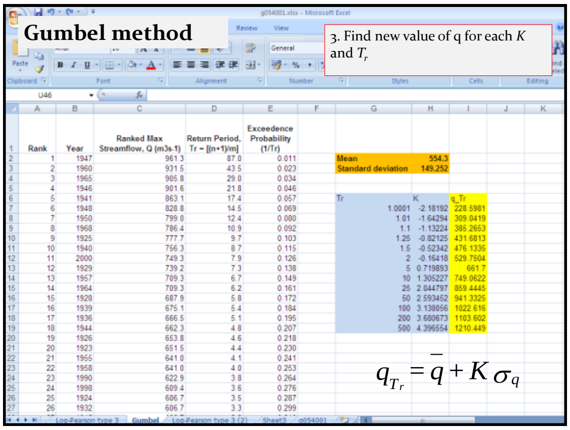
17	1936	666.5	5.1	0.195
				0.207
				0.218
				0.230
				0.241
				0.253
				0.264
				0.276
				0.287
26	1932	606.7	3.3	0.299

Mean	554.3
Standard deviation	149.252

Tr	K
1.0001	-2.18192
1.01	-1.64294
1.1	-1.13224
1.25	-0.82125
1.5	-0.52342
2	-0.16418
5	0.719893
10	1.305227
25	2.044797
50	2.593452
100	3.138056
200	3.680673
500	4.396554

An extreme flood with a return period of T_r will be K standard deviations above the average maximum annual flood.

$$K = -0.78\left[0.577 + \ln\left(\ln\frac{T_r}{T_r - 1}\right)\right]$$



Gumbel method

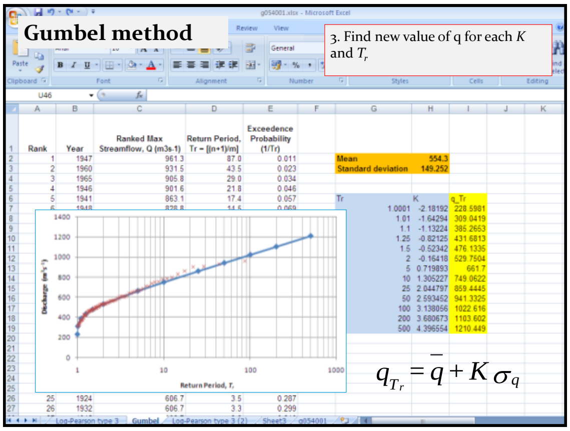
3. Find new value of q for each K and T_r

Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)
1	1947	961.3	87.0	0.011
2	1960	931.5	43.5	0.023
3	1965	905.8	29.0	0.034
4	1946	901.6	21.8	0.046
5	1941	863.1	17.4	0.057
6	1948	828.8	14.5	0.069
7	1950	799.0	12.4	0.080
8	1968	786.4	10.9	0.092
9	1925	777.7	9.7	0.103
10	1940	756.3	8.7	0.115
11	2000	749.3	7.9	0.126
12	1929	739.2	7.3	0.138
13	1957	709.3	6.7	0.149
14	1964	709.3	6.2	0.161
15	1928	687.9	5.8	0.172
16	1939	675.1	5.4	0.184
17	1936	666.5	5.1	0.195
18	1944	662.3	4.8	0.207
19	1926	653.8	4.6	0.218
20	1923	651.5	4.4	0.230
21	1955	641.0	4.1	0.241
22	1958	641.0	4.0	0.253
23	1990	622.9	3.8	0.264
24	1998	609.4	3.6	0.276
25	1924	606.7	3.5	0.287
26	1932	606.7	3.3	0.299

Mean	554.3
Standard deviation	149.252

Tr	K	q_Tr
1.0001	-2.18192	228.5981
1.01	-1.64294	309.0419
1.1	-1.13224	385.2653
1.25	-0.82125	431.6813
1.5	-0.52342	476.1335
2	-0.16418	529.7504
5	0.719893	661.7
10	1.305227	749.0622
25	2.044797	859.4445
50	2.593452	941.3325
100	3.138056	1022.616
200	3.680673	1103.602
500	4.396554	1210.449

$$q_{T_r} = \bar{q} + K\,\sigma_q$$



Gumbel method

3. Find new value of q for each K and T_r

Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)
1	1947	961.3	87.0	0.011
2	1960	931.5	43.5	0.023
3	1965	905.8	29.0	0.034
4	1946	901.6	21.8	0.046
5	1941	863.1	17.4	0.057
25	1924	606.7	3.5	0.287
26	1932	606.7	3.3	0.299

Mean	554.3
Standard deviation	149.252

Tr	K	q_Tr
1.0001	-2.18192	228.5981
1.01	-1.64294	309.0419
1.1	-1.13224	385.2653
1.25	-0.82125	431.6813
1.5	-0.52342	476.1335
2	-0.16418	529.7504
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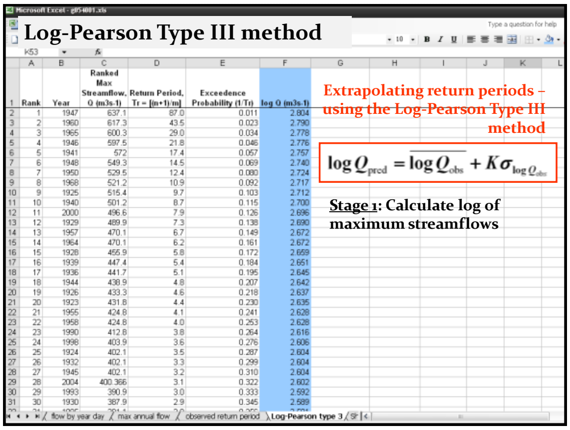
100	3.138056	1022.616
200	3.680673	1103.602
500	4.396554	1210.449

$$q_{T_r} = \bar{q} + K\,\sigma_q$$



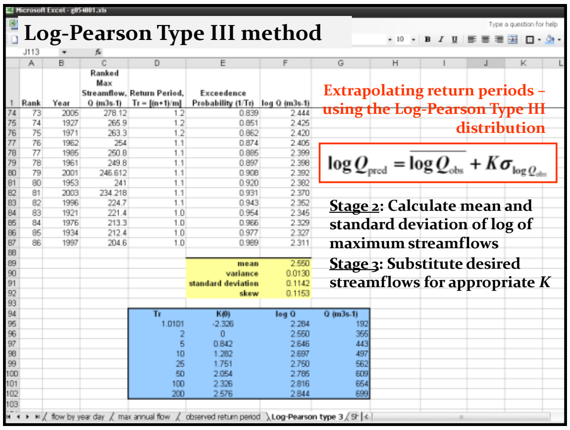
Log-Pearson Type III method

1	Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)	log Q (m3s-1)
2	1	1947	637.1	87.0	0.011	2.804
3	2	1960	617.3	43.5	0.023	2.790
4	3	1965	600.3	29.0	0.034	2.778
5	4	1946	597.5	21.8	0.046	2.776
6	5	1941	572	17.4	0.057	2.757
7	6	1948	549.3	14.5	0.069	2.740
8	7	1950	529.5	12.4	0.080	2.724
9	8	1968	521.2	10.9	0.092	2.717
10	9	1925	515.4	9.7	0.103	2.712
11	10	1940	501.2	8.7	0.115	2.700
12	11	2000	496.6	7.9	0.126	2.696
13	12	1929	489.9	7.3	0.138	2.690
14	13	1957	470.1	6.7	0.149	2.672
15	14	1964	470.1	6.2	0.161	2.672
16	15	1928	455.9	5.8	0.172	2.659
17	16	1939	447.4	5.4	0.184	2.651
18	17	1936	441.7	5.1	0.195	2.645
19	18	1944	438.9	4.8	0.207	2.642
20	19	1926	433.3	4.6	0.218	2.637
21	20	1923	431.8	4.4	0.230	2.635
22	21	1955	424.8	4.1	0.241	2.628
23	22	1958	424.8	4.0	0.253	2.628
24	23	1990	412.8	3.8	0.264	2.616
25	24	1998	403.9	3.6	0.276	2.606
26	25	1924	402.1	3.5	0.287	2.604
27	26	1932	402.1	3.3	0.299	2.604
28	27	1945	402.1	3.2	0.310	2.604
29	28	2004	400.366	3.1	0.322	2.602
30	29	1993	390.9	3.0	0.333	2.592
31	30	1930	387.9	2.9	0.345	2.589

Extrapolating return periods – using the Log-Pearson Type III method

$$\log Q_{\text{pred}} = \overline{\log Q_{\text{obs}}} + K\sigma_{\log Q_{\text{obs}}}$$

<u>Stage 1</u>: Calculate log of maximum streamflows



Log-Pearson Type III method

1	Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)	log Q (m3s-1)
74	73	2006	278.12	1.2	0.839	2.444
75	74	1927	265.9	1.2	0.851	2.425
76	75	1971	263.3	1.2	0.862	2.420
77	76	1962	254	1.1	0.874	2.405
78	77	1985	250.8	1.1	0.885	2.399
79	78	1961	249.8	1.1	0.897	2.398
80	79	2001	246.612	1.1	0.908	2.392
81	80	1953	241	1.1	0.920	2.382
82	81	2003	234.218	1.1	0.931	2.370
83	82	1996	224.7	1.1	0.943	2.352
84	83	1921	221.4	1.0	0.954	2.345
85	84	1976	213.3	1.0	0.966	2.329
86	85	1934	212.4	1.0	0.977	2.327
87	86	1997	204.6	1.0	0.989	2.311

mean	2.550
variance	0.0130
standard deviation	0.1142
skew	0.1153

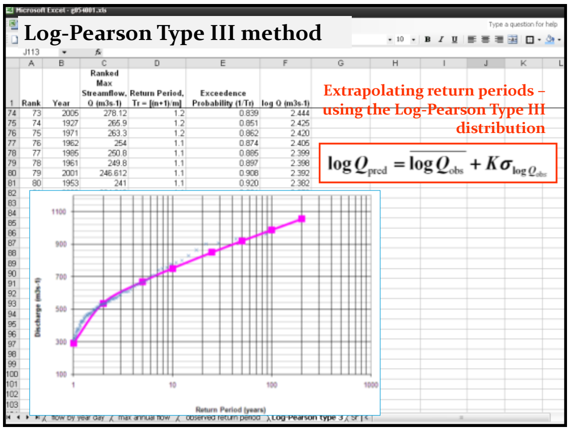
Tr	K(0)	log Q	Q (m3s-1)
1.0101	-2.326	2.284	192
2	0	2.550	355
5	0.842	2.646	443
10	1.282	2.697	497
25	1.751	2.750	562
50	2.054	2.785	609
100	2.326	2.816	654
200	2.576	2.844	699

Extrapolating return periods – using the Log-Pearson Type III distribution

$$\log Q_{\text{pred}} = \overline{\log Q_{\text{obs}}} + K\sigma_{\log Q_{\text{obs}}}$$

<u>Stage 2</u>: Calculate mean and standard deviation of log of maximum streamflows

<u>Stage 3</u>: Substitute desired streamflows for appropriate *K*

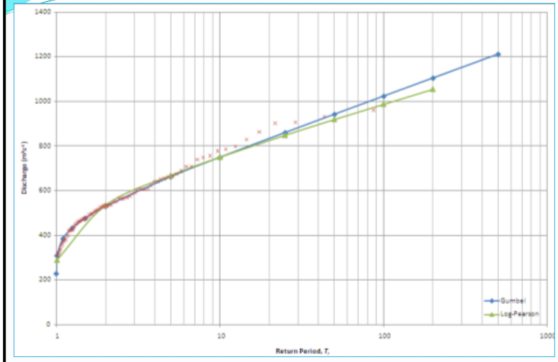


Log-Pearson Type III method

1	Rank	Year	Ranked Max Streamflow, Q (m3s-1)	Return Period, Tr = [(n+1)/m]	Exceedence Probability (1/Tr)	log Q (m3s-1)
74	73	2006	278.12	1.2	0.839	2.444
75	74	1927	265.9	1.2	0.851	2.425
76	75	1971	263.3	1.2	0.862	2.420
77	76	1962	254	1.1	0.874	2.405
78	77	1985	250.8	1.1	0.885	2.399
79	78	1961	249.8	1.1	0.897	2.398
80	79	2001	246.612	1.1	0.908	2.392
81	80	1953	241	1.1	0.920	2.382

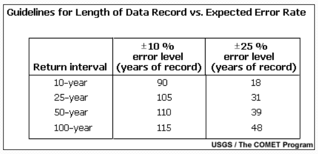
Extrapolating return periods – using the Log-Pearson Type III distribution

$$\log Q_{\text{pred}} = \overline{\log Q_{\text{obs}}} + K\sigma_{\log Q_{\text{obs}}}$$



Extrapolating return periods

- We should not over-extrapolate –
  - As we move beyond the observed record, accuracy drops quickly
  - We should not predict return periods for more than twice the length of the return period (i.e. 100 years of observation to predict the level of a flood with a 200 year return period).



Guidelines for Length of Data Record vs. Expected Error Rate

Return interval	±10 % error level (years of record)	±25 % error level (years of record)
10-year	90	18
25-year	105	31
50-year	110	39
100-year	115	48

USGS / The COMET Program

Flood frequency analysis - issues

- A major assumption is that the observation record should be from homogeneous conditions:
  - This means that each flood needs to occur under the *same type of conditions*.
    - Basin alterations (e.g. urbanisation) alter the behaviour of flood events, and can dramatically reduce the number of years of homogeneous data
    - For example, urbanisation 20 years ago means that a 100-year record could be reduced to only 20 useable years

Flood frequency analysis

- More Information:
  - Oregon State University website:
    - http://water.oregonstate.edu/streamflow/analysis/floodfreq/
  - MetEd website – Flood Frequency course:
    - http://www.meted.ucar.edu/hydro/basic/FloodFrequency/

Flood frequency and climate change

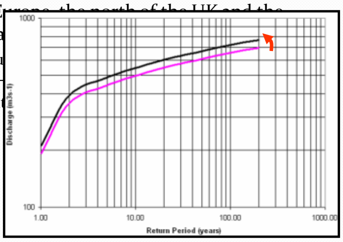
- As well as changing *averages*, climate change is likely to affect *extremes* of distributions.
- Possible effect of climate change on events:
  - Increased *frequency* and *magnitude* (return periods decreasing)
  - Therefore, increased *probability* and *consequences*
- Changes the *risk* and may increase *vulnerability* (risk management strategy no longer sufficient).

Flood frequency and climate change

- Climate change = non-homogeneous conditions
  - Past flood events are no longer a reliable indicator of the probability of future events
  - Complicates our analysis – difficult to determine length of reliable record
  - Change in probability may be cyclical in line with natural climate variability – e.g. ENSO

Flood frequency and climate change

- Lehner et al. (2006):
  - The study finds that, as early as 2020, across large parts of the northern E
    Iberian peninsula
    - floods with a retu
      to occur every 40-
    - the 100-year event



Flood risk and climate change

- If climate change is changing risk, good risk management will need to predict this – requires climate prediction
  - Problem – this is extremely difficult, and full of uncertainty!